FOOT FUNCTION IN LATERAL ANKLE SPRAINS AND CHRONIC ANKLE INSTABILITY

A Dissertation

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Doctor of Philosophy

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by

John J. Fraser, PT, MS, OCS

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ABSTRACT

Purpose: To compare three-dimensional multisegmented ankle-foot kinematic and clinical measures of foot posture and morphology, multisegmented joint motion and play, strength, and dynamic balance in in acute ankle sprain (LAS), chronic ankle instability (CAI), coper, and control groups. The effects of midfoot joint mobilizations and a one-week home exercise program (HEP) compared to a sham intervention and HEP on clinical measures were also studied in the LAS group.

Methods: A cross-sectional study of 80 recreationally-active individuals (Control: n=22, Coper: n=21, LAS: n=17, CAI: n=20) assessing group differences in sagittal, frontal, and transverse plane kinematics of the hallux, medial forefoot, lateral forefoot, medial midfoot, lateral midfoot, and rearfoot on shank during the stance phase of gait during barefoot walking using an electromagnetic motion capture. Clinical measures foot posture index (FPI), morphologic measures, joint motion and play at the rearfoot and forefoot, strength of the ankle and hallux, and Star Excursion Balance Test (SEBT) were also assessed.

A laboratory-based, crossover randomized control trial was performed in participants with a recent LAS. All participants were instructed in a stretching, strengthening, and balance HEP and were randomized *a priori* to receive midfoot joint mobilizations (forefoot supination cuboid glide and plantar 1st tarsometatarsal) or a sham laying-of-hands. Changes in pain, physical, psychological, and functional PROs, foot morphology, joint mobility, tissue reactivity, sensorimotor function, and dynamic balance were assessed pre-to-post treatment and one-week following. Participants crossed-over following a one-week washout to receive the contrast treatment and were assessed pre, post, and one-week following.

Results: The LAS group had up to 4.1° more rearfoot inversion during midstance of gait (mean difference: 3.1°) from 42 to 49% of stance phase compared to healthy controls. The CAI group had up to 5.3° more rearfoot inversion (mean difference: 3.6°) from 34% to 91% of stance phase compared to controls. There were no further statistical differences found between CAI and Copers, other planes, or segments of the ankle foot complex. There were no significant group differences in FPI or morphological measures. Compared to controls, LAS and CAI groups had decreased ankle dorsiflexion and greater forefoot and rearfoot frontal plane motion, increased 1st MT plantarflexion and sagittal excursion, increased talocrural glide and internal rotation, decreased forefoot inversion joint play, and decreased strength in all motions except dorsiflexion. The LAS group also demonstrated decreased distal tibiofibular and forefoot general laxity, and SEBT performance compared to controls.

Midfoot joint mobilization had greater effects in reducing pain 1-week post, and increasing Single Assessment Numeric Evaluation, Global Rating of Change, forefoot inversion, and plantar tarsometatarsal joint play compared to a sham treatment and HEP following LAS.

Conclusion: Groups with LAS and CAI demonstrate more rearfoot inversion and altered joint function and strength in the multisegmented ankle-foot complex compared to controls. Clinicians and researchers should include interventions that control inversion and increase eversion following LAS or CAI. Midfoot joint mobilizations and HEP yielded greater pain reduction, perceived improvement, and forefoot joint play compared to sham.

Department of Kinesiology

Curry School of Education

University of Virginia

Charlottesville, Virginia

APPROVAL OF THE DISSERTATION

This dissertation, “Foot function in lateral ankle sprains 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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Jay Hertel, Chair

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Susan F. Saliba

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Joseph M. Hart

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Joseph S. Park

_________________ Date

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MULTISEGMENTED ANKLE-FOOT GAIT KINEMATICS IN ACUTE ANKLE SPRAIN, CHRONIC ANKLE INSTABILITY, COPER, AND CONTROL GROUPS.

Abstract:

Purpose: To compare three-dimensional multisegmented ankle-foot kinematics in acute ankle sprain (LAS), chronic ankle instability (CAI), coper, and control groups.

Methods: A cross-sectional study of 80 recreationally-active individuals (Control: n=22, Coper: n=21, LAS: n=17, CAI: n=20) assessing group differences in sagittal, frontal, and transverse plane kinematics of the hallux, medial forefoot, lateral forefoot, medial midfoot, lateral midfoot, and rearfoot on shank during the stance phase of gait. Barefoot walking kinematics were assessed using an electromagnetic motion capture. The average joint excursions of 10-steps were analyzed using Statistical Parametric Mapping (SPM) ANOVA and *post hoc* t-tests comparing Coper, LAS, or CAI versus controls. Secondary analysis was performed comparing CAI versus Copers.

Results: The LAS group had up to 4.1° more rearfoot inversion during midstance (mean difference: 3.1°) from 42 to 49% of stance phase compared to healthy controls. The CAI group had up to 5.3° more rearfoot inversion (mean difference: 3.6°) from 34% to 91% of stance phase compared to controls. There were no further statistical differences found between CAI and Copers, other planes, or segments of the ankle foot complex. A trend of increased navicular dorsiflexion (LAS: p=.38, CAI: p=.10) and forefoot abduction (lateral forefoot: LAS: p=.31, CAI: p= .21; medial forefoot: LAS: p=.42, CAI: p=.28) during early to midstance that persisted to pre-swing was also observed.

Conclusion: Groups with LAS and CAI demonstrate more rearfoot inversion compared to controls. Clinicians and researchers should include interventions that control inversion and increase eversion following LAS or CAI.

INTRODUCTION

Lateral ankle sprains (LAS) are a common musculoskeletal injury incurred by competitive and tactical athletes[1,2] and the general public.[3] LAS result from high-velocity moments and extremes of inversion, internal rotation, and plantarflexion.[4–7] Forty percent of individuals who incur a LAS will develop Chronic Ankle Instability (CAI),[8] a condition described by perceived or episodic giving way of the ankle and functional limitation that persist at least one-year following injury.[9] There are potential biomechanical consequences in the ankle-foot complex following LAS and CAI that warrant investigation.[10]

Individuals with LAS and CAI have altered gait kinematics[11–15], muscle activity,[14,16–18] and a more lateral center of pressure progression in the foot[17–22] compared to healthy controls. Following LAS, individuals have diminished gait velocity, [23] step length, [23] time in single support,[23], more plantar flexion,[23,24] and a more inverted rearfoot pre-to-post initial contact compared to healthy controls.[24] Individuals who progress to CAI walk at lower velocities and with a wider base of support,[25] increased shank external rotation, a plantarflexed, inverted, and internally rotated foot,[14,15] and decreased stride to stride variability in shank-rearfoot coupling.[13] Center of pressure progression in the foot is more variable post initial contact,[26] more lateral throughout stance phase,[17,18,27] slower to progress to the central and lateral forefoot,[20] and delayed in the lateral forefoot pre-swing.[18] Plantar pressure is decreased in the heels and toes[20,27] and increased in the lateral midfoot and forefoot[18,27]

Alteration of ankle-foot biomechanics during gait is likely attributed to one or more mechanical and neurophysiologic mechanisms. Inability to decouple the rearfoot and forefoot due to mechanical or neurophysiological constraint may limit foot compliance necessary for ground accommodation during walking.[10] An inability to effectively couple the rearfoot and forefoot or bias extrinsic and intrinsic foot muscles (IFM) due to neuromotor dysfunction could also plausibly contribute to alteration of ankle-foot biomechanics.[10] Since most studies of ankle kinematics treat the foot as a rigid segment, it is unclear whether there are alteration of foot kinematics in the LAS and CAI population. No studies to our knowledge in the acute LAS population and only study in the CAI population[11] have investigated gait kinematics analyses using a multisegmented foot model. In the one study of multisegmented foot kinematics, participants with CAI were found to have increased rearfoot eversion from 56-73% of stance and a more inverted medial forefoot during mid to late stance phase.[14] The finding of eversion in the rearfoot contradicts a multitude of studies that found a more inverted foot in CAI patients, a finding that is postulated to result in the alteration of kinetics and giving way in the ankle.[28] Therefore, the purpose of this cross-sectional study was to compare three-dimensional multisegmented ankle-foot kinematics in acute ankle sprain, chronic ankle instability, coper, and control groups.

METHODS

Design

A laboratory-based, descriptive cross-sectional study was performed where the independent variable was group (Control, Coper, LAS, CAI) and the dependent variables were sagittal, frontal, and transverse plane kinematics of the hallux, medial forefoot, lateral forefoot, medial midfoot, lateral midfoot, and rearfoot on shank during gait initiation.

Participants

A convenience sample of 80 recreationally-active individuals (Control: n=22, Coper: n=21, LAS: n=17, CAI: n=20) aged 18-35 with and without history of a LAS and CAI were recruited from a public university for participation. The participants in this study were part of larger study of multisegmented foot function, with demographic and injury history previously reported.[29] **Table 1** details group demographic, injury history, and patient-reported outcome measures. Recreationally-active was defined as participation in some form of physical activity for at least 20-minutes per day, at least three times a week. Participants were included in the Control group if they did not have any history of ankle or foot sprain. Individuals who sustained an inversion sprain that affected function 2-8 weeks prior to consent were included in the LAS group. Participants with a history of at least one LAS at a minimum of 12-months prior to the study who did not experience perceived or episodic giving way and scored Identification of Functional Ankle Instability (IdFAI) ≤10, Foot and Ankle Ability Measure (FAAM) activities of daily living subscale (ADL) ≥99 and FAAM-Sport≥97 were included in the Coper group.[30] Individuals with a history of at least one LAS at a minimum of 12-months prior to the study who experienced continued perceived or episodes of giving way and scored IdFAI >10, FAAM-ADL <90 and FAAM-Sport < 85 and did not sprain their ankle in the past 8-weeks were included in the CAI group.[9] Details of participant demographic information, injury history, and self-report functional measures are reported in **Table 1**.

Individuals were excluded if they had a history of fracture in the leg or foot, self-reported disability due to neuromuscular impairment in the lower extremity, neurological or vestibular impairment that affected balance, diabetes mellitus, lumbosacral radiculopathy, a soft tissue disorder such as Marfan or Ehlers-Danlos syndrome, any absolute contraindication to ankle or foot joint manipulation, or were pregnant. Participants who met inclusion criteria provided informed consent. **Figure 1** details the study flow sheet from recruitment to analysis. Data was collected in the university's sports medicine laboratory. The study was approved by the Institutional Review Board.

Instruments

Three-dimensional joint kinematics of the ankle-foot complex was assessed using the Flock of Birds (Ascension Technologies, Inc., Burlington, Vermont) electromagnetic motion analysis system with one 7.9-mm and six 2-mm sensors sampling at 100 Hz and controlled by Motion Monitor software (Innovative Sports Training, Inc., Chicago, Illinois). A non-conductive forceplate (Bertec Corporation, Columbus, Ohio) sampling at 1-kHz was used to collect body mass and ground reaction forces demarcating the beginning and end of stance phase.

Procedures

Following consent, participants provided demographic information, health and injury history, and completed the Foot and Ankle Ability Measure (FAAM) ADL[31] and Sport subscales,[32] Identification of Functional Ankle Instability (IdFAI),[33] the Patient Reported Outcomes Measurement Information System (PROMIS) General Health Questionnaire,[34] the 11-item Tampa Scale of Kinesiophobia (TSK-11),[35] and the Godin Leisure-time Exercise Questionnaire.[36] Predicted EUROQOL (EQ-5D) quality of life scores were calculated using previously described methods.[37] Height, mass, and leg length were measured and foot posture index assessed.[38]

Data collection was performed by the primary author who was a physical therapist, board-certified orthopaedic clinical specialist with 15-years of clinical experience and 3-years of research experience using motion capture systems.

Participant Setup

Six 2-mm sensors were fastened on the dorsal aspect of the great toe proximal phalanx (hallux), dorsal mid 1st (medial forefoot) and 4th (lateral midfoot) metatarsal, medial navicular (medial midfoot), lateral cuboid (lateral midfoot), posterior calcaneus (rearfoot) using Leukotape (BSN Medical, Hamburg, Germany). A 7.9-mm sensor was fastened to the medial aspect of the mid-tibia (shank) using Leukotape and PowerFlex bandage (Andover Healthcare, Salisbury, Massachusetts) (**Figure 2**). Kinematics were assessed using X, Y', Z" Euler Angles with the segments referenced to the next proximal segment (rearfoot to shank, medial and lateral midfoot segments referenced to rearfoot, medial forefoot referenced to medial midfoot, lateral forefoot referenced to lateral midfoot, and hallux referenced to medial forefoot). The XY defined sagittal plane motion about a Z-axis (+ dorsiflexion, - plantarflexion), ZY defined frontal plane motion about an X-axis (+ eversion, - inversion,), and XZ defined transverse plane motion about the Y-axis (+ adduction, - abduction). Local coordinate systems (**Figure 2**) were digitized using the most dorsal aspect of the proximal and distal joint lines for each segment and a third point on the plane (**Table 2**).

Gait

Participants were positioned so their foot would contact the center of the forceplate during the initial step with the test limb. They were asked to keep their gaze forward while walking 4-6 steps at a self-selected pace across an 8.1-meter stage. Stance phase of gait was demarcated when ground reaction force exceeded a 20-N threshold during weight acceptance and persisted until force dropped below the threshold during the transition to swing phase. Kinematic data from each participant was reduced to 100 points and averaged across the 10 steps. Angular displacement at each time-point during stance phase was calculated from the difference in motion from the average quiet-standing values.

Statistical Analysis

A priori sample size estimation of 19 participants were needed to demonstrate large effects based on variance of multisegmented rearfoot eversion, an α=.05, and β=.20.[39] Levene's test of homogeneity of variance was performed prior to analysis of participant demographics, injury history, and patient-reported outcomes. Group differences (LAS, Coper, CAI, Controls) were assessed using a one-way ANOVA for variables that had significant homogeneity on Levene's test. Variables that failed to achieve significance with Levene's test were assessed using Welch's ANOVA. For significant findings, *post hoc* Tukey's Honestly Significant Differences (HSD) were calculated. Group demographics, injury history, and patient-reported outcomes, were analyzed using Statistical Package for Social Sciences (SPSS) Version 23.0 (IBM, Inc., Armonk, New York). The level of significance was $p \leq 0.05$ for all analyses.

Group means and standard deviations of the kinematic measures were calculated and assessed using Statistical Parametric Mapping (SPM) one-way analysis of variance

SPM_{ANOVA}.[40] *Post-hoc* analyses were performed using SPM *t*-tests (SPM_t) comparing kinematics in LAS, Copers, and CAI to healthy controls. Secondary analysis comparing Copers to CAI were also performed. Kinematic data was analyzed using spm1d Version 0.4, a package written by Pataky[41] for one-dimensional SPM analysis using MATLAB (MathWorks, Inc., Natick, Massachusetts).

RESULTS

There were no significant group differences for age, height, weight, BMI, or foot posture. **Table 1** details the demographic information, injury history, and patient-reported outcome measures for each group. The LAS and CAI group had significantly greater pain at present ($p<.001$) and worst pain in the preceding week ($p<.001$), lower PROMIS General Health Physical Composite scores ($p<.001$), decreased predicted quality of life ($p<.001$), increased kinesiophobia ($p<.001$), higher IdFAI scores ($p<.001$), and lower functional scores on the FAAM-ADL score ($p<.001$) and SANE ($p<.001$) and FAAM-Sport score ($p<.001$) and SANE ($p<.001$).[29]

Kinematic group means, standard deviations, and SPM($_{ANOVA}$) F scores are reported in **Figures 3-6.** A significant group difference was found for rearfoot frontal plane motion from 41-49% of stance ($p=.04$) (**Figure 3**). *Post hoc* analysis found that the LAS group had more rearfoot inversion (mean difference: 3.1°, range: 2.5°-4.1°) from 42% to 49% of stance phase compared to healthy controls. Similarly, the CAI group had increased rearfoot inversion (mean difference: 3.6°, range: 2.8°-5.5°) from 34% to 91% of stance phase compared to controls. There were no further statistical differences found between CAI and Copers, other planes of motion, or segments of the ankle foot complex. While non-significant, a trend of increased navicular dorsiflexion (LAS: 1.0°-3.0° throughout stance, p=.38; CAI: 3.9°-6.2° throughout stance, p=.10) (**Figure 4**), lateral forefoot abduction (LAS: 1.6°-3.0° from 19% to 91%, p=.31; CAI: 2.2°-2.6° from 0 to 91%, p=.21) (**Figure 5**), and medial forefoot abduction (LAS: 1.9°-2.2° from 60%-85%, p=.42; CAI: 2.3°-3.5° from 0%-92%, p=.28) (**Figure 5**) was observed in both LAS and CAI groups compared to healthy controls. Increased cuboid adduction (LAS: 3.5°-5.6°) was observed throughout stance phase in the LAS group only compared to healthy controls (**Figure 4**).

DISCUSSION

The principle findings of this cross-sectional kinematic study of gait using a multisegmented ankle-foot model were that groups with a subacute LAS demonstrated more inversion (mean difference: 3.1°, range: 2.5°-4.1°) in the rearfoot during midstance (42 to 49% of stance phase) compared to healthy controls. Similarly, the CAI group had more rearfoot inversion (mean difference: 3.6°, range: 2.8°-5.5°) from 34% to 91% of stance phase. A trend of increased navicular dorsiflexion and forefoot abduction in the latter half of stance was also observed.

Rearfoot

To our knowledge, this was the first study to investigate multisegmented foot kinematics during gait in individuals with a recent LAS. This study substantiates that aberrant rearfoot frontal plane kinematics commonly observed in CAI may present as early as 2-weeks post-injury. Altered movement strategies early in the injury course are likely a precursor to the more maladaptive motor patterns found in CAI. A previous study of kinematics in participants with acute LAS found a more inverted foot pre-to-post initial contact compared to healthy controls.[24] While the LAS group in our study had increased mean inversion throughout stance phase, the only significant increase was observed midstance. High kinematic variability is plausibly a consequence of heterogeneity of symptom severity, as many participants experienced a degree of recovery at the time of collection.

The findings of increased rearfoot inversion in the CAI group in our study is consistent with previously reported literature.[12,14,15] Delahunt and colleagues [14] studied rearfoot kinematics and found that individuals with CAI had up to 3.5° increased inversion compared to healthy controls 200-milliseconds pre-to-post initial contact during weight acceptance. Drewes and colleagues[12] found a 2.1° mean increase in rearfoot joint motion in a CAI group from 1% to 3%, 37% to 53%, and 68% to 94% of stance compared to healthy controls. Chinn and colleagues[15] also found a 2.9° increased inversion in the CAI group in the latter half of stance phase from 68% to 82%. Our finding of increased rearfoot inversion in the CAI group was contradictory to the only other study of multisegmented foot kinematics in this clinical population.[11] De Ridder and colleagues[11] found increased eversion in the rearfoot (mean difference: 2.7°) from 56% to 73% of stance phase. They hypothesized that a more everted rearfoot was possibly attributed to an invertor-evertor muscle imbalance or compensatory medial roll-off resulting from perceived lateral instability. [11] Our findings are inconsistent with these suppositions.

Midfoot and Forefoot

There was substantial midfoot and forefoot kinematic variability observed in both clinical and control groups. This is likely a function of heterogeneity of foot phenotype in the sample. There were no significant differences in foot posture between groups and diversity of foot morphotype within groups. There were a few non-significant trends observed in the midfoot and forefoot that warrant discussion. The LAS and CAI groups had increased navicular dorsiflexion compared to controls. The same groups were also found to have increased clinical measures of forefoot on rearfoot eversion joint motion,[29] a compensation that would plausibly be necessary to maintain medial forefoot in contact with the ground with a more inverted rearfoot. Increased navicular dorsiflexion is indicative of a greater deformation of the medial longitudinal arch. This finding may correspond with the laterally deviated plantar pressure progression reported in CAI patients.[18] A higher medial longitudinal arch has been found to be predictive of increased lateral plantar pressure and a more lateral plant pressure progression.[42] Altered fibularis longus activity and resultant 1st metatarsal plantarflexion can increase medial longitudinal height [43] and contribute to rearfoot inversion. Increased navicular dorsiflexion in the LAS and CAI groups is likely a result of motor strategies that attempt to shift plantar pressure to a more stable medial position during gait.

A trend of increased lateral and medial forefoot abduction was observed in both LAS and CAI groups. Rearfoot supination is a triplanar motion that incorporates inversion, plantarflexion, and internal rotation. Due to the internal rotation component of supination, it conceivable that compensatory forefoot on rearfoot abduction would be required to counter the excess motion in the rearfoot. It is also possible that the plantarflexion of the 1st MT from sustained contraction of the peroneus longus for CAI patients. By increasing medial arch height, this could secondarily drive the hindfoot into a more inverted or varus position. Lateral midfoot ligament and capsular injury is common following LAS as a result of adduction stress and tensile forces.[10,44] Increased forefoot abduction could plausibly be compensatory to avoid tensile force and pain elicited in the injured lateral midfoot.

Clinical & Research Implications

Due to the potential for biomechanical consequence in both the rearfoot and forefoot following LAS or CAI, clinicians and researchers should examine all the segments of the foot and ankle following injury. A comprehensive physical examination of the multisegmented foot should be performed in conjunction with gait assessment.[10,29] Clinical findings on physical examination may help to contextualize and serve as a clinical correlate for abnormal biomechanical findings in gait.

Interventions used to limit inversion motion during gait such as bracing or taping of the rearfoot may be beneficial following LAS.[45] Joint protection of the midfoot should also be considered following injury to mitigate abnormal gait patterns that may develop early in the injury course. Gait training should include judicious use of assistive devices and progressive loading early in the rehabilitation course. Neuromotor strategies that may include stretching, strengthening, balance training, and rearfoot[10] and midfoot joint mobilization[46] may be useful in correcting deviations such as rearfoot inversion and a more lateral plantar progression. Use of orthotics with a lateral heel posting or recessed first ray may further prevent rearfoot inversion and thereby decrease the risk of recurrent LAS.

Limitations

There are limitations to this study. This was a cross-sectional study, so cause and effect relations cannot be determined. It is unclear if rearfoot inversion preceded initial injury in the LAS and CAI groups. Based on the similarity in foot phenotype, an assumption can be made that this was not the case in our sample. We utilized a sample of recreationally active young adults in this study. Generalizability is limited to individuals of similar age and activity levels. We captured kinematics during single step as opposed to multiple consecutive steps in this study, which likely contributed to motor variability. This was a result of a limitation of the equipment, as the short length of the motion capture leads system precluded capture over multiple consecutive steps. To the mitigate effects of motor variability, we utilized the average of 10 steps in analysis.

Conclusion

The subacute LAS group demonstrated a more inverted rearfoot during midstance of gait compared to healthy controls. The CAI group had a more inverted rearfoot during the latter half of stance phase gait. A trend of increased navicular dorsiflexion and forefoot abduction during early to midstance that persisted to pre-swing was also observed. We recommend that clinicians include interventions to increase rearfoot eversion and limit inversion as part of a comprehensive rehabilitation program when caring for individuals following LAS or CAI.

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Table 1. Group demographic, injury history, and patient-reported outcome measures in individuals with acute ankle sprain, chronic ankle instability, coper, and control groups

	Control (n=22) 9 males 13 females	LAS (n=17) 8 males 9 females	Coper (n=21) 8 males 13 females	CAI (n=20) 5 males 15 females	
	Mean ± SD				*p*
Age (years)	19.6±0.9	21.0±2.3	20.8±2.9	19.8±1.3	.08
Height (cm)	171.1±10.1	172.3±2.2	171.0±8.9	167.4±9.3	.42
Weight (kg)	66.5±14.5	71.6±12.5	69.3±8.7	70.4±14.3	.62
BMI (kg/m^2)	22.5±3.2	24.1±3.7	23.7±2.9	21.5±4.5	.17
Foot Posture Index	4.2±3.9	2.5±3.4	3.6±4.1	4.4±3.6	.38
Ankle sprains (n)	0±0‡§	2.9±2.3*	1.2±0.7§	5.3±5.6*†	<.001
Time to last injury (months)	-	0.9±0.6†§	56.9±37.8‡§	21.6±16.0†‡	<.001
Pain (10-cm VAS): At present	0±0‡§	1.7±1.8*†	0.0±0.1‡§	1.8±2.0*†	<.001
At worst in past week	0±0‡§	3.4±1.8*†	0.1±0.2‡§	3.3±2.3*†	<.001
PROMIS General Health:					
Physical Composite (*T*) Score	59.1±4.9‡§	50.7±6.3*†	57.7±3.3‡§	51.4±5.8*†	<.001
Mental Composite (*T*) Score	59.5±6.3	59.2±8.1	58.6±7.5	55.5±8.6	.40
Quality of Life (Predicted EQ5-D)	83.0±3.8‡§	75.0±8.2*†	82.0±3.4‡§	76.6±7.0*†	<.001
Kinesiophobia (TSK-11)	17.4±5.8‡§	22.1±4.7*†	16.1±4.7‡§	22.6±6.0*†	<.001
Godin Leisure Time Activity	78.1±28.1	44.8±25.2	76.9±65.6	77.0±50.2	.002
IdFAI	0.4±0.9†‡§	23.5±5.1*†§	6.8±2.6*‡§	23.6±3.5*†‡	<.001
FAAM: ADL Score	100.0±0.2‡§	76.5±14.9*†§	99.5±1.5‡§	89.2±6.9*†‡	<.001
ADL SANE	100.0±0.0‡§	79.7±18.8*†	99.6±1.2‡§	85.7±13.1*†	<.001
Sport Score	100.0±0.0‡§	69.9±15.7*†§	99.1±2.2‡§	80.9±26.5*†‡	<.001
Sport SANE	100.0±0.0‡§	55.8±27.2*†§	99.4±1.5‡§	79.4±15.4*†‡	<.001

LAS=Lateral ankle sprains, CAI=Chronic Ankle Instability, cm=centimeters, kg=kilograms, BMI=body mass index VAS=visual analogue scale, PROMIS=Patient Reported Outcome Measures Information System, EQ5-D=EuroQol five dimensions, TSK=Tampa Scale Kinesiophobia, IdFAI=Identification of Functional Ankle Instability, FAAM=Foot and Ankle Ability Measure, ADL=activities of daily living, SANE=single assessment numeric evaluation. Tukey's Honest Significant Difference statistically significant (p≤.05) as compared to: * Control, ‡ LAS, † Copers, § CAI

Table 2. Anatomical Landmarks used in Local Coordinate Digitization

Segment	Proximal	Distal	Third point on plane	Positive side of plane
Shank	Tibial tubercle	Talocrural joint, anterior mid-malleolar line	Mid-shaft Tibia, anterior aspect	Anterior
Rearfoot	Talocrural joint, posterior mid-malleolar line	Talocrural joint, anterior mid-malleolar line	Medial Malleolus	Dorsal
Medial Midfoot	Calcaneonavicular joint	Naviculocuneiform joint	Navicular tubercle	Dorsal
Lateral Midfoot	Calcaneocuboid joint	5th Tarsometatarsal joint	Cuboid, mid-body	Dorsal
Medial Forefoot	1st Tarsometatarsal joint, dorsal aspect	1st Metatarsophalangeal joint, dorsal aspect	1st Metatarsal, dorsal aspect	Dorsal
Lateral Forefoot	4th Tarsometatarsal joint, dorsal aspect	4th Metatarsophalangeal joint, dorsal aspect	4th Metatarsal, dorsal aspect	Dorsal
Hallux	1st Metatarsophalangeal joint, dorsal aspect	1st Interphalangeal joint, dorsal aspect	1st Proximal Phalanx, dorsal aspect	Dorsal

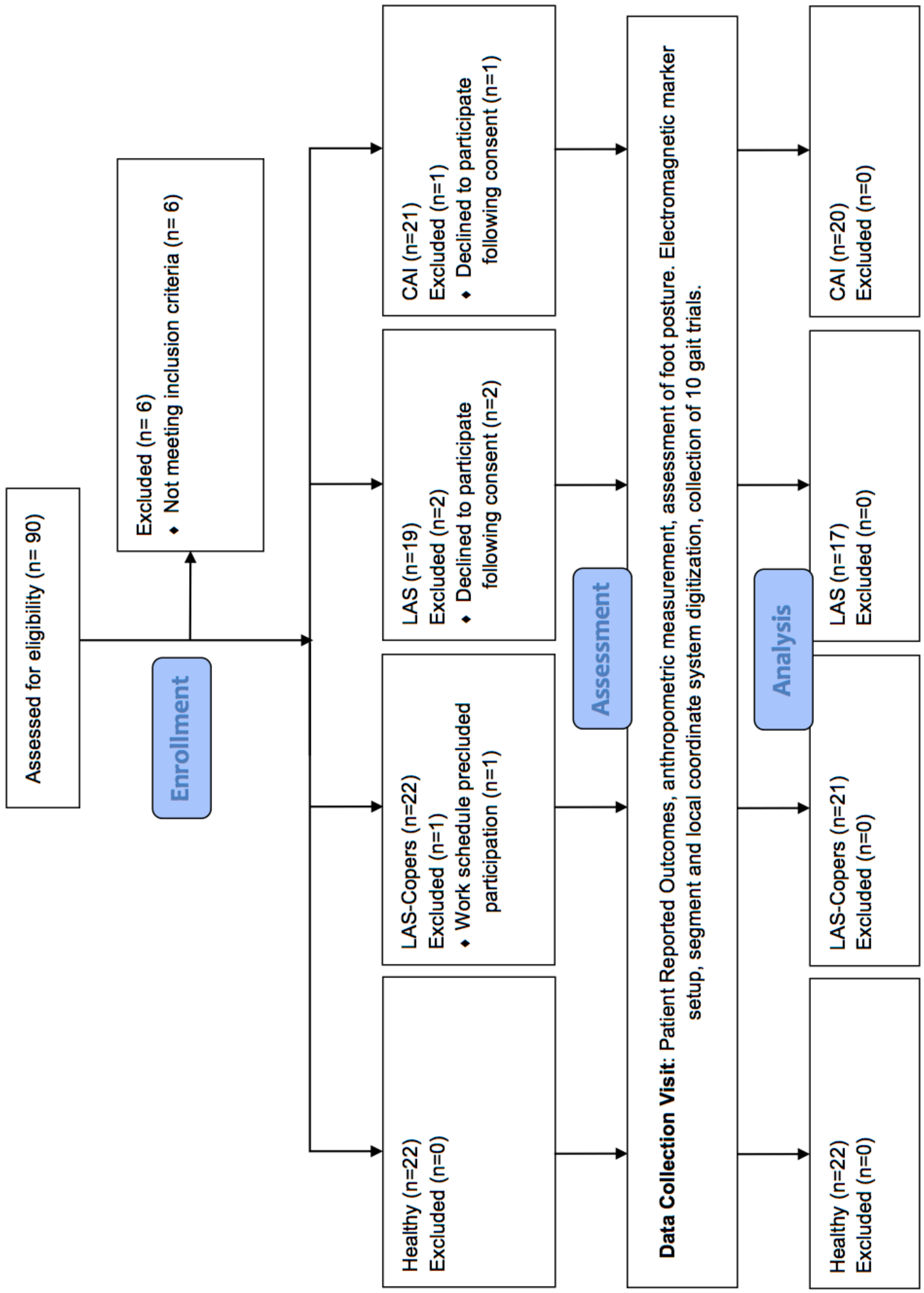

Figure 1. Study Flow Diagram.

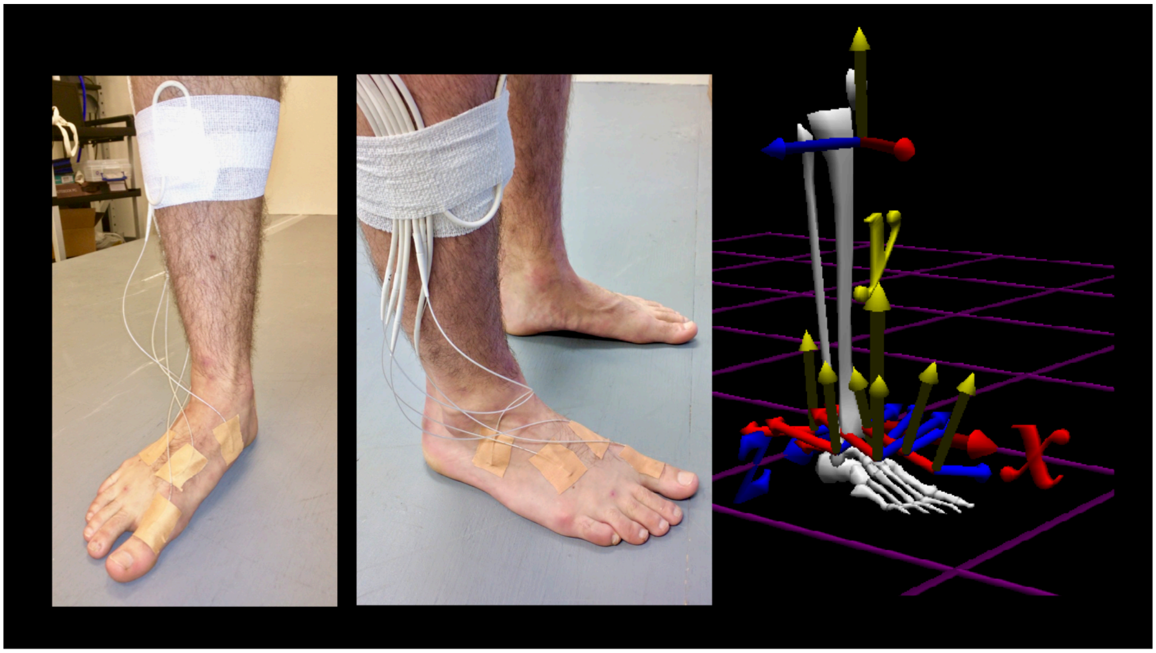

Figure 2. Sensor Setup and Digitized Local Coordinate Systems

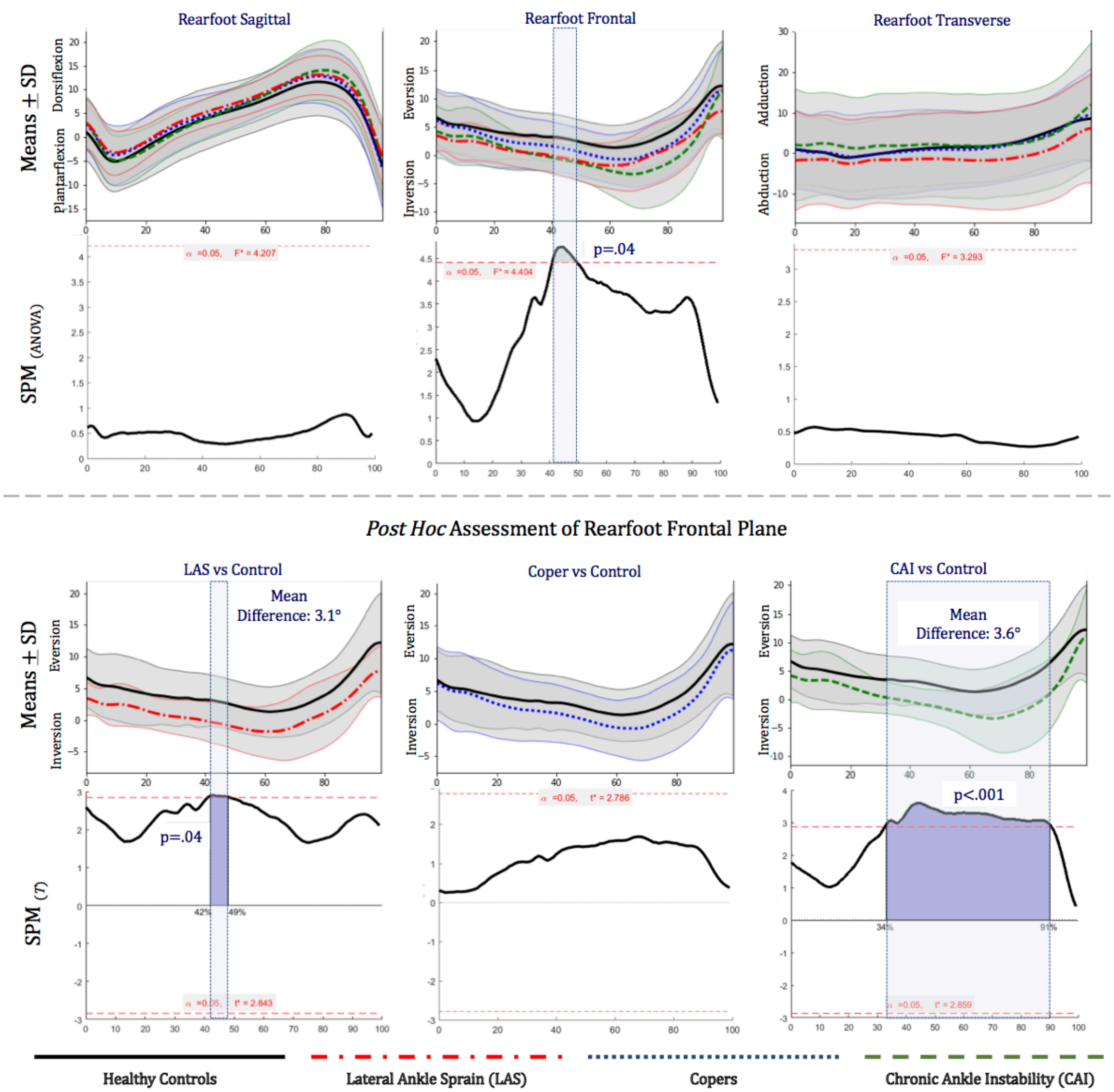

Figure 3. Group comparison of rearfoot gait kinematics. SPM=statistical parametric mapping, SD=standard deviation

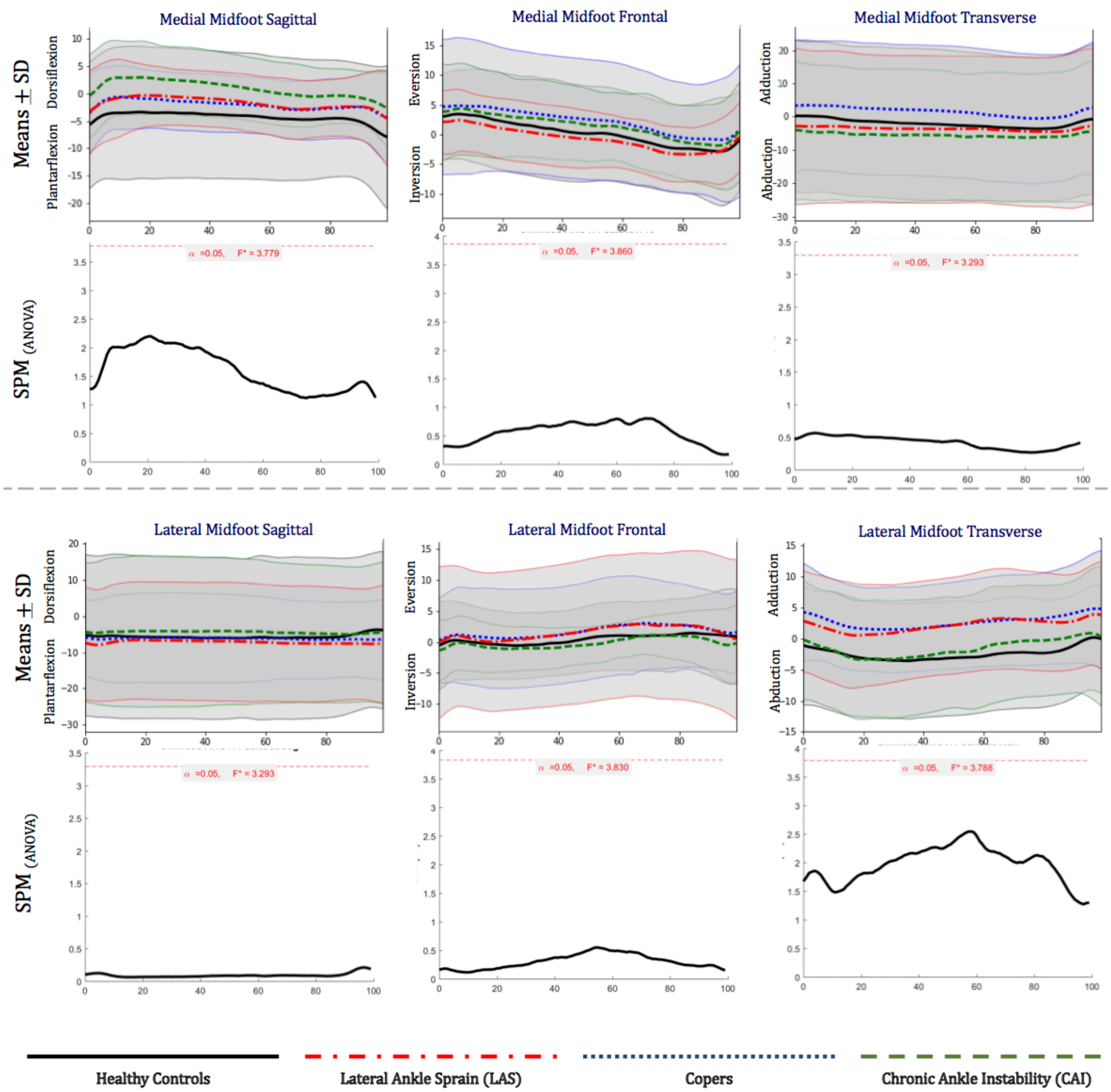

Figure 4. Group comparison of midfoot gait kinematics. SPM=statistical parametric mapping, SD=standard deviation

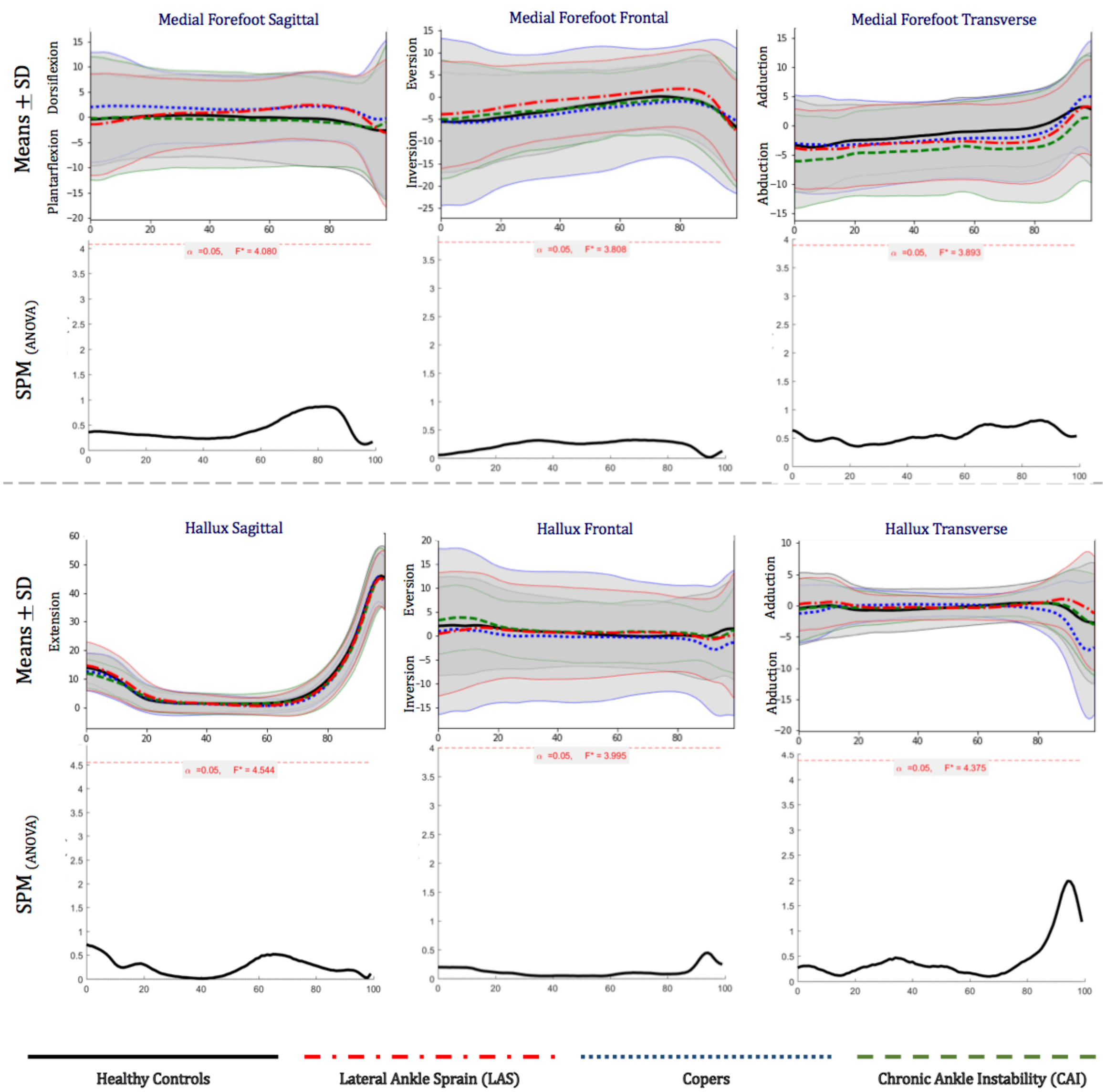

Figure 5. Group comparison of medial forefoot and hallux gait kinematics. SPM=statistical parametric mapping, SD=standard deviation

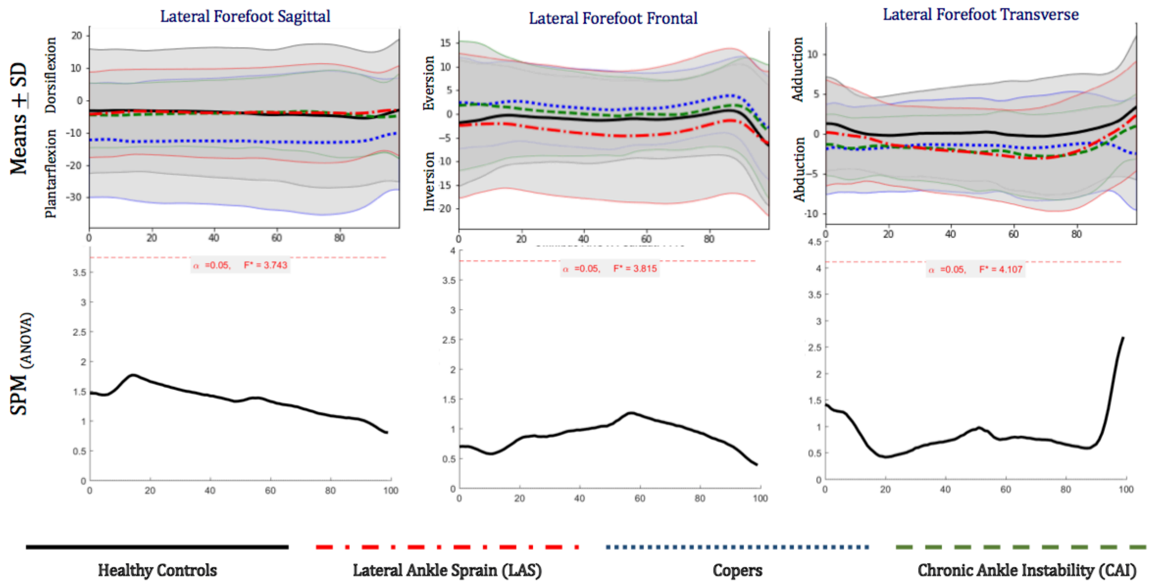

Figure 6. Group comparison of lateral forefoot kinematics. SPM=statistical parametric mapping, SD=standard deviation

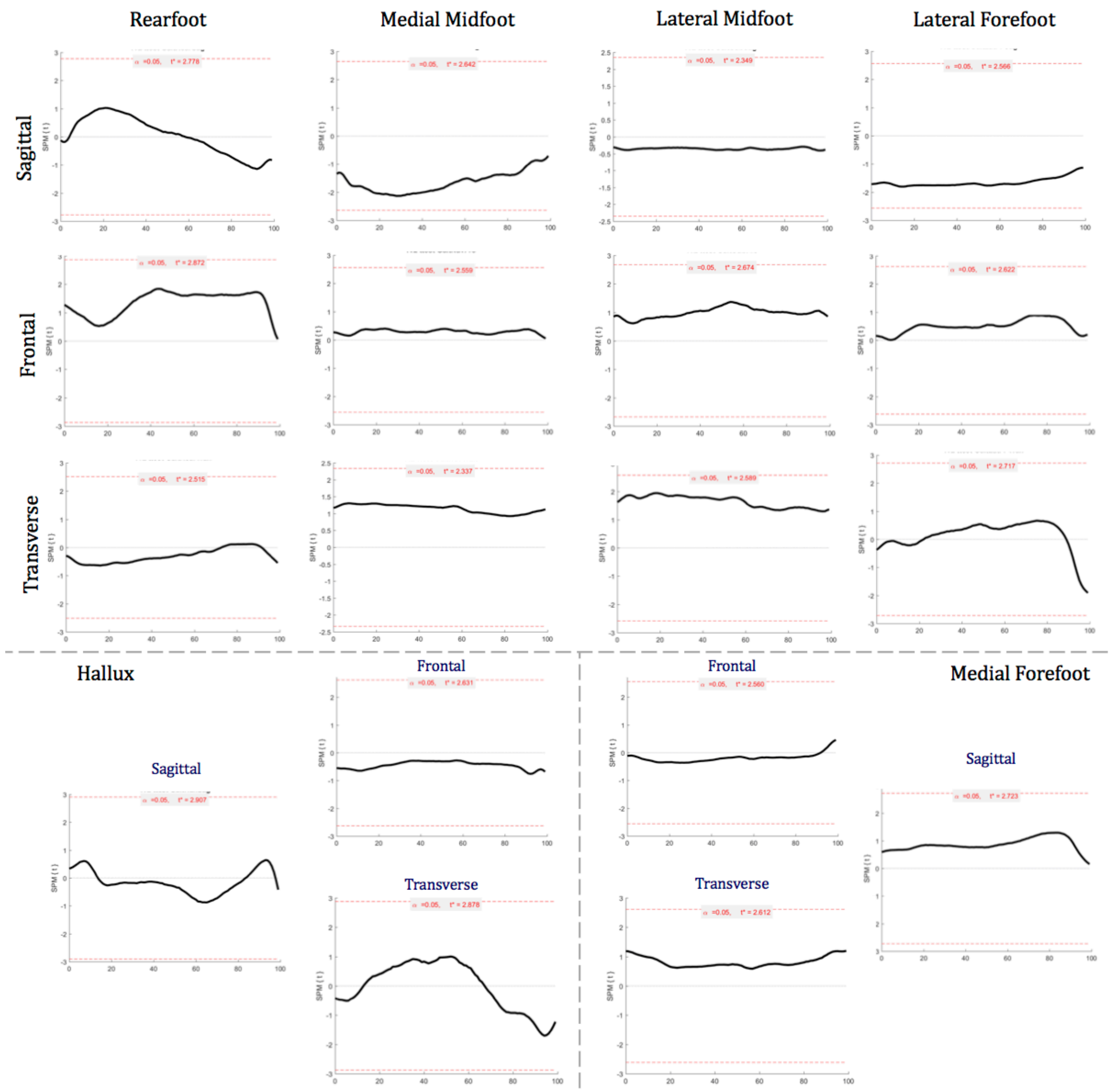

Figure 7. Multisegmented kinematic comparison of Chronic Ankle Instability and Coper groups.

SECTION II: MANUSCRIPT II

ANKLE-FOOT MORPHOLOGY AND FUNCTION IN ACUTE ANKLE SPRAIN, CHRONIC ANKLE INSTABILITY, COPER, AND CONTROL GROUPS.

Abstract:

Purpose: To investigate clinical measures of foot posture and morphology, multisegmented joint motion and play, strength, and dynamic balance in 4 groups of recreationally-active young adults: lateral ankle sprain (LAS), chronic ankle instability (CAI), coper, and control.

Methods: 80 recreationally-active individuals (Control: n=22, Coper: n=21, LAS: n=17, CAI: n=20) were included. Foot posture index (FPI), morphologic measures, joint motion at the rearfoot and forefoot (weight-bearing dorsiflexion (WBDF), rearfoot dorsiflexion, plantarflexion, inversion, eversion; forefoot inversion, eversion; hallux flexion, extension), joint play of the tibiofibular; talocrural, subtalar, forefoot; 1st tarsometarsal and metatarsophalangeal joints, strength of the ankle and hallux, and Star Excursion Balance Test (SEBT) were assessed. Group differences were assessed using an ANOVA and *post hoc* Tukey's HSD. Cohen's *d* effect sizes were calculated for significant findings.

Results: There were no significant group differences in FPI or morphological measures. Compared to controls, LAS and CAI groups had decreased ankle dorsiflexion (LAS: *d*=1.2, CAI: *d*=0.6,) and greater forefoot and rearfoot frontal plane motion (LAS: *d*=0.8-1.1, CAI: *d*=0.9-1.4), increased 1st MT plantarflexion and sagittal excursion (LAS: *d*=1.0-1.4, CAI: *d*=1.2-1.4); increased talocrural glide and internal rotation (LAS: *d*=0.7-1.2, CAI: *d*=0.9-1.3), decreased forefoot inversion joint play (LAS: *d*=1.4, CAI: *d*=0.9), and decreased strength in all motions (LAS: *d*=0.9-1.9, CAI: *d*=1.4-1.7) except dorsiflexion. The LAS group also demonstrated decreased distal tibiofibular (*d*=0.8) and forefoot general laxity (*d*=0.6), and SEBT performance (*d*=0.9-1.6) compared to controls.

Conclusion: Individuals with LAS or CAI have altered joint function and strength in the multisegmented ankle-foot complex that warrant examination following injury.

INTRODUCTION

Lateral ankle sprains (LAS) are a very common injury incurred by athletes[1] and non-athletes[2] alike and are responsible for more than one-million emergency room visits per annum in the United States.[3] LAS are produced by high velocity moments and extremes of inversion, internal rotation, and plantarflexion.[4] that result in neuromotor,[5–7] ligamentous,[8–10] and osseous-cartilaginous[11] injury in the ankle-foot complex. While the majority of individuals will recover from a LAS within the first year-post injury (Copers), 40% of LAS will progress to develop chronic ankle instability (CAI),[12] a condition described by persistent perceived or episodic giving-way of the ankle and continued disability at least one-year post injury.[13]

Midfoot ligamentous injury, [8,10] calcaneocuboid joint disruption,[14] and tibial and peroneal nerve injury[6,7] is common following LAS and may contribute to changes in ankle-foot function. Individuals with CAI have altered intrinsic foot muscle (IFM) morphology[15] and spinal level inhibition in the soleus,[16] a myotome shared by the IFM. Alteration in midfoot mobility, stability, and locking mechanisms are also plausible following LAS and in CAI as a result of ligamentous and capsular insult, impaired strength, or altered timing or duration of muscle activity.[17] A combination of factors such as ligamentous instability, joint hypomobility and hypermobility, and impaired neuromotor function likely contribute to ankle-foot impairment and activity limitation in individuals with LAS and CAI.[17]

It is important clinically to examine and treat all the segments of the ankle-foot complex, including the midfoot and forefoot, following LAS.[17] The midfoot and forefoot may have a substantial contribution to neurophysiologic and mechanical function that warrants examination following LAS and CAI.[17] Collection of a detailed clinical history that includes symptom location, behavior, and impact on function and performing a physical assessment that includes palpatory examination, measurement of foot morphology across loading, intersegmental motion and joint play in the midfoot and forefoot, and strength testing of the toe flexors has been suggested to be clinically pertinent in patients following LAS or CAI.[17] However, research is scant regarding clinical measures of multisegmented ankle-foot function distal to the rearfoot in this clinical population. Therefore, the purpose of this cross-sectional study was to investigate self-reported measures of pain, physical and mental health, and function and clinical measures of foot posture and morphology, multisegmented joint excursion and play, ligamentous reactivity, strength, and dynamic balance in recreationally-active young adults with and without a history of a LAS and CAI.

METHODS

Design

A laboratory-based, descriptive cross-sectional study was performed where the independent variable was group (Control, Coper, LAS, CAI). The dependent variables were self-reported measures of pain, physical and mental health, and function, and clinical measures of foot morphology, joint excursion, joint play, ligamentous reactivity during palpation, strength, and dynamic balance.

Participants

A convenience sample of 80 recreationally-active individuals (Control: n=22, Coper: n=21, LAS: n=17, CAI: n=20) aged 18-50 with and without history of a LAS and CAI were recruited from a public university for participation. **Table 1** details group demographic, injury history, and patient-reported outcome measures. Recreationally-active was defined as participation in some form of physical activity for at least 20-minutes per day, at least three times a week. Participants were included in the Control group if they did not have any history of ankle or foot sprain. Individuals who sustained an inversion sprain that affected function 2-8 weeks prior to consent were included in the LAS group. Participants with a history of at least one LAS at a minimum of 12-months prior to the study who did not experience perceived or episodic giving way and scored Identification of Functional Ankle Instability (IdFAI) ≤10, Foot and Ankle Ability Measure (FAAM) activities of daily living subscale (ADL) ≥99 and FAAM-Sport≥97 were included in the Coper group.[18] Individuals with a history of at least one LAS at a minimum of 12-months prior to the study, experienced continued perceived or episodes of giving way, and scored IdFAI >10, FAAM-ADL <90 and FAAM-Sport < 85 were included in the CAI group.[13] Details of participant demographic information, injury history, and self-report functional measures are reported in **Table 1**. Individuals were excluded if they had a history of fracture in the leg or foot, self-reported disability due to neuromuscular impairment in the lower extremity, neurological or vestibular impairment that affected balance, diabetes mellitus, lumbosacral radiculopathy, a soft tissue disorder such as Marfan or Ehlers-Danlos syndrome, any absolute contraindication to ankle or foot joint manipulation, or were pregnant. Participants with CAI who had an ankle sprain in the past 8-weeks were also excluded. Participants who met inclusion criteria provided informed consent. **Figure 1** details the study flow sheet from recruitment to analysis. Data was collected in the university's sports medicine laboratory. The study was approved by the Institutional Review Board.

Procedures

Following consent, participants provided demographic information, health and injury history, and completed the Foot and Ankle Ability Measure (FAAM) ADL[19] and Sport subscales,[20] Identification of Functional Ankle Instability (IdFAI),[21] the Patient Reported Outcomes Measurement Information System (PROMIS) General Health Questionnaire,[22] the 11-item Tampa Scale of Kinesiophobia (TSK-11),[23] and the Godin Leisure-time Exercise Questionnaire.[24] Predicted EUROQOL (EQ-5D) quality of life scores were calculated using methods described by Revicki and colleagues.[25] Height, mass, and leg length were measured and foot posture index assessed.[26]

Demographic information, medical history, joint play assessments, and physical examination of the non-clinical group were performed by the primary author who was a physical therapist and was a board-certified orthopaedic clinical specialist with 15-years of clinical experience. Physical examinations of the LAS and CAI groups were performed by either an athletic trainer with three-years clinical experience or a physical therapist with two-years clinical experience who were blinded to the participants' medical history and functional status

<u>Morphologic Foot Assessment</u>

Foot posture was assessed in standing using the Foot Posture Index–6 item version (FPI-6), a categorical measure of foot type that is based on five observations and one palpatory assessment.[26] Morphologic measurements were performed using the Arch

Height Index Measurement System (JAKTOOL Corporation, Cranberry, NJ). Total and truncated foot length, arch height, and foot width were measured in sitting and standing. Change in arch height index,[27] arch flexibility[28] and foot mobility magnitude[29] were calculated from the morphologic foot measurements across loading.

Joint Excursion Measures

Weight bearing dorsiflexion (WBDF) was measured using a flexible tape measure as described by Bennell and colleagues.[30] Joint motion measures of rearfoot dorsiflexion, plantarflexion, inversion, and eversion, forefoot inversion and eversion, and hallux flexion and extension were measured as described by Fraser and colleagues.[31] Joint motion measures of rearfoot dorsiflexion, plantarflexion, inversion, and eversion were performed using a 30.5-cm transparent double arm plastic goniometer (Merck Corporation, Kenilworth, NJ). Forefoot inversion and eversion was measured using a digital inclinometer (Fabrication Enterprises, White Plains, NY). First metatarsal (MT) dorsiflexion and plantarflexion were measured utilizing a custom measuring device consisting of two metal rulers bent to 90° as described by Gresiberg and colleagues.[32] First metatarsophalangeal flexion and extension were measured with a 17-cm double arm plastic goniometer with a semicircular scale (Upjohn Corporation, Kalamazoo, MI). The mean of three measures were recorded for forefoot on rearfoot inversion and eversion, 1st MT dorsiflexion and plantarflexion. The total arc of motion within a plane was used for analysis of joint excursion.

Joint Play Motion

Joint play was assessed for the proximal tibiofibular translation; rearfoot anterior, posterior, medial and lateral glides, internal and external rotation; forefoot on rearfoot inversion, eversion, abduction, and adduction; and 1st tarsometarsal and metatarsophalangeal dorsal and plantar glides using previously described methods.[31] Proximal tibiofibular joint mobility was assessed for the presence or absence of hypomobility. Joint play was assessed using a 7-point Likert scale (0=ankylosed, 1=considerable hypomobility, 2=slight hypomobility, 3=normal, 4= slight hypermobility, 5=considerable hypermobility, 6=unstable) developed for quantification of passive mobility intervertebral motion by Gonnella and colleagues.[33] Segmental general laxity was calculated from the mean of all joint play measures within the rearfoot and forefoot.

Ligamentous Reactivity

A palpatory examination was performed of the tibiofibular syndesmosis (mid-malleolar line) and the deltoid, anterior talofibular (ATFL), calcaneofibular, posterior talofibular (PTFL), and bifurcate ligaments for the presence or absence of pain.

Muscle Strength

Muscle strength of ankle dorsiflexion, plantarflexion, inversion, eversion, hallux flexion, and lesser toe flexion were assessed with the microFET2 digital handheld dynamometer (Hoggan Health Industries, West Jordan, UT) using previously described methods.[31] An estimate of torque was derived from the product of force and segment length, normalized to body mass, and reported in Newton-meters per kilogram (Nm kg^{-1}). The IFM test was performed and graded using the scale (1=Poor; 2=Fair; 3=Satisfactory) described by Jam.[34] For toe flexion strength measures, the ankle was positioned in 45º plantarflexion to reduce contribution of the extrinsic foot muscles through active insufficiency and increase demand of the IFMs.[35] Measures of hallux and lesser toe strength were normalized to hallux length (difference in total and truncated foot lengths).

Strength measures were based on highest force of three trials. In the case of an invalid trial (due to equipment difficulty, deviation from test position, or substitution motion), the participant rested prior to retesting to mitigate effects from fatigue. The IFM test was performed in single-limb standing as described by Jam.[34]

Dynamic Balance

Dynamic balance was assessed using the anterior, posteromedial, and posterolateral directions of the Star Excursion Balance Test (SEBT) as described by Hertel and colleagues.[36] Reach distance was normalized to leg length.[37] A composite measurement was calculated from the mean of the three directions.

Statistical Analysis

The level of significance was $p \leq 0.05$ for all analyses. *A priori* sample size estimation of 8 participants were needed per group to demonstrate large effects based on a minimum change of 15 degrees in forefoot on rearfoot excursion, α=.05, and β=.20.[31] Descriptive statistics were calculated for group demographic and clinical outcome measures. Calculations of proportion and 95% CI were performed for dichotomous variables. Group comparison of dichotomous outcomes (proportion of the sample with proximal tibiofibular hypomobility or tenderness to palpation) were performed using Pearson's χ^2 or Fisher's Exact test (frequencies < 5). Group differences of categorical variables with less than five items were analyzed using the Kruskal-Wallis H test. Ordinal measures that had greater than five items (FPI, joint play measures) were treated as continuous data during analysis.[38,39] Prior to group comparison analysis, Levene's test of homogeneity of variance were performed. Variables that had significant homogeneity were assessed using a one-way ANOVA. Variables that failed to achieve significance with

Levene's test were assessed using Welch's ANOVA. For significant findings, *post hoc* Tukey's Honestly Significant Differences (HSD) and Cohen's *d* effect size (ES) estimates were calculated for each clinical group compared to healthy controls. ES were interpreted using the scheme proposed by Cohen:[40] <0.2 equates to a trivial ES, 0.2-0.49 small, 0.5-0.79 moderate, and >0.8 large. ES point estimates and 95% CI were statistically significant when the CI did not cross the '0' threshold. Data was analyzed using Statistical Package for Social Sciences (SPSS) Version 23.0 (IBM, Inc., Armonk, New York). Cohen's *d* effect sizes, proportion estimates, and 95% confidence intervals (CI) were calculated using Excel for Mac 2016 (Microsoft Corp., Redmond, WA).

RESULTS

There were no significant group differences for age, height, weight, BMI, or foot posture. **Table 1** details the demographic information, injury history, and patient-reported outcome measures for each group and **Figure 2** illustrates the ES and 95% CI for statistically significant differences in outcomes. The CAI group had significantly more ankle sprains as compared to Copers and no statistical differences compared to the LAS group ($p<.001$). Compared to controls, the LAS and CAI group had significantly greater pain at present (LAS: d=1.4 CAI: d=1.3, $p<.001$) and worst pain in the preceding week (LAS: d=3.0 CAI: d=2.2, $p<.001$), lower PROMIS General Health Physical Composite scores (LAS: d=1.5 CAI: d=1.4, $p<.001$), decreased predicted quality of life (LAS: d=1.3 CAI: d=1.2, $p<.001$), increased kinesiophobia (LAS: d=0.9 CAI: d=0.9, $p<.001$), higher IdFAI scores (LAS: d=6.8 CAI: d=9.3, $p<.001$), and lower functional scores on the

FAAM ADL (Score: LAS: *d*=2.4 CAI: *d*=2.3, p<.001; SANE: LAS: *d*=1.7 CAI: *d*=1.6, p<.001) and Sport (Score: LAS: *d*=2.8 CAI: *d*=2.8, p<.001, SANE: LAS: *d*=2.5 CAI: *d*=2.0, p<.001). Compared to Copers, the CAI group had significantly increased pain (present: *d*=1.2, past week: *d*=2.0), kinesiophobia (*d*=1.2), and IdFAI scores (*d*=5.5) and decreased general physical health (*d*=1.4), predicted quality of life (*d*=1.0), FAAM ADL (Score: *d*=2.1, SANE: *d*=1.5) and Sport (Score: *d*=2.7, SANE: *d*=1.9) (**Figure 6**).

Table 2 details group means of ankle-foot morphologic and joint motion measures and **Figure 3** illustrates the ES and 95% CI for significant measures. The LAS group had significantly less weight-bearing dorsiflexion (*d*=1.5, p=.001) compared to healthy controls. Both LAS and CAI groups had significantly decreased ankle dorsiflexion (LAS: *d*=1.2, CAI: *d*=0.6, p=.001), greater rearfoot inversion (LAS: *d*=0.8, CAI: *d*=1.4, p<.001), rearfoot eversion (LAS: *d*=1.1, CAI: *d*=0.9, p=.003), rearfoot frontal plane excursion (LAS: *d*=1.1, CAI: *d*=1.5, p<.001), 1st MT plantarflexion (LAS: *d*=1.4, CAI: *d*=1.4, p<.001), and total 1st MT sagittal excursion (LAS: *d*=1.0, CAI: *d*=1.2, p<.001) compared to the Control group. When compared to Copers, the CAI group had significantly increased rearfoot inversion (*d*=1.6), eversion (*d*=0.8), and frontal plane excursion (*d*=1.4), increased forefoot frontal plane excursion (*d*=.8), 1st MT plantarflexion (*d*=1.5) and sagittal plane excursion (*d*=1.4), and hallux sagittal plane excursion (*d*=1.1) (**Figure 6**).

The LAS group had significant decreases in distal tibiofibular posterior glide mobility (*d*=0.8, p=.04) and mean forefoot general laxity (*d*=0.6, p=.05) compared to the Control group. The CAI group had significantly increased laxity in rearfoot inversion (*d*=1.1, p=.04) and 1st metatarsophalangeal plantar glide (*d*=0.9, p=.04). Both LAS and

CAI groups demonstrated increased anterior talocrural glide (LAS: *d*=0.7, CAI: *d*=0.9, p=.02), talar internal rotation (LAS: *d*=1.2, CAI: *d*=1.3, p<.001), and decreased forefoot on rearfoot inversion (LAS: *d*=1.4, CAI: *d*=0.9, p<.001) mobility comparative to the Control group. **Table 3** details group means of ankle-foot joint play measures and **Figure 4** illustrates the ES and 95% CI for significant variables. When compared to Copers, the CAI group had significant and large increases in anterior talocrural glide (*d*=0.8), talar internal rotation (*d*=1.0), and decreased forefoot on rearfoot inversion (*d*=0.8) joint mobility (**Figure 6**).

Table 4 details the proportion of the sample that experienced pain during palpation of the ligaments of the ankle-foot complex. Approximately 5% of Copers had residual tissue reactivity in the deltoid ligament and AFTL. Among the LAS group, 17.6% had syndesmotic or bifurcate ligament reactivity. In addition to persistent lateral ankle symptoms, the CAI group experienced syndesmotic (15.0%), deltoid ligament (40.0%), and bifurcate ligament 5.0%) reactivity. Between groups, there were significant differences noted for the syndesmosis (p=.05), deltoid ligament (p=.001), ATFL (p=.003), calcaneofibular ligament (p=.02), PTFL (p<.001), and bifurcate ligament (p=.05) with higher proportions noted in the LAS and CAI groups. There was a significant proportion of the LAS group with ATFL and PTFL reactivity and a significant proportion of the CAI group with deltoid ligament reactivity with non-overlapping 95% CIs compared to the Control group. There were no significant differences between the LAS and CAI groups. Despite the CAI group having substantially larger proportion point estimates of ligamentous reactivity compared to the Coper group, 95% CIs overlapped for all ligaments tested indicating no significant differences between these two groups.

The LAS and CAI groups had significantly lower normalized strength in plantarflexion (LAS: *d*=1.0, CAI: *d*=1.0, p<.001), inversion (LAS: *d*=1.6, CAI: *d*=1.3, p<.001), eversion (LAS: *d*=1.3, CAI: *d*=1.2, p<.001), hallux flexion (LAS: *d*=1.4, CAI: *d*=1.3, p<.001), and lesser toe flexion (LAS: *d*=1.8, CAI: *d*=1.4, p<.001) when compared to the Control and Coper groups. **Table 5** details group means of normalized strength and dynamic balance measures and **Figure 5** illustrates the ES and 95% CI for significant variables. When compared to Copers, the CAI group had significantly lower plantarflexion (*d*=1.5), inversion (*d*=1.6), eversion (*d*=1.7), hallux flexion (*d*=1.9), and lesser toe flexion (*d*=1.2) strength (**Figure 6**).

The LAS group had significantly lower normalized SEBT measures in the anterior (*d*=0.9, p=.02), posteromedial (*d*=1.2, p<.001), and posterolateral (*d*=1.6, p<.001) directions or in the composite score (*d*=1.5, p<.001) compared to the Control group. Surprisingly, there were no significant differences between the CAI group and the Control group in all three directions of the SEBT or the composite. When compared Copers, the CAI group had significantly diminished normalized posteromedial (*d*=0.9) and posterolateral (*d*=0.7) measurements (**Figure 6**). There were no other significant differences for the remaining variables.

DISCUSSION

The principal findings of this study were that the subacute LAS and CAI groups had increased pain and ligamentous reactivity, impaired joint motion, joint play, and strength in the ankle-foot complex that contributed to diminished general physical health, functional limitation, kinesiophobia, and poorer predicted quality of life compared to the Control group. There were no differences in foot posture or morphology across loading conditions between groups. Only the LAS group had significantly diminished dynamic balance in all three directions of the SEBT compared to healthy controls. When contrasted with Copers, the CAI group had increased rearfoot joint motion and play, forefoot motion, pain, and kinesiophobia, and decreased forefoot on rearfoot joint play, strength, dynamic balance in the posteromedial and posterolateral directions, and functional limitation.

Foot Posture and Morphologic Composite Measurements

There is some evidence to suggest that individuals with a high medial longitudinal arch height, greater foot width, and cavovarus foot deformity are at greatest risk for sustaining a LAS or CAI.[41] Others have concluded that that there is no association between foot morphology and risk of LAS.[42,43] Our data supports the latter conclusion that foot structural phenotype is not associated with risk of LAS or CAI. Foot posture was heterogeneous in both LAS or CAI groups and no differences were found in foot posture or morphologic measurements across loading conditions compared to healthy controls. Based on the diversity of foot phenotype observed in our sample, future study is needed to assess how specific foot types may affect function following LAS.

Rearfoot Joint Function

Both LAS and CAI groups had increased rearfoot inversion motion, joint play measures, and lateral ankle tissue reactivity commonly found following LAS.[9,10,44] The CAI group had large increases in general rearfoot joint laxity, a finding that is characteristic of ligamentous injury following repetitive macrotraumatic insult.[45]

Surprisingly, a high proportion of both LAS and CAI groups had deltoid ligament reactivity and rearfoot eversion hypermobility. Inversion sprains may result in medial ankle capsular and ligamentous injury that result from subtalar rotation during injury.[9] These findings likely coincided with the finding of rearfoot rotary instability and increased eversion motion observed in both LAS and CAI groups. Recurrent ankle injuries and abnormal rotation in the setting of pre-existing injury to the lateral ligamentous complex may also place significant biomechanical stress on the deltoid complex. Increased eversion rearfoot motion in women and subtalar instability have been identified as major risk factors for development of LAS and CAI.[41] It is unknown whether these findings preceded the LAS as a risk factor to injury or were a consequence following. Rearfoot instability is likely a contributory precursor to the development of perceived or episodic giving way of the ankle in CAI.

Individuals in the LAS group had diminished distal tibiofibular joint mobility, a finding likely attributed to the anterior fibular positional fault and joint hypomobility that ensues following LAS.[46] It is likely that an anterior fibular positional fault disrupts the anatomical relation of the talus in the mortise, contributing to rotational instability. The pattern of increased physiologic motion, joint accessory motion, and a high proportion of the sample with deltoid ligament pain in our sample suggests a contributory axial talocrural rotational instability following LAS and in CAI.[47]

Midfoot and Forefoot Joint Function

Midfoot injury is common following LAS, with 21-41% of individuals found to have midfoot ligamentous injury [8,10] and 33% with midfoot joint capsular involvement.[10] We observed lower proportions of participants with LAS who reported tissue reactivity with palpation of the bifurcate ligament. Acuity of injury may influence this finding. Many individuals with LAS in our study were experiencing a degree of symptom resolution by the time they were evaluated, whereas previously reported prevalence was based on patients assessed shortly following injury.[10]

Diminished midfoot joint play observed in the LAS and CAI groups is likely a result of calcaneocuboid disruption or midfoot capsular injury.[17] The LAS group had decreased mean general laxity in the forefoot compared healthy controls. The finding of polyarticular hypomobility in the midfoot and forefoot is likely related to joint trauma sustained during the LAS. During inversion injury, there are rotatory, tensile, and compressive forces[48] that traumatize the multiple joints of the medial and lateral foot columns that may result in joint hypomobility.

Both LAS and CAI groups had significantly increased forefoot on rearfoot eversion motion and 1st MT plantarflexion compared to healthy controls, a finding plausibly attributed to midfoot ligamentous injury. Increased eversion and medial forefoot plantarflexion is also a likely adaptation related to increased rearfoot inversion and needed to keep the medial forefoot in contact with the ground. Another plausible explanation is that that there is a shift in total range of motion of the joint further into eversion, similar to what is observed with internal-external rotation of the glenohumeral joint.[49] In this model, physiologic shifts in joint motion become problematic when there are increases in total arc of motion in the pathological joint.[49] This may help to explain why there were no differences in forefoot inversion or eversion motion between Copers and CAI, but total excursion was significantly increased in the CAI group. Another potential explanation for the plantarflexion of the 1st MT could be related to sustained peroneus longus activation, a condition often seen in CAI.

While forefoot on rearfoot inversion motion in the LAS and CAI groups was not statistically different from healthy controls, passive inversion joint play was significantly diminished. The disparity between these related measures was likely related to how joint play is assessed. Inversion motion measurement was determined from a horizontal reference point, whereas joint play was based on clinician judgement of accessory motion displacement comparative to the unaffected contralateral limb. While the quantity of foot motion prior to injury is unknown, it is plausible that the LAS group had higher proportion of phenotypes with increased generalized joint laxity. Since general laxity was not measured in this study, future research investigating the role of joint phenotype is needed. Injury and reduced mobility in the midfoot following LAS would decrease group mean joint motion more similar to measures obtained in the Control group, whereas joint play factors in an individual's phenotype into the measure.

Strength

Substantial neuromotor deficit was observed in both LAS and CAI groups in all muscles assessed that are innervated by the tibial and superficial fibular nerves. Our findings of diminished plantarflexor, invertor, and eversion strength is consistent with previous literature.[15] The ankle dorsiflexors, which are innervated by the deep peroneal nerve, were the only muscle that did not have statistical differences compared to healthy controls. To our knowledge, this is the first study to investigate and report toe flexion strength in this clinical population. Our findings of diminished lesser toe and hallux flexion strength, when tested in ankle plantarflexion with the resulting increased demand on the IFM,[35] are indicative of both extrinsic and intrinsic motor deficit.

Tibial and fibular nerve injury is common following LAS,[6,7] with 10-17% of patients of grade II and 83-86% grade III sprains presenting with injury.[7] Traction axonotmesis or neurotmesis of the superficial fibular nerve or neuropraxia of the tibial nerve in the posterior compartment, tarsal tunnel, or plantar compartments following LAS is plausible. Spinal[16] and cortical[50] inhibition has been found in patients with CAI and is a probable contributor to the deficit observed in these individuals. Neuromotor deficit is likely deleterious to intersegment coupling, foot-shaping, intersegmental stability, and force attenuation of the foot during function.[17]

Dynamic Balance

SEBT performance is dependent on sensorimotor function, but may also be influenced by factors such as dorsiflexion range of motion[51] and foot phenotype.[52] The LAS group had significantly diminished dynamic balance in all three directions and the composite score of the SEBT compared to healthy controls. This group also had the greatest deficit in joint motion, joint play, and strength in the foot and ankle. Our findings of diminished tri-directional reach distances following LAS are consistent with those reported by Doherty and collegues.[53] There were no differences in CAI performance compared to healthy controls, a finding that is likely related to the fairly normal ankle dorsiflexion motion measures and similarity in foot phenotype between groups. The authors of a systematic review comparing SEBT performance in CAI to healthy controls found heterogeneity of results across studies.[54] They also recommended against controlling for foot type when using SEBT as an outcome measure.[54] Performance of the

CAI groups in the posteromedial and posterolateral directions approached significance, but high variability of performance influenced group comparisons.

Ankle-Foot Function in Chronic Ankle Instability vs. Copers

When compared to Copers, the CAI group had increased pain and kinesiophobia, as well as impaired rearfoot joint motion and play, forefoot joint motion and play, strength, and self-reported physical function. Our findings of between-group equivalence for WBDF,[55] tissue reactivity,[56] increased rearfoot frontal plane joint laxity,[56] and self-reported disability[55,56] were consistent to those previously reported. However, in contrast to prior studies, we did not find differences in dorsiflexion motion,[56] total sagittal excursion,[56] dorsiflexion strength[55] and decreased inversion, eversion, and plantarflexion strength[55] measures. Dynamic balance in the posteromedial and posterolateral directions were significantly different, as the Coper group outperformed the Control group during assessment of dynamic balance. Plante and Wikstrom[55] also found decreased posteromedial reach, but not posterolateral or anterior directions, in their study of CAI compared to Copers.

Clinical Applications

It is not unusual for individuals with CAI to have mechanical deficit,[45] sensorimotor deficit,[5] or a combination of both factors. Clinical measures of multisegmented foot function may have added benefit for differentiating individuals with a history of LAS who may later develop CAI. Because the rearfoot, midfoot, and forefoot are commonly injured during LAS, it is imperative that clinicians examine all segments of the ankle-foot complex in all patients who incur an inversion injury.[17] The novel findings of increased eversion motion and internal talocrural rotation joint play in the rearfoot, increased forefoot on rearfoot and 1st metatarsophalangeal plantarflexion motion, relative hypomobility in inversion and tarsometatarsal plantar glide in the forefoot, and impaired hallux and toe flexion strength observed in our study substantiate this recommendation. Consideration for more conservative management, to include a period of protection and optimal loading that may include immobilization or reduced weight bearing, may be of benefit when joint instability is found following LAS. Assessment should include both mechanical and neurophysiologic function of the multiple segments of the ankle-foot complex and shank. Joint mobilization, stretching, strengthening exercises may be clinically indicated for hypomobility or neurophysiologic deficit.[17] Clinicians should be cognizant of factors such as kinesiophobia that may influence outcomes and take an active role in improving resiliency and self-efficacy following injury.

Limitation

This study is not without limitations. Because participants in this study were recreationally active young adults, external validity of these findings are limited to this population. The mechanical and neurophysiologic consequences of LAS may affect individuals with various foot phenotypes differently. Future study is warranted that is powered to include foot phenotype as an independent factor during analysis. Morphologic foot assessments were compared from sitting to standing on both legs. Methodological consideration for assessment of the foot from unloaded to loading in single limb standing may better differentiate individuals with mechanical or neuromotor deficit for future study. Lastly, causal relationships cannot be determined from these data due to the inherent limitation of a cross-sectional design.

CONCLUSION

Individuals with LAS or CAI had increased pain, impaired joint motion, joint play, ligamentous reactivity, and strength in the ankle-foot complex that contributed to diminished general physical health, functional limitation, kinesiophobia, and poorer predicted quality of life compared to healthy controls. There were no differences in foot posture or morphology across loading conditions between groups. Only the LAS group had significantly diminished dynamic balance in all three directions of the SEBT compared to healthy controls. When contrasted with Copers, the CAI group had increased rearfoot joint motion and play, forefoot motion, pain, and kinesiophobia, and decreased forefoot on rearfoot joint play, strength, dynamic balance in the posteromedial and posterolateral directions, and functional limitation. Clinicians should assess multiple segments of the ankle-foot complex when caring for individuals with a LAS or CAI.

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Figure 5. Effect size estimates and 95% confidence intervals of strength and dynamic balance in the Lateral Ankle Sprain (LAS), Coper, and Chronic Ankle Instability (CAI) groups compared to Healthy Controls.

Figure 6. Effect size estimates and 95% confidence intervals of patient-reported outcomes, joint motion, joint play, strength, and dynamic balance measures in the Chronic Ankle Instability (CAI) group compared to the Coper group.

Table 1. Group demographic, injury history, and patient-reported outcome measures in individuals with acute ankle sprain, chronic ankle instability, coper, and control groups

	Control (n=22) 9 males 13 females	LAS (n=17) 8 males 9 females	Coper (n=21) 8 males 13 females	CAI (n=20) 5 males 15 females	
	Mean ± SD				*p*
Age (years)	19.6±0.9	21.0±2.3	20.8±2.9	19.8±1.3	.08
Height (cm)	171.1±10.1	172.3±2.2	171.0±8.9	167.4±9.3	.42
Weight (kg)	66.5±14.5	71.6±12.5	69.3±8.7	70.4±14.3	.62
BMI (kg/m^2)	22.5±3.2	24.1±3.7	23.7±2.9	21.5±4.5	.17
Foot Posture Index	4.2±3.9	2.5±3.4	3.6±4.1	4.4±3.6	.38
Ankle sprains (n)	0±0‡§	2.9±2.3*	1.2±0.7§	5.3±5.6*†	<.001
Time to last injury (months)	-	0.9±0.6†§	56.9±37.8‡§	21.6±16.0†‡	<.001
Pain (10-cm VAS): At present	0±0‡§	1.7±1.8*†	0.0±0.1‡§	1.8±2.0*†	<.001
At worst in past week	0±0‡§	3.4±1.8*†	0.1±0.2‡§	3.3±2.3*†	<.001
PROMIS General Health:					
Physical Composite (*T*) Score	59.1±4.9‡§	50.7±6.3*†	57.7±3.3‡§	51.4±5.8*†	<.001
Mental Composite (*T*) Score	59.5±6.3	59.2±8.1	58.6±7.5	55.5±8.6	.40
Quality of Life (Predicted EQ5-D)	83.0±3.8‡§	75.0±8.2*†	82.0±3.4‡§	76.6±7.0*†	<.001
Kinesiophobia (TSK-11)	17.4±5.8‡§	22.1±4.7*†	16.1±4.7‡§	22.6±6.0*†	<.001
Godin Leisure Time Activity	78.1±28.1	44.8±25.2	76.9±65.6	77.0±50.2	.002
IdFAI	0.4±0.9†‡§	23.5±5.1*†§	6.8±2.6*‡§	23.6±3.5*†‡	<.001
FAAM: ADL Score	100.0±0.2‡§	76.5±14.9*†§	99.5±1.5‡§	89.2±6.9*†‡	<.001
ADL SANE	100.0±0.0‡§	79.7±18.8*†	99.6±1.2‡§	85.7±13.1*†	<.001
Sport Score	100.0±0.0‡§	69.9±15.7*†§	99.1±2.2‡§	80.9±26.5*†‡	<.001
Sport SANE	100.0±0.0‡§	55.8±27.2*†§	99.4±1.5‡§	79.4±15.4*†‡	<.001

LAS=Lateral ankle sprains, CAI=Chronic Ankle Instability, cm=centimeters, kg=kilograms, BMI=body mass index VAS=visual analogue scale, PROMIS=Patient Reported Outcome Measures Information System, EQ5-D=EuroQol five dimensions, TSK=Tampa Scale Kinesiophobia, IdFAI=Identification of Functional Ankle Instability, FAAM=Foot and Ankle Ability Measure, ADL=activities of daily living, SANE=single assessment numeric evaluation.
Tukey's Honest Significant Difference statistically significant ($p \leq .05$) as compared to: * Control, ‡ LAS, † Copers, § CAI

Table 2. Ankle-foot morphology and joint motion in individuals with acute ankle sprain, chronic ankle instability, coper, and control groups

		Control (n=22)	LAS (n=17)	Coper (n=21)	CAI (n=20)	
		Mean ± SD				*p*
Foot Morphology	Δ Arch Height Index with loading (%)	2.9±1.2	2.3±0.9	2.5±1.0	2.9±0.9	.21
	Arch Flexibility ($cm \cdot kg^{-1}$)	1.5±0.7	1.2±0.6	1.3±0.6	1.5±0.5	.39
	Foot Mobility Magnitude (cm)	2.4±1.8	2.7±1.7	1.8±1.2	2.2±1.2	.33
Rearfoot Joint Motion	WBDF (cm)	13.4±3.3‡	8.7±3.1*†§	13.2±4.8‡	13.0±3.4‡	.001
	Dorsiflexion (°)	20.7±6.5‡	13.1±6.0*†	20.7±6.3‡	17.0±6.0	.001
	Plantarflexion (°)	63.0±11.5	63.9±8.6	62.4±8.4	67.1±11.4	.54
	Total Rearfoot Sagittal Excursion (°)	83.7±15.5	77.1±11.4	83.1±9.4	84.1±12.8	.23
	Inversion (°)	26.1±9.2§	32.7±8.3	25.8±6.6§	39.6±10.3*†	<.001
	Eversion (°)	7.4±4.3‡§	12.6±5.5*†	7.8±5.1‡§	11.8±5.4*†	.003
	Total Rearfoot Frontal Excursion (°)	33.6±9.7‡§	45.3±12.6*†	33.6±10.3‡§	51.4±14.4*†	<.001
Forefoot – Midfoot Joint Motion	Inversion (°)	35.4±6.6	34.7±8.9	34.4±6.5	39.7±11.7	.18
	Eversion (°)	14.7±4.2	19.2±7.7†	13.7±4.8‡	18.0±6.2	.01
	Total Forefoot Frontal Excursion (°)	50.0±7.9	53.9±10.9	48.0±6.7§	57.7±16.2†	.03
	1st MT Dorsiflexion (mm)	5.4±1.1	5.5±1.7	5.1±1.1	6.2±1.8	.08
	1st MT Plantarflexion (mm)	5.2±1.5‡§	7.5±1.8*†	5.0±1.4‡§	7.7±2.2*†	<.001
	Total 1st MT Sagittal Excursion (mm)	10.5±2.3‡§	13.0±2.8*†	10.1±1.8‡§	13.9±3.5*†	<.001
	Hallux Extension (°)	85.6±11.8	83.5±16.5	78.3±9.1	86.9±16.3	.08
	Hallux Flexion (°)	32.5±16.3	32.1±16.4	28.9±11.7	36.5±16.4	.43
	Total Hallux Sagittal Excursion (°)	118.1±20.1	115.6±20.4	107.2±12.7§	123.4±16.3†	.009

LAS=lateral ankle sprain, cm=centimeters, kg=kilograms, WBDF=weight bearing dorsiflexion, MT=metatarsal, mm=millimeters
Tukey's Honest Significant Difference statistically significant ($p \leq .05$) as compared to: * Control, ‡ LAS, † Copers, § CAI

Table 3. Ankle-foot joint play and reactivity in individuals with acute ankle sprain, chronic ankle instability, coper, and control groups

		Control (n=22)	LAS (n=17)	Coper (n=21)	CAI (n=20)	
		Mean ± SD				*p*
Shank	Proximal tibiofibular hypomobility, proportion, % (95% CI)	4.5 (0.8, 21.8)	17.6 (6.2, 41.0)	4.8 (0.8, 22.7)	10.0 (2.8, 30.1)	.45
	Distal fibular posterior glide	3.0±0.7‡	2.4±0.7*	2.9±0.4	2.7±0.8	.04
Rearfoot	Anterior talar glide (drawer)	3.1±0.6§	3.5±0.6	3.1±0.9§	3.8±0.8*†	.02
	Posterior talar glide (drawer)	3.1±0.6	3.2±0.6	3.0±0.6	3.1±0.4	.41
	External talar rotation	3.1±0.4	3.1±0.3	3.2±0.5	3.2±0.4	.96
	Internal talar rotation	3.4±0.5‡§	4.0±0.6*†	3.5±0.8§	4.2±0.8*†	<.001
	Subtalar inversion	3.8±0.6§	3.9±0.6§	4.0±0.6	4.4±0.5*‡	.04
	Subtalar eversion	2.9±0.8	2.8±0.6	2.7±0.8	2.9±0.8	.78
	Subtalar medial glide	3.1±0.8	3.4±0.7	3.0±0.8	3.3±0.9	.44
	Subtalar lateral glide	2.7±0.8	2.8±1.0	2.8±0.8	3.2±1.0	.47
	Mean Rearfoot Laxity	3.1±0.4	3.2±0.3	3.1±0.4	3.4±0.4	.10
Forefoot – Midfoot	Forefoot inversion	3.0±1.0‡§	1.9±0.2*†	2.8±0.6‡§	2.3±0.6*†	<.001
	Forefoot eversion	3.0±0.5	2.7±0.7	3.1±0.5	3.1±0.5	.29
	Forefoot abduction	3.0±0.2	2.8±0.6	3.1±0.5	3.1±0.5	.08
	Forefoot adduction	3.1±0.4	3.3±0.8	3.2±0.5	3.2±0.6	.59
	Dorsal 1st tarsometatarsal glide	2.9±0.5	2.9±0.6	3.1±0.7	3.0±0.7	.63
	Plantar 1st tarsometatarsal glide	2.6±0.8	2.2±0.6	2.7±0.8	2.7±1.0	.30
	Dorsal 1st metatarsophalangeal glide	3.2±0.5	3.0±0.4	3.1±0.6	3.0±0.4	.29
	Plantar 1st metatarsophalangeal glide	2.5±0.6§	2.7±0.5	2.6±0.6	2.7±0.6*	.04
	Mean Forefoot Laxity	2.9±0.4	2.7±0.2	3.0±0.4	2.9±0.3	.05

LAS=lateral ankle sprain, CI=confidence interval, TTP=tenderness to palpation, l.=ligament
Tukey's Honest Significant Difference statistically significant ($p \leq .05$) as compared to: * Control, ‡ LAS, † Copers, § CAI

Table 4. Ligamentous reactivity to palpation in individuals with acute ankle sprain, chronic ankle instability, coper, and control groups

	Control (n=22)	LAS (n=17)	Coper (n=21)	CAI (n=20)	
	Proportion, % (95% CI)				*p*
Syndesmosis	0.0 (0.0, 14.9)	17.6 (6.2, 41.0)	0.0 (0.0, 15.5)	15.0 (5.2, 36.0)	.05
Deltoid ligament	0.0 (0.0, 14.9)	29.4 (13.3, 53.1)	4.8 (0.8, 22.7)	40.0 (21.9, 61.3)	.001
Anterior talofibular ligament	0.0 (0.0, 14.9)	35.3 (17.3, 58.7)	4.8 (0.8, 22.7)	30.0 (14.5, 51.9)	.003
Calcaneofibular ligament	0.0 (0.0, 14.9)	25.3 (9.6, 47.3)	0.0 (0.0, 15.5)	15.0 (5.2, 36.0)	.02
Posterior talofibular ligament	0.0 (0.0, 14.9)	41.2 (21.6, 64.0)	0.0 (0.0, 15.5)	20.0 (8.1, 41.6)	<.001
Bifurcate ligament	0.0 (0.0, 14.9)	17.6 (6.2, 41.0)	0.0 (0.0, 15.5)	5.0 (0.9, 23.6)	.05

LAS=lateral ankle sprain, CI=confidence interval

Table 5. Strength and dynamic balance in individuals with acute ankle sprain, chronic ankle instability, coper, and control groups

		Control (n=22)	LAS (n=17)	Coper (n=21)	CAI (n=20)	
		Mean ± SD				p
Strength	Dorsiflexion (Nm kg^{-1})	3.1±0.6	3.1±0.8	3.1±0.8	2.9±0.7	.63
	Plantarflexion (Nm kg^{-1})	7.2±2.0‡§	5.3±2.2*†	7.3±2.2‡§	4.8±1.3*†	<.001
	Inversion (Nm kg^{-1})	3.0±0.6‡§	2.1±0.6*†	3.0±0.7‡§	2.0±0.6*†	<.001
	Eversion (Nm kg^{-1})	2.9±0.7‡§	2.2±0.6*†	2.9±0.6‡§	2.0±0.5*†	<.001
	Hallux Flexion (Nm kg^{-1})	1.3±0.3‡§	0.8±0.2*†	1.3±0.3‡§	0.8±0.3*†	<.001
	Lesser Toe Flexion (Nm kg^{-1})	1.2±0.3‡§	0.7±0.2*†	1.1±0.3‡§	0.7±0.3*†	<.001
	Intrinsic Foot Muscle Test	2.1±0.9	2.3±0.8	2.1±1.0	2.1±0.9	.56
SEBT (normalized)	Anterior (%)	68.0±6.1	63.1±4.1	67.0±7.1	67.9±8.5	.02
	Posteromedial (%)	82.4±13.0‡	68.8±9.0*†	85.8±11.7‡§	76.3±10.5†	<.001
	Posterolateral (%)	91.3±10.8‡	77.2±6.0*†§	92.1±9.4‡	85.3±9.7†‡	<.001
	Composite (%)	80.7±8.7‡	69.7±5.0‡	81.6±6.7*†§	76.5±8.9‡	<.001

LAS=lateral ankle sprains, N=Newton, cm=centimeter, SEBT = Star Excursion Balance Test
Tukey's Honest Significant Difference statistically significant (p≤.05) as compared to: * Control, ‡ LAS, † Copers, § CAI

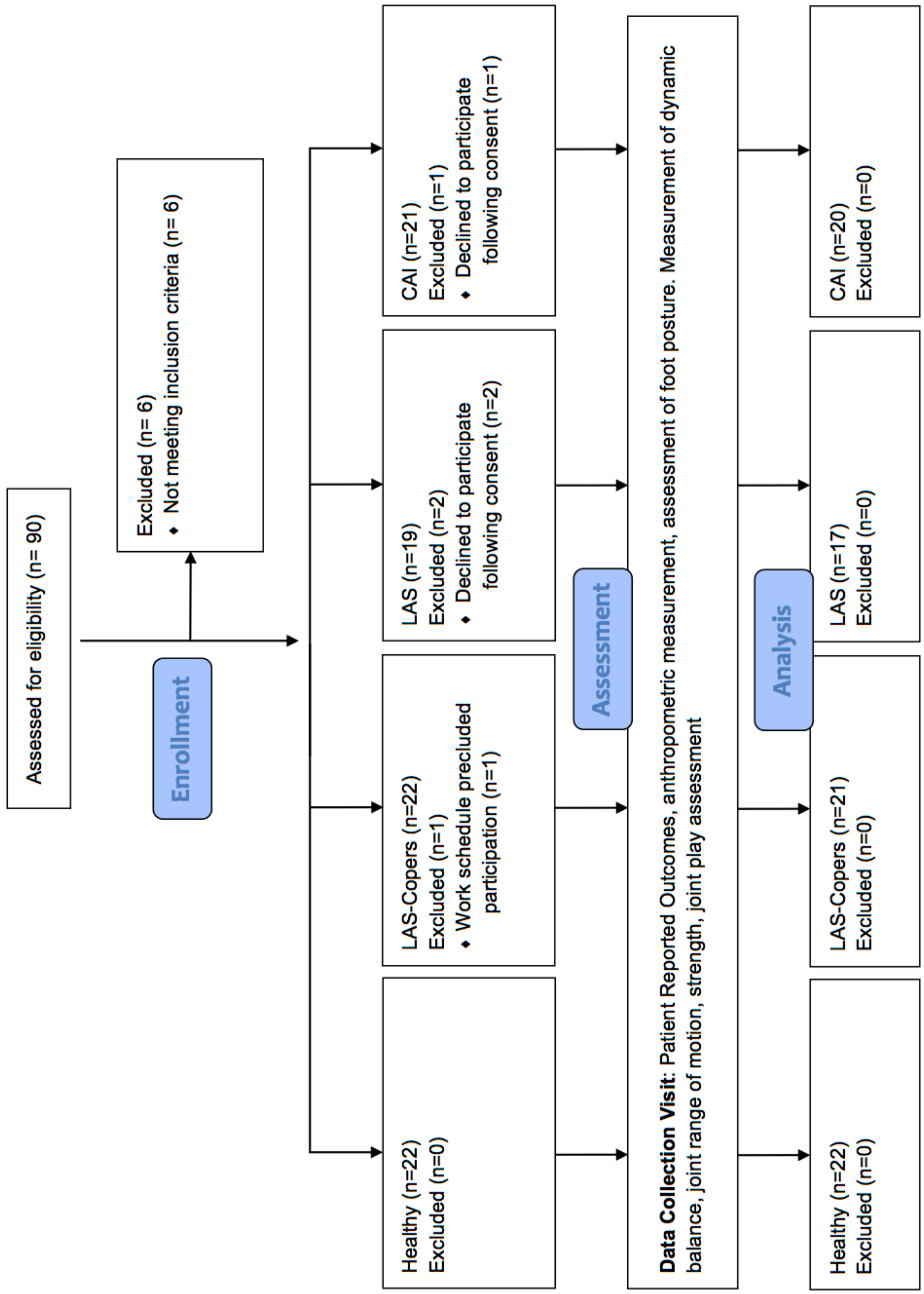

Figure 1. Study Flow Diagram. LAS: Lateral ankle sprains, CAI=Chronic Ankle Instability

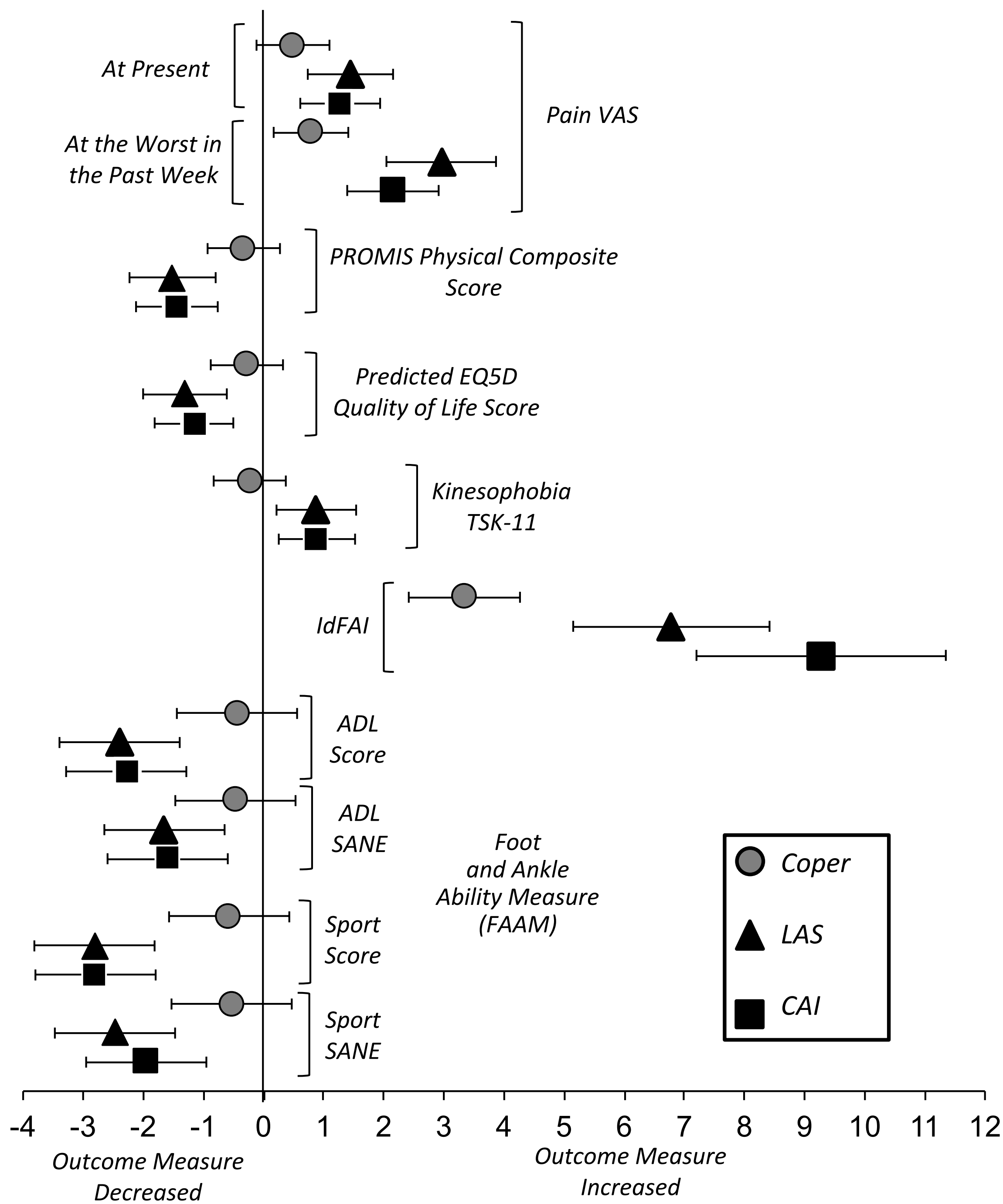

Figure 2. Effect size estimates and 95% confidence intervals of Patient Reported Outcome Measures in the Lateral Ankle Sprain (LAS) Coper, Lateral Ankle Sprain, and Chronic Ankle Instability (CAI) Groups Compared to Healthy Controls. VAS=visual analogue scale, PROMIS=Patient Reported Outcome Measures Information System, EQ5-D=EuroQol five dimensions, TSK=Tampa Scale Kinesiophobia, IdFAI=Identification of Functional Ankle Instability, FAAM=Foot and Ankle Ability Measure, ADL=activities of daily living, SANE=single assessment numeric evaluation

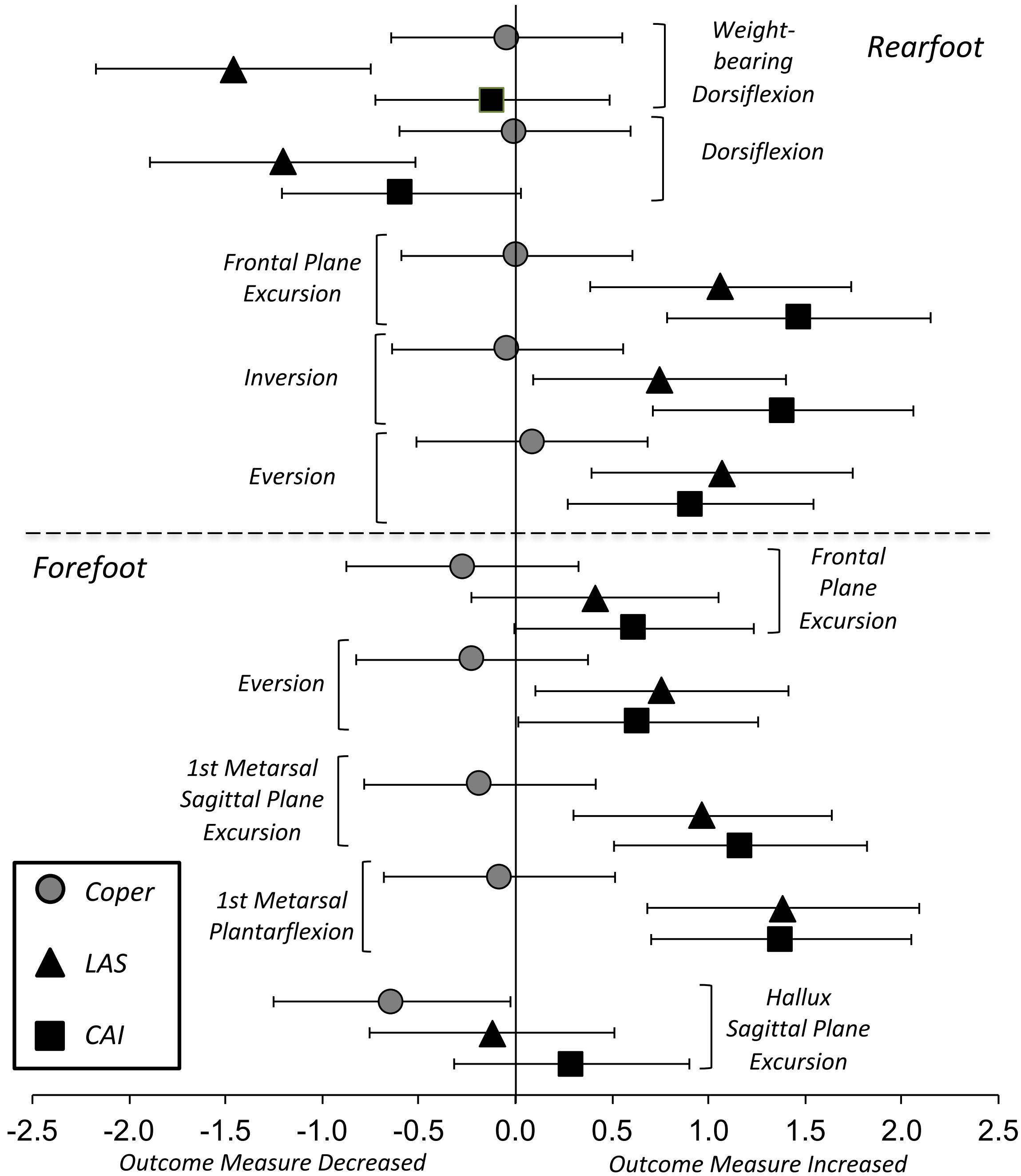

Figure 3. Effect size estimates and 95% confidence intervals of joint motion measures in the Lateral Ankle Sprain (LAS), Coper, and Chronic Ankle Instability (CAI) groups compared to Healthy Controls.

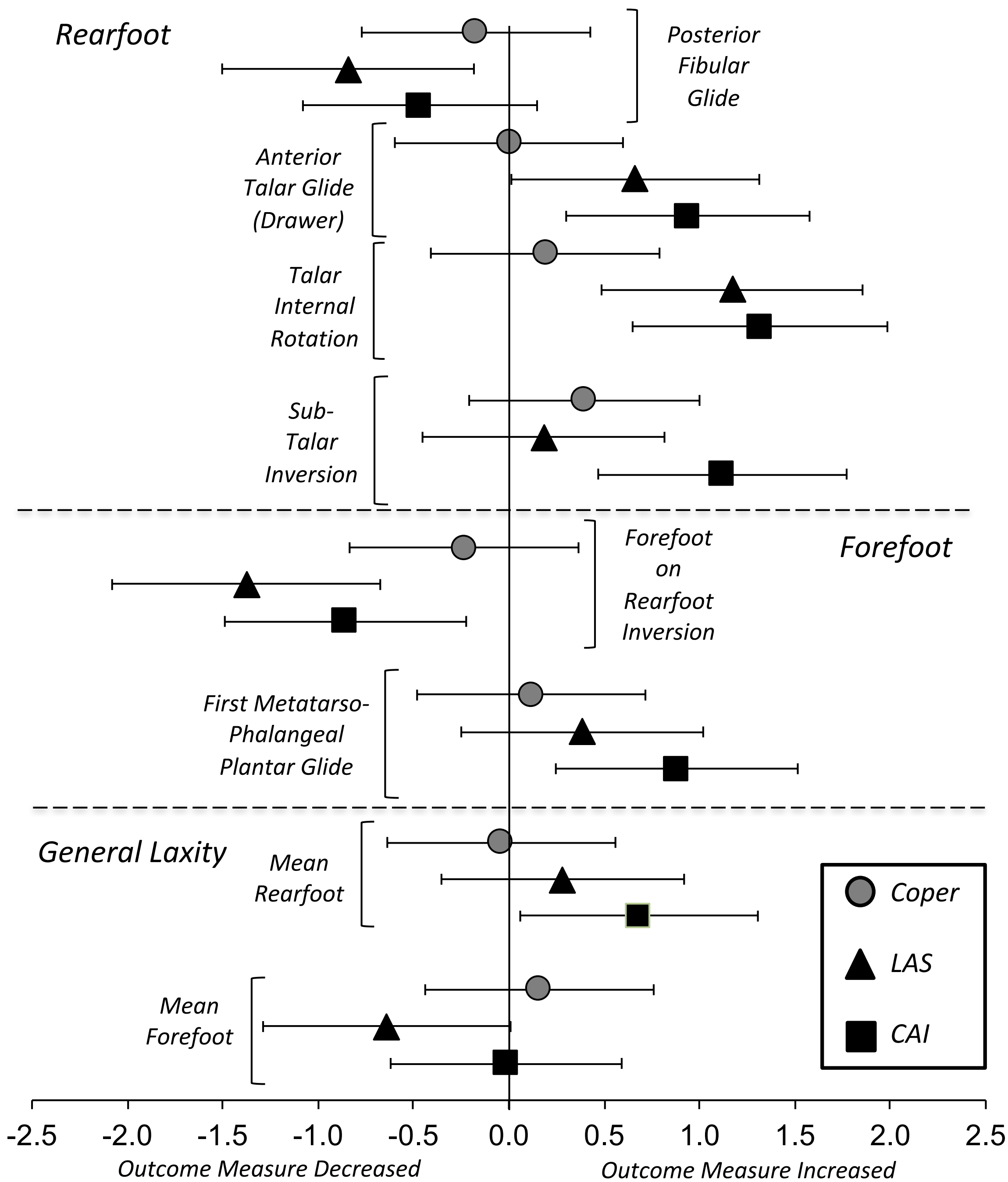

Figure 4. Effect size estimates and 95% confidence intervals of joint play measures in the Lateral Ankle Sprain (LAS), Coper, and Chronic Ankle Instability (CAI) groups compared to Healthy Controls.

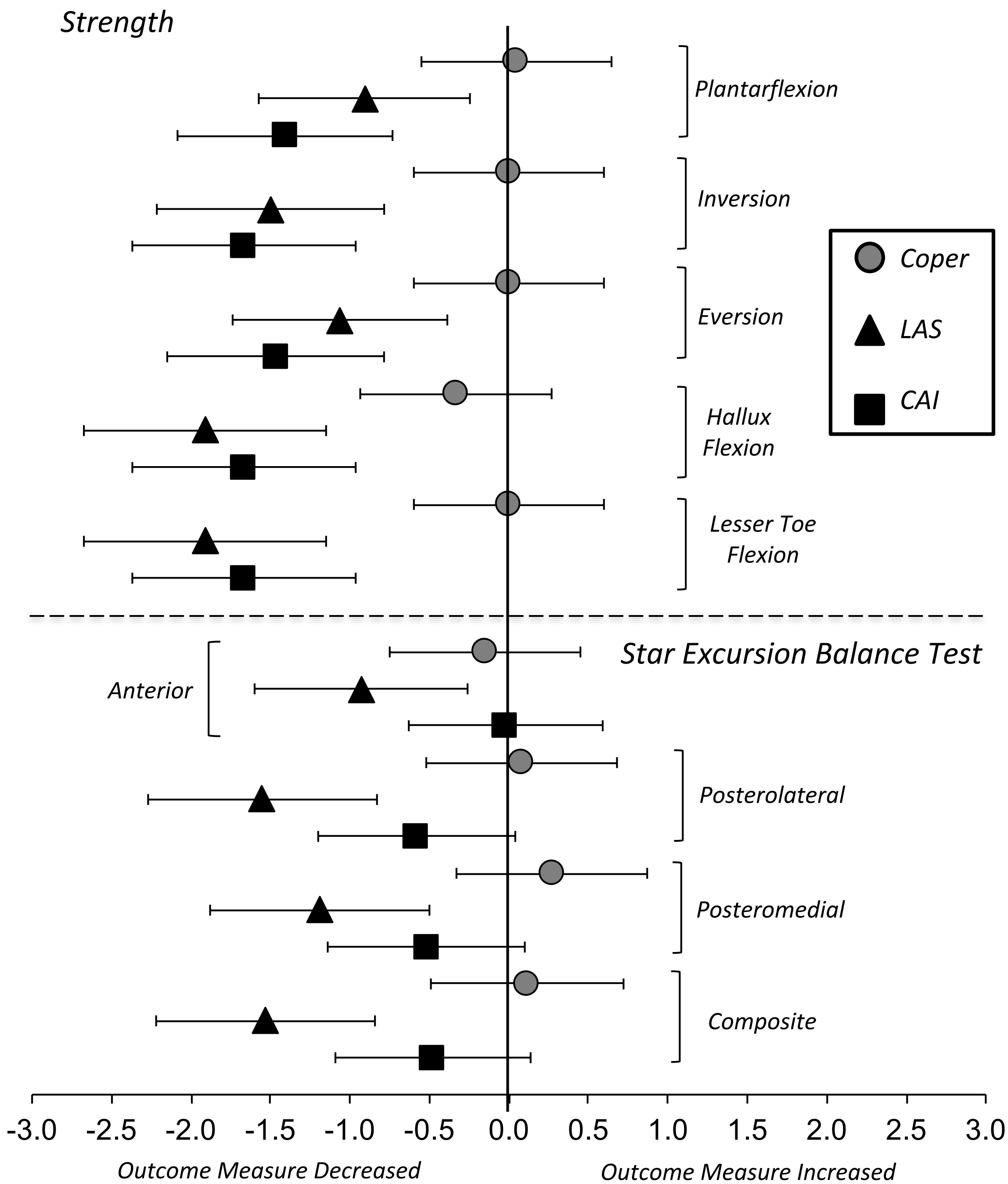

Figure 5. Effect size estimates and 95% confidence intervals of strength and dynamic balance in the Lateral Ankle Sprain (LAS), Coper, and Chronic Ankle Instability (CAI) groups compared to Healthy Controls.

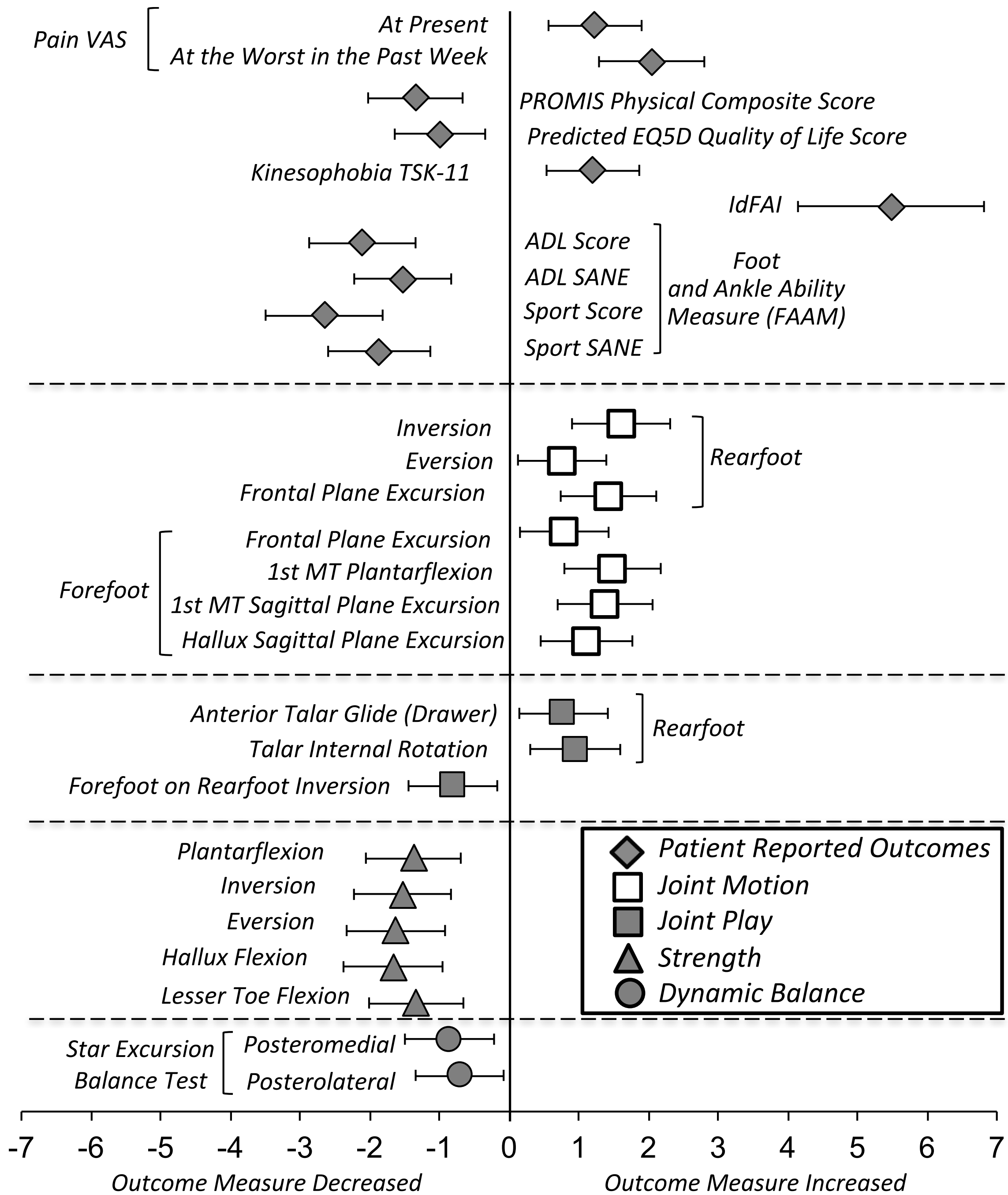

Figure 6. Effect size estimates and 95% confidence intervals of patient-reported outcomes, joint motion, joint play, strength, and dynamic balance measures in the Chronic Ankle Instability (CAI) group compared to the Coper group.

SECTION II: MANUSCRIPT III

EFFECTS OF MIDFOOT JOINT MOBILIZATION ON ANKLE-FOOT MORPHOLOGY AND FUNCTION FOLLOWING ACUTE ANKLE SPRAIN. A RANDOMIZED CONTROL TRIAL.

Abstract

Purpose: To investigate the effects of midfoot joint mobilizations and a one-week home exercise program (HEP) compared to a sham intervention and HEP on pain, patient-reported outcomes (PROS), ankle-foot joint mobility, and sensorimotor function in recreationally-active young adults with a recent LAS.

Methods: A laboratory-based, crossover randomized control trial was performed. All participants were instructed in a stretching, strengthening, and balance HEP and were randomized *a priori* to receive midfoot joint mobilizations (forefoot supination, cuboid glide and plantar 1st tarsometatarsal) or a sham laying-of-hands. Changes in pain, physical, psychological, and functional PROs, foot morphology, joint mobility, tissue reactivity, sensorimotor function, and dynamic balance were assessed pre-to-post treatment and one-week following. Participants crossed-over following a one-week washout to receive the alternate treatment and were assessed pre and immediately post intervention, as well as one-week following intervention. ANOVAs, *t*-tests, proportions, and 95% confidence intervals (CI) were calculated to assess changes in outcomes. Cohen's *d* and 95% CI compared treatment effects at each time-point.

Results: Midfoot joint mobilization had greater effects ($p<.05$) in reducing pain 1-week post (d=0.8), and increasing Single Assessment Numeric Evaluation (immediate: d =0.6), Global Rating of Change (immediate: d =0.6), forefoot inversion (immediate: d =2.1, 1-week: d =3.2), and plantar tarsometatarsal joint play (immediate: d =0.7, 1-week: d =.7) compared to a sham treatment and HEP.

Conclusion: Midfoot joint mobilizations and HEP yielded greater pain reduction, perceived improvement, and forefoot joint play compared to sham and is recommended in a comprehensive rehabilitation program following LAS.

INTRODUCTION

Lateral ankle sprains (LAS) are a common musculoskeletal injury incurred by athletes[1,2] and the general public.[3] LAS involve high-velocity moments and extremes of inversion, internal rotation, and plantarflexion[4,5] that result in injury of the lateral ligaments of the talocrural articulation[6,7] and midfoot.[8–10] Forty-percent of LAS will progress to chronic ankle instability (CAI),[11] a clinical condition described by perceived or episodic giving-way of the ankle and persistent activity limitation and participation restriction that persist beyond one-year post injury.[12] CAI is a heterogeneous condition resulting from both mechanical instability[13] and sensorimotor deficit.[14]

Midfoot injury is common following inversion sprain and may contribute to the signs and symptoms experienced by patients with LAS.[15] In studies of patents who incurred LAS, 21-41% were found to have midfoot ligamentous involvement[8,10] and 33% with midfoot joint capsular injury.[10] Approximately one-quarter of individuals with isolated bifurcate ligament injury post-inversion injury were initially diagnosed as having a LAS.[8] Midfoot injury may contribute to or mimic LAS symptoms.[15] Similar to LAS, persistent pain, swelling, giving-way, and repeat episodes of injury are potential consequences up to at least 12-months following midfoot injury.[10] Disrupted congruency of the calcaneocuboid joint, commonly known as Cuboid Syndrome, is a potential consequence following LAS.[16] This syndrome is theorized to result from rearfoot inversion with the forefoot loaded (relative forefoot eversion)[16] or an eversion moment of the cuboid during a forceful fibularis longus contraction during LAS.[17] Joint mobility assessment of all segments of the ankle-foot complex, especially the midfoot and forefoot, has been recommended for all patients following LAS regardless of symptom presentation.[15,18]

In a recent cross-sectional study of ankle-foot morphology and function comparing copers, LAS, and CAI compared to healthy controls, the LAS group demonstrated increased forefoot eversion and tarsometatarsal motion and no differences in total joint excursion.[18] Diminished forefoot inversion and 1st tarsometarsal plantar joint play measures were also observed.[18] These findings were postulated to be a result from a shift in relative motion further into eversion,[18] a finding that is consistent with the mechanism thought to occur with Cuboid Syndrome.[16]

Joint mobilization, stretching, and strengthening exercises have been suggested when managing patients with midfoot joint impairment.[15,17,18] However, evidence for midfoot joint mobilization and exercise following LAS is limited.[17,19] Therefore, the purpose of this crossover randomized control trial was to investigate the effects of midfoot joint mobilization and a one-week home exercise program (HEP) compared to a sham intervention and HEP on patient-reported measures of pain, physical health, mental health, and function, clinical measures of ankle-foot morphology, joint excursion and play, tissue reactivity, sensorimotor function, and dynamic balance in recreationally-active young adults with a recent history of LAS.

METHODS

DESIGN

A laboratory-based, crossover randomized control trial was performed where the independent variable was treatment (50% allocated to initially receive the joint mobilization, 50% allocated to initially receive the sham intervention) and the primary dependent variables were changes in patient-reported pain and function, foot morphology composite measures (foot mobility magnitude, arch height flexibility), joint excursion (weight-bearing dorsiflexion, rearfoot and hallux goniometry, forefoot inclinometry, 1st metatarsal displacement), joint play, strength (handheld dynamometry), plantar sensation, and dynamic balance (Star Excursion Balance Test, SEBT) immediately post-treatment and one-week following. There were no changes made to the study methodology following trial commencement. The trial was registered with the National Institutes of Health (NCT02697461) and can be accessed at https://goo.gl/uPTjrp.

PARTICIPANTS

A convenience sample of 17 recreationally-active individuals (8 males, 9 females) aged 18-35 with a recent history of a LAS were recruited from a public university. Recreationally-active was defined as participation in some form of physical activity for at least 20-minutes per day, at least three times a week. Participants who sustained a substantial inversion sprain that affected function in the past 2-8 weeks were included. Details of participant demographic information and self-report measures are in **Table 1**. Participants enrolled in this trial were part of larger study of multisegmented foot function in acute ankle sprain, chronic ankle instability, coper, and control groups.[18] Individuals were excluded if they had a history of fracture in the leg or foot, self-reported disability due to neuromuscular impairment in the lower extremity, neurological or vestibular impairment that affected balance, diabetes mellitus, lumbosacral radiculopathy, a soft tissue disorder such as Marfan or Ehlers-Danlos syndrome, any absolute contraindication to manual therapy, or if they were pregnant. Participants who met inclusion criteria provided informed consent. **Figure 1** details the CONSORT[20] flow sheet from recruitment to analysis. Data was collected in a suburban university's sports medicine laboratory. The study was approved by the Institutional Review Board.

PROCEDURES

Baseline Visit

Following consent, participants provided demographic information, health and injury history, and completed the Foot and Ankle Ability Measure (FAAM) ADL[21] and Sport subscales,[22] Identification of Functional Ankle Instability (IdFAI),[23] the Patient Reported Outcomes Measurement Information System (PROMIS) General Health Questionnaire,[24] the 11-item Tampa Scale of Kinesiophobia (TSK-11),[25] and the Godin Leisure-time Exercise Questionnaire.[26] Predicted EUROQOL (EQ-5D) quality of life scores were calculated using previously described methods.[27] Height, mass, and leg length were measured from the anterior superior iliac spine to the medial malleolus. Foot posture was assessed in standing using the Foot Posture Index–6 item version (FPI), a categorical measure of foot type that is based on five observations and one palpatory assessment.[28]

Demographic information, medical history, FPI, and joint play assessment were performed by the primary author who was a physical therapist and board-certified orthopaedic clinical specialist with 15-years of clinical experience and extensive training in manual therapy. Physical examinations were performed by either an athletic trainer with three-years clinical experience or a physical therapist with two-years clinical experience who were blinded to the participants' medical history, functional status, and treatment allocation.

Morphologic Foot Assessment

Morphologic foot measurements were obtained using the Arch Height Index Measurement System (JAKTOOL Corporation, Cranberry, NJ). Total and truncated foot length, arch height, and foot width were measured in sitting and standing. Arch height flexibility[29] and foot mobility magnitude[30] were calculated from morphologic foot measurements across loading conditions.

Ligamentous Reactivity

A palpatory examination was performed of the tibiofibular syndesmosis (mid-malleolar line) and the deltoid, anterior talofibular (ATFL), calcaneofibular, posterior talofibular (PTFL), and bifurcate ligaments for the presence or absence of pain.

Joint Excursion Measures

Weight bearing dorsiflexion (WBDF) was measured using a tape measure as described by Bennell and colleagues.[31] Joint motion measures of rearfoot dorsiflexion, plantarflexion, inversion, and eversion, forefoot inversion and eversion, and hallux flexion and extension were measured as described by Fraser and colleagues.[32] Joint motion measures of rearfoot dorsiflexion, plantarflexion, inversion, and eversion were performed using a 30.5-cm transparent double arm plastic goniometer (Merck Corporation, Kenilworth, NJ). Forefoot inversion and eversion was measured using a digital inclinometer (Fabrication Enterprises, White Plains, NY). First metatarsal (MT) dorsiflexion and plantarflexion were measured utilizing a custom measuring device consisting of two metal rulers bent to 90° as described by Gresiberg and colleagues.[33]

First metatarsophalangeal flexion and extension were measured with a 17-cm double arm plastic goniometer with a semicircular scale (Upjohn Corporation, Kalamazoo, MI). The mean of three measures were recorded for forefoot on rearfoot inversion and eversion, 1st MT dorsiflexion and plantarflexion. The total arc of motion within a plane was used for analysis of joint excursion.

Joint Play Motion

Joint play was assessed for proximal tibiofibular translation; rearfoot anterior, posterior, medial and lateral glides, internal and external rotation; forefoot on rearfoot inversion, eversion, abduction, and adduction; and 1st tarsometarsal and metatarsophalangeal dorsal and plantar glides using previously described methods.[32] Proximal tibiofibular joint mobility was assessed for the presence or absence of hypomobility. Joint play was assessed using a 7-point Likert scale (0=ankylosed, 1=considerable hypomobility, 2=slight hypomobility, 3=normal, 4= slight hypermobility, 5=considerable hypermobility, 6=unstable) developed for quantification of passive mobility intervertebral motion by Gonnella and colleagues.[34] Segmental general laxity was calculated from the mean of all joint play measures within the rearfoot and forefoot.

Plantar Sensation

Plantar sensation was assessed at the heel, the base of the 5th metatarsal, and the head of the 1st metatarsal using Semmes-Weinstein Monofilaments (Smith & Nephew, Inc, Germantown, WI) and the 4-2-1 stepping protocol.[35,36]

Muscle Strength

Ankle dorsiflexion, plantarflexion, inversion, eversion, and hallux flexion and lesser toe flexion strength were assessed with the microFET2 digital handheld dynamometer (Hoggan Health Industries, West Jordan, UT) using previously described methods.[32] For toe flexion strength measures, the ankle was positioned in 45º plantarflexion to reduce contribution of the extrinsic foot muscles through active insufficiency and increase demand of the IFMs.[37] Strength measures were based on the highest value of three trials. In the case of an invalid trial (due to equipment difficulty, deviation from test position, or substitution motion), the participant rested prior to retesting to mitigate effects from fatigue. An estimate of torque was derived from the product of force and segment length, normalized to body mass, and reported in Newton-meters-per kilogram (Nmkg^{-1}). The IFM test was performed and graded using the scale (1=Poor; 2=Fair; 3=Satisfactory) described by Jam.[38]

Dynamic Balance

Dynamic balance was assessed using the anterior, posteromedial, and posterolateral directions of the Star Excursion Balance Test (SEBT) as described by Hertel and colleagues.[39] Reach distance was normalized to leg length.[40] A composite measurement was calculated from the mean of the three directions.

Intervention

Following baseline assessment, all participants were instructed in a HEP consisting of gastrocnemius and soleus stretching; a four-way foot stretch of the rearfoot, midfoot, and forefoot; isotonic inversion, eversion and dorsiflexion exercises against resistance tubing; single-limb heel raising; and a single limb reaching balance exercise (**Figure 2**). Participants were asked to perform all exercises three times daily. All participants were provided a handout detailing the exercises and verbalized understanding following instruction.

Joint mobility was assessed for forefoot on rearfoot inversion and 1st tarsometatarsal plantar joint play limitation. Participants were randomized *a priori* using a random number generator by the senior author and stratified by sex to receive either the midfoot joint mobilizations or a sham intervention. Allocation was performed by an uninvolved member of our laboratory, concealed in a sealed opaque serialized envelope, and opened by the treating clinician. Participants allocated to receive the midfoot mobilizations were provided a dorsolateral cuboid glide with forefoot supination and a 1st tarsometatarsal plantar glides using previously described methods.[15] Each mobilization technique was an oscillatory Maitland Grade IV applied for a 30-second duration. If a cavitation was not experienced during the first bout of oscillations, a second 30-second bout of oscillatory mobilizations were provided. Participants allocated to the sham treatment were explained that they were to receive a gentle soft-tissue technique similar to massage and were provided a "laying of hands" for 30-seconds using the same hand position and contacts used for the two joint mobilizations. Participants were asked to rate the change of symptoms using a single assessment numeric evaluation (SANE, -100%=full exacerbation, 0=no change, 100%=full resolution) immediately post-intervention and completed the Global Rating of Change (GROC).

Follow-up Visit

Participants returned to the laboratory following a seven-day washout for reassessment. They completed the PROMIS, Godin, FAAM-ADL and Sport, SANE, and GROC. HEP compliance was assessed by having the participants return demonstrate the instructed exercises. Participants were rated by the treating clinician whether or not they could demonstrate the exercises without hesitation and with appropriate technique.

Participants were asked to rate their compliance using a SANE, with 0% reflective of complete non-compliance with all home exercises and 100% representing performance of all exercises three times daily. Any deficiencies in exercise technique were corrected and participants were provided encouragement to continue.

Repeat physical examinations were performed pre-and post-intervention. Following the pre-intervention physical examination, participants crossed over to receive the second intervention (i.e. individuals originally allocated to receive the sham intervention during the baseline visit now received the midfoot joint mobilizations). Participants rated treatment response (SANE) immediately post-intervention and at the end of the visit and completed the GROC.

Final Visit

Participants returned to the laboratory seven-days later for the final reassessment visit. They completed the PROMIS, Godin Leisure-Time questionnaire, TSK-11, GROC, SANE, FAAM-ADL, and FAAM-Sport. HEP compliance was reassessed at the beginning of the final visit.. A final physical assessment was performed and the participant was dismissed from the study. No changes in trial outcomes were made during the duration of the trial.

STATISTICAL ANALYSIS

A priori sample size estimation of 14 participants were needed to demonstrate large effects post-intervention for the FAAM Sport with an α=.05, and β=.20.[41] Descriptive statistics were calculated for demographic and self-reported measures for each subset of the sample allocated to receive either sham or midfoot mobilization during the first visit. Independent t-tests were used to assess differences between allocation groups.

Treatment effectiveness of the two interventions was compared using dependent *t*-tests for pain in the past week and pre-and post-intervention patient-reported outcomes measures. Proportion estimates and 95% CI were calculated for all dichotomous variables. The Wilcoxon's signed rank test was used to assess differences between treatments for the IFM test at each time point. The effects of treatment (midfoot joint mobilization, sham) and time (immediate change, pre-to-1-week change) for clinical measures were assessed using within-subjects repeated measures ANOVAs. Change scores that had a 95% confidence intervals (CI) that did not cross zero were considered to have a significant change at each time point. Ordinal measures that had greater than five items (joint play, plantar sensation, GROC) were treated as continuous data during analysis.[42,43]

Post hoc Cohen's *d* effect size (ES) point estimates and 95% CI [44] comparing treatments were calculated for all significant treatment or treatment by time interactions for immediate pre-to-post and 1-week change scores. ES were interpreted using the scheme proposed by Cohen:[44] <0.2 equates to a trivial ES, 0.2-0.49 small, 0.5-0.79 moderate, and >0.8 large. Pre-to-post treatment ES point estimates and 95% CI were statistically significant when the CI did not cross the '0' threshold.

Data was analyzed using Statistical Package for Social Sciences (SPSS) Version 23.0 (IBM, Inc., Armonk, New York). Proportion point estimates, Cohen's *d* effect sizes, and 95% confidence intervals were calculated using Microsoft Excel for Mac 2016 (Microsoft Corp., Redmond, WA). The level of significance was $p \leq 0.05$ for all analyses.

RESULTS

There were no statistical differences in demographics, injury history, foot posture, or patient-reported outcome measures between allocation groups at initial baseline, with the exception of idFAI. (**Tables 1 & 2**). The group allocated to receive the sham intervention first had significantly greater self-reported instability (IdFAI=26.6±3.5) compared to the group who initially received the joint mobilization (IdFAI= 20.7±4.6, p=.009). Objective physical measures were similar between groups prior to treatment. (**Tables 3-6**). In the assessment of potential carryover effects between baselines 1 and 2, rearfoot inversion motion was the only measure that had a significant treatment by order interaction and 1st metatarsal plantar glide joint play and SEBT performance in the posteromedial and posterolateral directions had significant time by order interactions. There were no other significant carryover effects.

Midfoot inversion and 1st tarsometatarsal plantar hypomobility was present in all participants in the sample. As a result, all participants were eligible for random allocation. Joint cavitation was experienced by 35.3% of the sample during the forefoot mobilization and none during tarsometatarsal mobilization. Between allocation groups, 85.7% of the first mobilization group and 83.3% of the second mobilization group participants received a second forefoot mobilization. All participants received a second bout of tarsometatarsal mobilizations. No participants who received the second bout of mobilizations experienced a cavitation in either the midfoot or forefoot.

Self-reported compliance with the HEP on initial and final follow-up was 56.3±29.9% and 65.4±21.6% in the initial sham allocation group and 74.5±16.1% and 60.6±31.9% in the initial joint mobilization group, respectively. Seventy-five percent of the sham allocation group was able to appropriately return demonstrate the HEP following the first and second weeks. The proportion of the mobilization group able to return-demonstrate the HEP was 62.5±31.9% during the first week and 87.5±34.6% during the second week of the trial.

PATIENT-REPORTED OUTCOME MEASURES

There were significant improvements made following both treatments for worst pain in the past week, PROMIS physical health composite, FAAM-ADL (score and SANE), and FAAM-Sport (score and SANE) from baseline to follow-up visits. Only the mobilization treatment had a small, but significant decrease in PROMIS mental health composite score. There were no other significant changes in patient-reported outcomes following the first week of the trial. From follow-up to final visits, both treatments had significant improvements in worst pain in the past week, Godin leisure activity, FAAM-ADL score, and FAAM-Sport (score and SANE). Only the sham treatment had improvement in PROMIS physical and mental health composite scores. There were no further changes resulting from either treatment during the second week of the trial.

There was a significantly greater perceived improvement immediately following joint mobilization as compared to the sham treatment (SANE: $p=.04$, $d=0.6$, 95% CI: -0.1, 1.3; GROC: $p=.05$, $d=0.6$, 95% CI: -0.1, 1.3) that lasted to 1-week following treatment (SANE: $p<.001$ GROC: $p<.001$). A greater reduction in pain was observed following joint mobilizations at 1-week following treatment ($p=.004$, $d=-0.8$, 95% CI: -1.5, -0.1). There were no significant differences between treatments for pain at the present ($p=.10$) or worst in the past week ($p=.10$). Both treatments resulted in a significant decrease in kinesiophobia following the 2-week trial (mean change=-3.1±2.6, p<.001, *d*=0.8, 95% CI: 0.1, 1.3). While there were no other significant differences between treatments immediate post or 1-week following intervention, group means improved as a result of both treatments. **Table 2** details the comparison of treatment on change in patient-reported outcome measures. Effect size estimates and 95% CI are detailed in **Figure 6**.

PHYSICAL OUTCOME MEASURES

Pre-intervention descriptive statistics for both allocation groups at Baselines 1 and 2 are detailed in **Tables 3-6**. Immediate post-intervention and 1-week mean change scores and 95% CI for the joint mobilization and sham treatments are detailed in **Figures 3-5**. Effect size estimates and 95% CI are detailed in **Figure 6**.

Foot Morphology

There was a significant increase in arch height flexibility immediate post-mobilization, but not at 1-week post-treatment. There were no further significant changes post-intervention changes immediately or 1-week following and no treatment, time, or treatment by time interactions for foot morphologic composite measures (**Table 3)**.

Ligament Reactivity

There were no statistically significant differences pre-to-post intervention or between treatments for proportion of participants with syndesmotic, bifurcate, anterior talofibular, calcaneofibular, or posterior talofibular reactivity (**Table 3)**.

Joint Motion and Play

In the rearfoot, there was a significant decrease in lateral glide joint play following joint mobilization treatment and a trend of increasing mobility in sham treatment 1-week post-intervention, resulting in a significant treatment by time interaction (p=.03, immediate: *d* =0.1, 95% CI: -0.6, 0.8, 1-week: *d* =-0.9, 95% CI: -1.6, 0.2. While there was a significant treatment by time interaction for internal rotation joint play, both treatments had non-significant changes at either time-point (p=.03, immediate: *d* =0.4, 95% CI: -0.3, 1.1, 1-week: *d* =-0.4, 95% CI: -1.1, 0.3) (**Figure 4).**

In the forefoot, there was a significant increase in forefoot inversion motion and frontal plane excursion motion immediate post sham intervention, but not at 1-week post. First tarsometatarsal excursion significantly increased immediately following joint mobilization.

There was an immediate and lasting significant increase in forefoot inversion (p<.001, Immediate: *d* =2.1, 95% CI:1.3, 2.9, 1-week: 3.2 95% CI: 2.2, 4.2) and 1st tarsometatarsal plantar glide (p=.04, Immediate: *d* =0.7, 95% CI: 0.0, 1.4, 1-week: 0.7 95% CI: 0.0, 1.4) joint play following joint mobilization. (**Figure 5**). A significantly increased passive forefoot abduction joint play was observed immediate following both treatments, which diminished at 1-week post (p=.03). First metatarsophalangeal plantar glide joint play decreased at 1-week post intervention. There were no other significant group, time, or treatment by time interactions for any joint motion or joint play measures in the rearfoot or forefoot (**Figure 3-4**).

<u>Sensorimotor Function and Dynamic Balance</u>

There was a significant time effect for plantar sensation, with no change in the sensory thresholds following joint mobilization immediate post-treatment and decreased threshold 1-week following at the heel (p=.02) and the 5th metatarsal (p=.03) sites. Only the 5th metatarsal site had a significant decrease in sensory threshold at 1-week post mobilization. (**Figure 5**)

A small, but significant decrease in normalized strength was observed immediately post-intervention for the joint mobilization treatment only. There were no significant treatment differences in IFM performance immediate (p=.56, *d* =0.6, 95% CI: -.1, 1,3) and 1-week post treatment (p=.56, *d* =0.3, 95% CI: -0.4, 1.0). There were no other significant changes immediately or 1-week post-intervention and no treatment, time, or treatment by time interactions for strength measures (**Figure 5**).

For dynamic balance measures, there were significant time effects for improved normalized SEBT anterior (p=.05), posterolateral (p=.05), posteromedial (p=.007), and composite (p<.001) scores. The joint mobilization treatment significantly improved anterior reach immediate and 1-week post-intervention and composite score at 1-week post-intervention. The sham treatment significantly improved posterolateral and posteromedial reach at 1-week post intervention. There were no other significant changes immediately or 1-week post-intervention and no treatment, time, or treatment by time interactions (**Figure 5)**.

DISCUSSION

The principal findings of this crossover randomized control trial were that midfoot joint mobilization and a HEP consisting of stretching, strengthening, and balance had greater effects in reducing pain, perceived improvement, and rearfoot, midfoot, forefoot joint motion and play, and improved sensation as compared to a combined sham treatment and HEP. Regardless of treatment, participants experienced reduction of worst pain in the past week, increased self-reported physical activity, function, kinesiophobia, plantar sensation at the heel and SEBT performance post-treatment. **Figure 7** provides a graphical summary of significant effects of joint mobilization on clinical outcomes.

The mechanism of effectiveness of manual therapy is complex and may result in psycho-emotional, neurophysiologic, and mechanical effects.[45] Together, these effects may facilitate functional restoration following LAS. Specific effects encompassed in the three domains include pain rating, expectations, psychological measures, and neuromotor response.[45] The findings of our study support that midfoot joint mobilization, when combined with a HEP, may help to improve impairment in these three domains and facilitate resumption of activity.

Pain reduction was achieved immediately and 1-week following joint mobilization, a finding that can be contextualized using the minimal important differences (MID). Landorf and colleagues[464746] reported that the average MID for foot conditions to be 0.8 cm on the VAS pain scale. In our study, only the joint mobilization treatment exceeded this MID at 1-week post intervention. Both treatments reduced severity of pain at its worst that exceeded the MID. There was also improved function in the FAAM-ADL and Sport that exceeded minimal detectable change following the two treatments.[21]

We observed positive psychological effects following the joint mobilization intervention. Perceived improvement was significantly higher following the joint mobilization treatment compared to sham. Psychological traits such as high resiliency and self-efficacy have been suggested to have an important role in injury recovery and return to sport.[47,48] While the long-term effects of joint mobilization are unclear from our findings, we anticipate that earlier improvements in perceived pain and recovery will create greater optimism and personal investment into treatment that may influence functional outcomes. Since kinesiophobia has been described as a predictor for disability in patients with foot conditions,[49] the significant decrease in this measure following treatment was a good prognostic indicator for favorable functional outcomes.

A progressive increase in sensory threshold and dynamic balance was observed following both treatments. Following LAS, there is peripheral[50,51] and central[52,53] neurophysiologic consequences following injury. Manual therapy has previously been shown to influence plantar peripheral sensation[54] and dynamic balance.[41] It is unclear from these data if improvements were a result of a neurophysiologic treatment effect, time and healing, or from motor learning when performing a novel task. Ankle dorsiflexion is a covariate with SEBT performance,[55] a measure that also increased with time.

While there were no significant changes in forefoot frontal plane motion, joint play measures improved. The disparity between these measures is likely a consequence of physiologic triplanar motion. Forefoot inversion motion was measured with an inclinometer about the frontal plane, whereas joint play measure assessment allowed for triplanar motion within the physiologic plane. Another plausible explanation for the disparity is that while joint motion measures are purely quantitative, joint play assessment is reliant on clinician judgement, factors in an individual's phenotype, and has a qualitative element of motion nuance that joint excursion measures lack.

CLINICAL RECOMMENDATIONS

Midfoot joint mobilizations are highly recommended in patients with LAS when clinically indicated. Patient with midfoot joint hypomobility or a more inverted rearfoot (with physiologic shift of the forefoot into eversion) may benefit from this treatment.[18] Significant clinical improvements were also observed following the sham treatment who performed exercises that specifically addressed the midfoot and forefoot. While we did not observe ideal compliance with the home exercise program, participants in both allocation groups still performed a substantial volume of exercise and demonstrated improvements with time. Inclusion of stretching and strengthening exercises for the midfoot should is recommended.

In practice, the midfoot should not be treated in isolation using a single intervention approach. The design of our study was necessary to demonstrate treatment effects specific to midfoot mobilization in isolation without potential confounding introduced by treatment of the rearfoot. The standards of care dictate that a comprehensive treatment plan that includes protection, optimal loading, therapeutic exercise, sensorimotor training, and joint mobilization of the rearfoot and shank.[56] Coupled with a comprehensive treatment program that addresses rearfoot deficit, midfoot joint mobilization is likely value added.

LIMITATIONS

This study is not without limitations. A constraint of the crossover design is the potential for carryover effects. Comfort may be taken with the knowledge that the sample was equally allocated and only a few secondary outcomes had significant time by order or treatment by order interactions. Also, the decision to use change scores was made *a priori* to mitigate carryover effects following a one-week washout period. The experimental treatment intervention included only a single session midfoot mobilization and a 1-week home exercise program. Further research is needed to investigate midfoot mobilization as part of a comprehensive ankle rehabilitation program of longer duration. We utilized recreationally active young adults in our study, which limits the generalizability of our findings to other populations. In our delimitations, we included any participant with a recent ankle sprain regardless of number of ankle sprains. Participants with both first-time ankle sprains and acute-on-chronic injuries were included. While this may have improved external validity, it is unclear how this affected treatment responsiveness.

CONCLUSION

Midfoot joint mobilization and a HEP consisting of stretching, strengthening, and balance had greater effects in reducing pain, perceived improvement, and rearfoot, midfoot, forefoot joint play, and improved sensation as compared to a combined sham treatment and HEP. Regardless of treatment, participants had reduced severity of pain in the week previous, increased self-reported physical activity, function, kinesiophobia, plantar sensation at the heel and SEBT performance. This improvement is likely partly attributed to the effects of the home exercise program and healing. Midfoot joint mobilizations, stretching, and strengthening exercises are highly recommended as part of a comprehensive rehabilitation program in patients with LAS with midfoot hypomobility or a more inverted rearfoot.

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Table 1. Demographic, injury history, and patient-reported outcome measures in individuals with ankle sprain

	Participants allocated to receive sham intervention first (n=8) 4 males 4 females	Participants allocated to receive midfoot mobilization first (n=9) 4 males 5 females		Total Sample (n=17) 8 males 9 females
	Mean ± SD		*p*	Mean ± SD
Age (years)	20.4±1.3	23.2±5.3	.17	21.0±2.3
Height (cm)	170.2±8.8	174.1±9.5	.39	172.3±2.2
Weight (kg)	67.1±13.5	75.7±10.6	.17	71.6±12.5
BMI (kg/m^2)	23.1±3.4	25.0±3.9	.29	24.1±3.7
Foot Posture Index	2.0±3.6	3.0±3.2	.56	2.5±3.4
Ankle sprains (n)	2.5±1.4	3.2±3.0	.54	2.9±2.3
Time to injury (months)	0.9±0.5	0.9±0.7	.84	0.9±0.6
IdFAI	26.6±3.5	20.7±4.6	.009	23.9±4.7
Kinesiophobia (TSK-11)	23.9±4.7	20.4±4.3	.14	22.1±4.7

cm=centimeters, kg=kilograms, BMI=body mass index, IdFAI=Identification of Functional Ankle Instability, TSK=Tampa Scale Kinesiophobia

Table 2. Comparison of treatment on change in patient-reported outcome measures in individuals with ankle sprain

		Baseline 1	Pre-to-Post Change	Baseline 2	Pre-to-Post Change	
		Mean±SD				*p*
Pain Visual Analogue Scale (cm) Present	Sham	1.4±1.5*	IMM:0.3±1.8 1wk: -0.2±1.3	0.9±1.0†	IMM:0.4±0.6 1wk: 0.4±0.6	.10‡ .004§ .08||
	Treatment	2.0±2.1†	IMM:-0.6±1.3 1wk: -1.1±1.4	1.2±1.7*	IMM:0.2±0.7 1wk: -0.8±1.7	
Worst in the Past Week	Sham	3.5±1.9*	-1.9±1.7	1.8±1.1†	-0.7±1.3	.10
	Treatment	3.3±1.8†	-1.6±1.6	1.6±1.8*	-0.9±1.6	
PROMIS General Health: Physical Composite (*t*)	Sham	49.2±5.8*	2.9±5.5	55.6±3.9†	2.4±6.7	.87
	Treatment	52.0±6.8†	2.4±6.7	52.0±6.0*	1.8±5.9	
Mental Composite (*t*)	Sham	55.9±7.0*	1.3±5.2	61.7±4.5†	3.1±2.1	.28
	Treatment	62.1±8.3†	-2.8±3.0	57.1±11.0*	1.9±7.5	
Predicted Quality of Life (EQ5-D) (%)	Sham	73.3±8.0*	2.1±6.9	80.5±2.9†	1.0±3.0	.72
	Treatment	76.6±8.4†	2.1±6.4	75.4±7.5*	2.9±6.7	
Godin Leisure Time Activity	Sham	47.1±27.2*	3.5±13.5	84.3±101.4†	9.8±19.5	.32
	Treatment	42.8±24.7†	39.5±92.7	50.6±19.0*	7.1±13.4	
FAAM ADL Score (%)	Sham	74.0±17.1*	12.3±16.1	92.6±4.0†	2.0±3.9	.81
	Treatment	78.7±13.3†	12.0±10.5	86.3±9.4*	4.4±4.8	
ADL SANE (%)	Sham	79.3±24.2*	11.0±24.7	89.1±7.9†	1.3±9.9	.69
	Treatment	80.0±12.3†	6.6±14.0	90.3±7.3*	0.8±4.8	
Sport Score (%)	Sham	46.9±27.7*	19.9±22.0	70.5±18.7†	13.1±16.0	.88
	Treatment	46.6±31.4†	22.9±21.3	66.8±20.3*	10.8±11.3	
Sport SANE (%)	Sham	55.5±26.0*	24.5±23.2	72.3±20.6†	16.6±18.9	.18
	Treatment	56.1±29.8†	16.6±18.9	80.0±11.2*	3.4±7.0	
Perceived Improvement SANE (%)	Sham		IMM:4.0±12.7* 1wk: 35.7±34.1*		IMM:10.0±31.3† 1wk: 65.0±29.8†	.04‡ <.001§ .27||
	Treatment		IMM:36.2±42.5† 1wk: 56.9±33.1†		IMM:21.4±21.7* 1wk: 56.9±37.0*	
Global Rating of Change	Sham		IMM:-0.1±1.4* 1wk: 2.0±1.9*		IMM:.63±2.0† 1wk: 4.1±1.7†	.05‡ <.001§ .19||
	Treatment		IMM 2.4±2.6† 1wk: 3.1±2.0†		IMM:1.4±2.3* 1wk: 3.9±2.4*	

IMM=Immediate pre-to-post change, 1wk=Pre-to-1-week post change, PROMIS=Patient Reported Outcome Measures Information System, EQ5-D=EuroQol five dimensions, FAAM=Foot and Ankle Ability Measure, ADL=activities of daily living, SANE=single assessment numeric evaluation

*Received sham intervention first, †Received midfoot joint mobilization first

‡ Treatment Main Effect, § Time Main Effect, || Treatment by Time Interaction

Table 3. Comparison of treatment on composite morphologic foot measurement and proportion with ligamentous reactivity in individuals with ankle sprain

Composite Foot Measures		Baseline 1 (Mean±SD)	Baseline 2 (Mean±SD)	Pre-to-Post Change (95% CI)	p
Arch Height Flexibility (cm kg^{-1})	Sham	1.3±0.8*	1.5±0.8†	IMM:0.0 (-0.3, 0.3) 1-wk: 0.0 (-0.2, 0.2)	26‡ .88§ .91‖
	Treatment	1.2±0.4†	2.4±1.0*	IMM:0.3 (0.1, 0.5) 1-wk: 0.2 (-0.1, 0.5)	
Foot Mobility Magnitude (cm)	Sham	1.9±1.5*	3.5±3.0†	IMM:0.4 (-0.3, 1.1) 1-wk: 0.2 (-0.7, 2.1)	.70‡ .73§ .60‖
	Treatment	3.4±1.7†	3.4±0.7*	IMM:-0.2 (-0.6, 1.0) 1-wk: 0.2 (-0.8, 1.2)	
Ligamentous Reactivity		Proportion (95% CI)		Pre-to-Post Change (95% CI)	
Syndesmosis (%)	Sham	12.5 (2.2, 47.1) *	12.5 (2.2, 47.1) †	-5.8 (-30.0, 19.0)	
	Treatment	22.2 (6.3, 54.7) †	12.5 (2.2, 47.1) *	-11.4 (-35.3, 13.5)	
Deltoid ligament (%)	Sham	50.0 (21.5, 78.5) *	12.5 (2.2, 47.1) †	2.1 (-28.3, 32.3)	
	Treatment	11.1 (2.0, 43.5) †	50.0 (21.5, 78.5) *	4.4 (-32.4, 24.9)	
Anterior talofibular ligament (%)	Sham	50.0 (21.5, 78.5) *	25.0 (7.1, 59.1) †	-17.7 (-44.1, 12.0)	
	Treatment	22.2 (6.3, 54.7) †	12.5 (2.2, 47.1) *	7.7 (-21.4, 35.8)	
Calcaneofibular ligament (%)	Sham	12.5 (2.2, 47.1) *	12.5 (2.2, 47.1) †	-5.8 (-30.0, 19.0)	
	Treatment	33.3 (12.1, 64.6) †	12.5 (2.2, 47.1) *	-11.0 (-36.4, 16.3)	
Posterior talofibular ligament (%)	Sham	25.0 (7.1, 59.1) *	25.0 (7.1, 59.1) †	-11.7 (-38.0, 17.0)	
	Treatment	55.6 (26.7, 81.1) †	12.5 (2.2, 47.1) *	-22.8 (-47.9, 6.8)	
Bifurcate ligament (%)	Sham	12.5 (2.2, 47.1) *	12.5 (2.2, 47.1) †	-6.2 (-31.4, 20.0)	
	Treatment	22.2 (6.3, 54.7) †	0.0 (0.0, 32.4) *	-4.3 (-29.6, 22.8)	

cm=centimeters, kg=kilograms, IMM=immediate, wk=week
*Received sham intervention first, †Received midfoot joint mobilization first
‡ Treatment Main Effect, § Time Main Effect, || Treatment by Time Interaction

Table 4. Comparison of treatment on rearfoot joint motion and play measurements in individuals with ankle sprain

Joint Motion Measures		Baseline 1	Baseline 2
		Mean±SD	
Rearfoot Dorsiflexion (°)	Sham	13.8±7.7 *	14.0±4.5†
	Treatment	12.6±4.5†	15.3±5.1 *
Rearfoot Plantarflexion (°)	Sham	67.5±9.7 *	58.9±8.4†
	Treatment	60.8±6.5†	66.9±10.1 *
Total Rearfoot Sagittal Excursion (°)	Sham	81.3±13.3 *	72.9±7.1†
	Treatment	73.3±8.5†	82.1±11.8 *
Rearfoot Inversion (°)	Sham	31.3±9.2 *	35.4±9.5†
	Treatment	34.0±7.8†	30.4±8.7 *
Rearfoot Eversion (°)	Sham	11.1±5.4 *	12.6±4.1†
	Treatment	13.9±5.6†	10.8±4.8 *
Total Rearfoot Frontal Excursion (°)	Sham	50.6±10.0 *	48.0±12.4 †
	Treatment	47.9±12.4†	41.1±13.2 *
Weight bearing Dorsiflexion (cm)	Sham	9.8±3.2 *	9.7±2.6†
	Treatment	12.0±7.8†	11.0±3.0 *
Joint Play Measures			
Talocrural Anterior Drawer	Sham	3.4±0.7 *	3.5±0.8†
	Treatment	3.7±0.5†	3.8±0.7 *
Posterior Drawer	Sham	3.3±0.7 *	3.0±0.0†
	Treatment	3.2±0.4†	3.0±0.0 *
Rearfoot Inversion	Sham	3.6±0.7 *	4.1±0.4†
	Treatment	4.1±0.3†	3.9±0.6 *
Eversion	Sham	3.0±0.8 *	2.9±0.4†
	Treatment	2.7±0.5†	2.5±0.8 *
Medial Glide	Sham	3.3±0.7 *	3.4±0.7†
	Treatment	3.4±0.7†	3.1±0.8 *
Lateral Glide	Sham	2.5±1.1 *	2.6±0.9†
	Treatment	3.0±0.9†	3.0±1.2 *
External Rotation	Sham	3.0±.0.0 *	3.0±0.0†
	Treatment	3.2±0.4†	3.0±0.0 *
Internal Rotation	Sham	4.0±0.8 *	3.9±0.4†
	Treatment	4.0+0.5†	3.9±0.8 *
Distal tibiofibular Glide	Sham	2.4±0.9 *	2.6±0.5†
	Treatment	3.2±0.4†	2.8±0.5 *
Proximal tibiofibular hypomobility Proportion (%) (95% CI)	Sham	25.0 (7.1, 59.1) *	0.0 (0.0, 32.4) †
	Treatment	11.1 (2.0, 43.5) †	12.5 (2.2, 47.1) *

*Received sham intervention first, †Received midfoot joint mobilization first

Table 5. Comparison of treatment on forefoot joint motion and play measurements in individuals with ankle sprain

Joint Motion Measures		Baseline 1	Baseline 2	Joint Play Measures		Baseline 1	Baseline 2
		Mean±SD				Mean±SD	
Forefoot Inversion (º)	Sham	32.9±7.9*	42.8±7.8†	Forefoot Inversion	Sham	2.0±0.0*	2.9±0.4†
	Treatment	36.2±9.8†	32.8±7.3*		Treatment	1.9±0.3†	2.0±0.0*
Eversion (º)	Sham	17.7±5.2*	18.0±6.9†	Eversion	Sham	2.6±0.9*	3.0±0.0†
	Treatment	20.5±9.5†	16.5±4.6*		Treatment	2.8±0.4†	2.8±0.5*
Total Frontal Excursion (º)	Sham	50.6±10.0*	60.8±12.2†	Abduction	Sham	2.8±0.7*	3.0±0.0†
	Treatment	56.7±11.4†	49.3±8.5*		Treatment	2.8±0.4†	2.9±0.4*
1st Metatarsal Dorsiflexion (mm)	Sham	5.3±1.5*	5.8±1.1†	Adduction	Sham	2.3±0.7*	3.4±0.5†
	Treatment	5.7±1.9†	5.0±1.6*		Treatment	3.1±0.8†	3.4±0.7*
Plantarflexion (mm)	Sham	6.8±2.1*	7.7±1.3†	1st Tarsometatarsal Dorsal Glide	Sham	2.9±0.8*	2.9±0.4†
	Treatment	8.0±1.4†	6.9±1.8*		Treatment	3.0±0.0†	3.3±0.5*
Total Sagittal Excursion (mm)	Sham	12.1±2.7*	13.5±2.3†	Plantar Glide	Sham	2.8±0.5*	2.9±0.4†
	Treatment	13.7±2.8†	11.8±3.0*		Treatment	2.2±0.4†	2.4±0.7*
Hallux Extension (º)	Sham	85.6±14.8*	82.3±15.3†	1st Metatarsophalangeal Dorsal Glide	Sham	3.1±0.4*	3.0±0.0†
	Treatment	81.7±18.5†	85.6±14.7*		Treatment	2.9±0.3†	3.4±0.5*
Flexion (º)	Sham	37.5±13.6*	31±14.8†	Plantar Glide	Sham	2.8±0.5*	2.4±0.5†
	Treatment	27.2±17.9†	40.0±22.4*		Treatment	2.7±0.5†	2.9±0.6*
Total Sagittal Excursion (º)	Sham	123.1±22.4*	113.3±11.0†				
	Treatment	108.9±16.9†	125.6±29.1*				

*Received sham intervention first, †Received midfoot joint mobilization first

Table 6. Comparison of treatment on sensorimotor function and dynamic balance in individuals with ankle sprain

		Baseline 1	Baseline 2
Plantar Sensory Threshold		Mean±SD	
Heel (g)	Sham	5.8±6.3 *	1.1±0.8 †
	Treatment	4.3±0.6 †	5.5±9.9 *
Base of the 5th Metatarsal (g)	Sham	1.2±1.8 *	0.3±0.1 †
	Treatment	3.4±0.6 †	0.7±0.5 *
Head of the 1st Metatarsal (g)	Sham	0.6±0.6 *	0.4±0.4 †
	Treatment	3.6±0.5 †	0.5±0.5 *
Strength (normalized)			
Ankle Dorsiflexion ($Nmkg^{-1}$)	Sham	3.1±0.8 *	3.1±1.4 †
	Treatment	3.2±0.9 †	3.2±0.7 *
Plantarflexion ($Nmkg^{-1}$)	Sham	5.2±1.4 *	5.2±3.6 †
	Treatment	5.5±2.8 †	5.6±1.5 *
Inversion ($Nmkg^{-1}$)	Sham	2.3±0.6 *	1.9±1.0 †
	Treatment	2.0±0.6 †	2.5±0.6 *
Eversion ($Nmkg^{-1}$)	Sham	2.2±0.6 *	2.1±1.1 †
	Treatment	2.2±0.6 †	2.3±0.6 *
Hallux Flexion ($Nmkg^{-1}$)	Sham	0.9±0.2 *	0.6±0.3 †
	Treatment	0.6±0.2 †	1.0±0.2*
Lesser Toe Flexion ($Nmkg^{-1}$)	Sham	0.8±0.2 *	0.6±0.3 †
	Treatment	0.6±0.2 †	0.9±0.1 *
Intrinsic Foot Muscle Test	Sham	2.4±0.7 *	2.0±1.1 †
	Treatment	2.2±0.8 †	2.0±1.1 *
Dynamic Balance (normalized)			
Anterior (%)	Sham	63.3±5.5 *	66.8±3.7 †
	Treatment	62.9±2.6 †	67.2±5.0 *
Posterolateral (%)	Sham	75.8±4.4 *	81.7±6.3 †
	Treatment	78.5±7.2 †	85.1±6.6 *
Posteromedial (%)	Sham	67.5±8.7 *	72.9±8.1 †
	Treatment	70.0±10.0 †	78.7±6.0 *
Composite (%)	Sham	68.9±5.2 *	73.8±3.9 †
	Treatment	70.4±5.0 †	77.0±4.6 *

*Received sham intervention first, †Received midfoot joint mobilization first

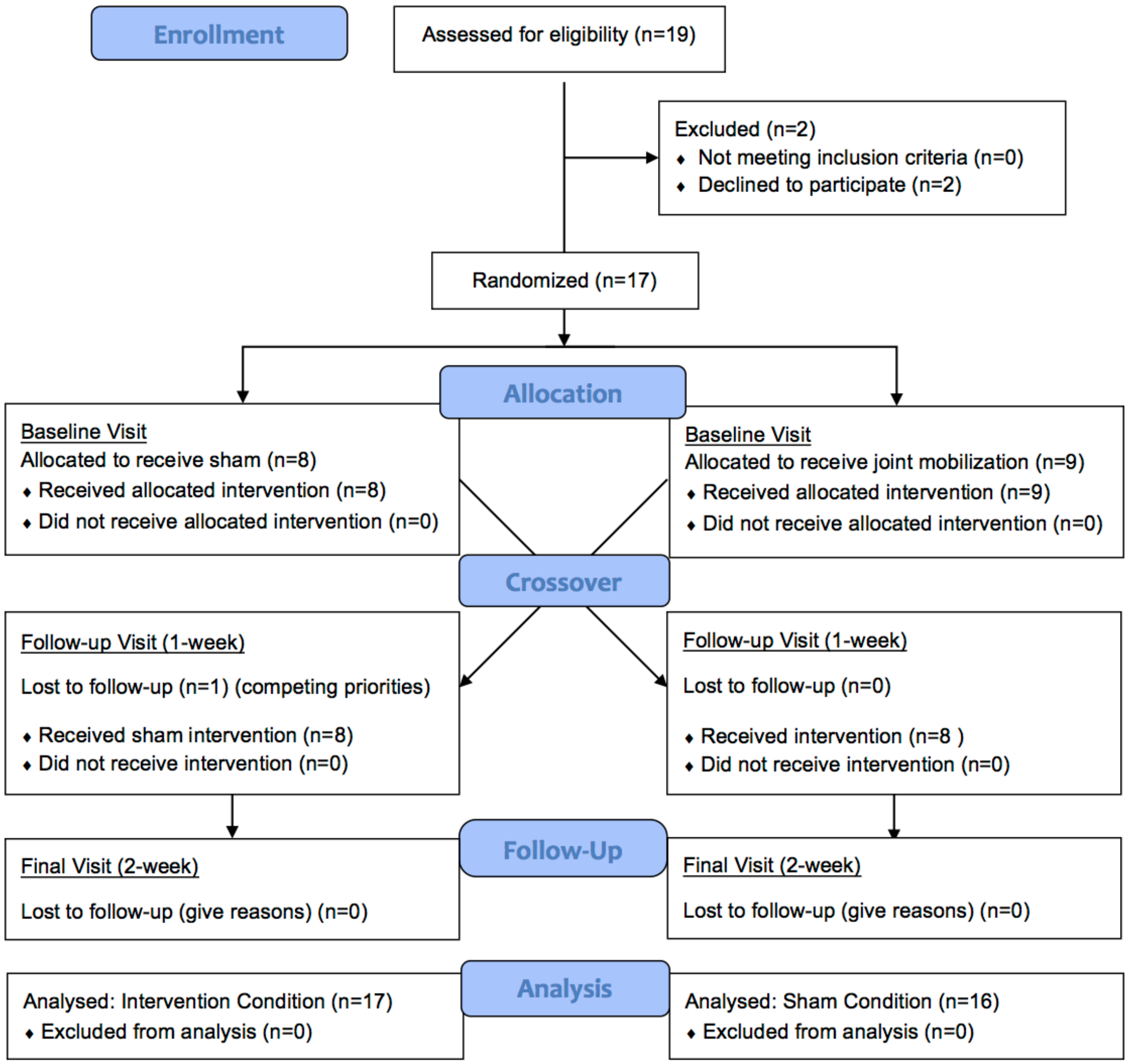
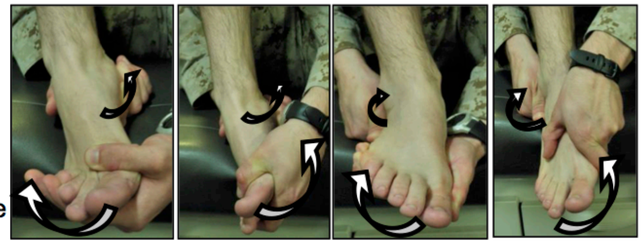


Figure 1. CONSORT Flow Diagram.

Four-Way Foot Stretch

With rear hand cupping the heel and the forward hand gripping the forefoot, the participant was asked invert the calcaneus while inverting the forefoot for 30-sec, followed forefoot eversion for 30-sec. This was repeated with the rearfoot everted. The exercise was performed three times daily.

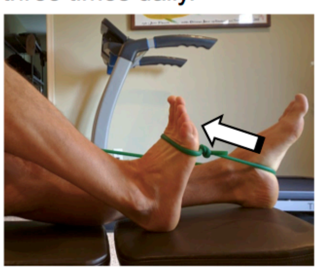


Calf Stretching

With the heel in contact with the ground, participants were asked to perform stretching of the gastrocnemius and soleus with knee straight for 30-sec. The stretch was repeated with knee bent for 30-sec, This was performed three times daily

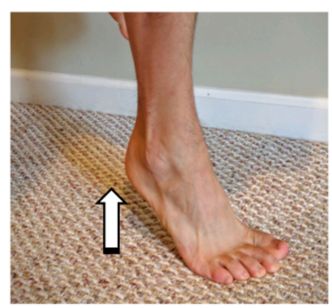
Single Leg Forward Reaching

Participants were asked to place their shoe approximately 0.5 m in front of them at a 12 o'clock position. While standing on the affected side, they were asked to pick the shoe up while maintaining balance on the single limb. With their eyes closed, they returned the shoe to the starting position. The exercise were progressed to the 10 & 2 o'clock positions . The exercise was performed for 10 repetitions, three times daily.



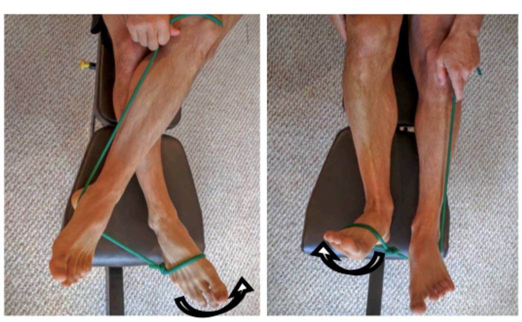
Resisted Dorsiflexion

With resistance tubing wrapped around the foot, the participant performed resisted dorsiflexion with a 2-sec concentric phase and a 4-sec eccentric phase. Thirty repetitions of the exercise were performed, three times daily.



Single-limb heel raises

In single limb stance, the participant performed a heel raise with 2-sec concentric phase and 4-sec eccentric phase. Thirty repetitions of the exercise were performed, three times daily.



Resisted Inversion and Eversion

With resistance tube wrapped around the foot, the participant performed resisted dorsiflexion with a 2-sec concentric phase and a 4-sec eccentric phase. Thirty repetitions of the exercise were performed, three times daily.

Figure 2. Home exercise program.

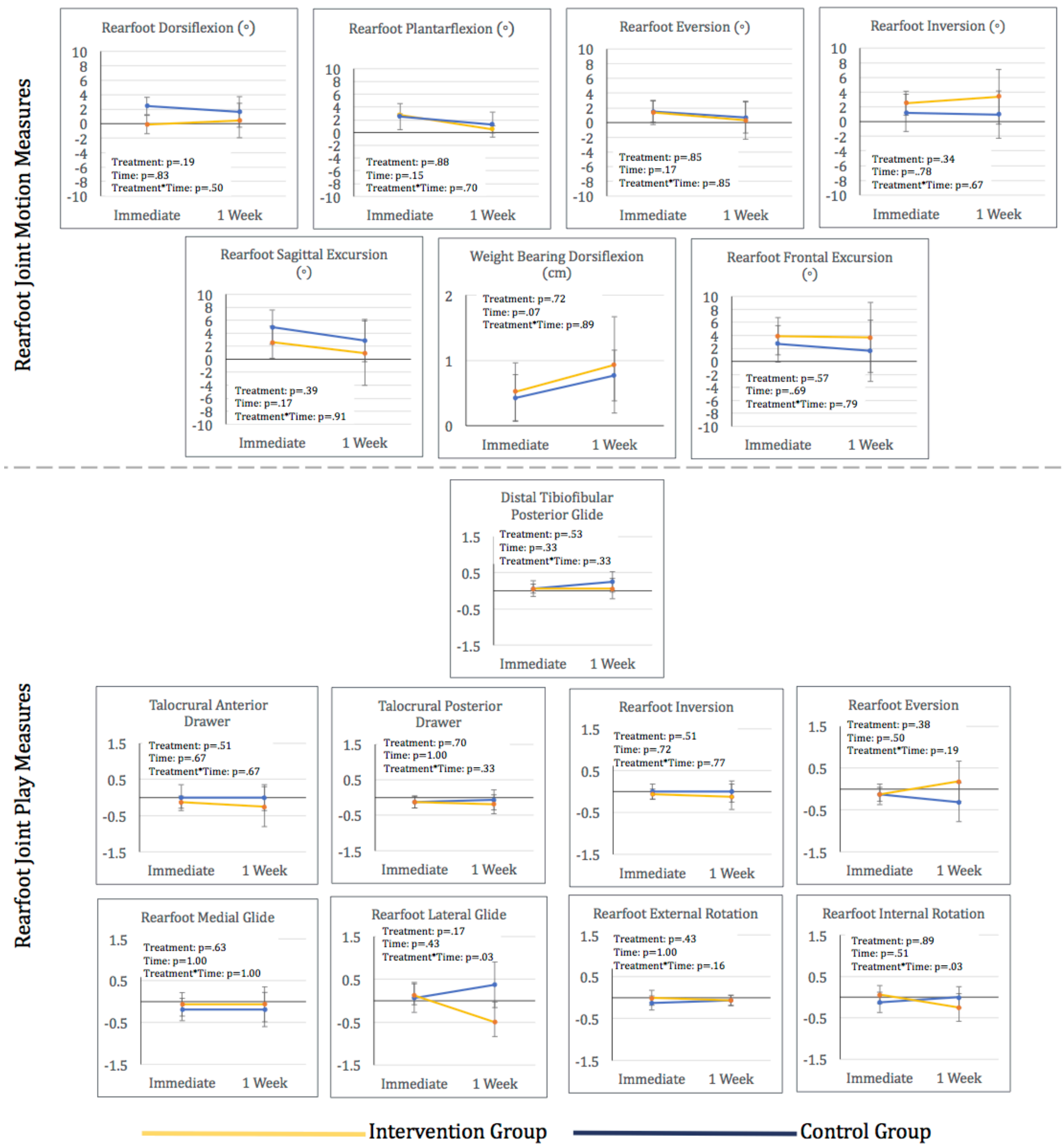


Figure 3. Rearfoot joint motion and play change measures.

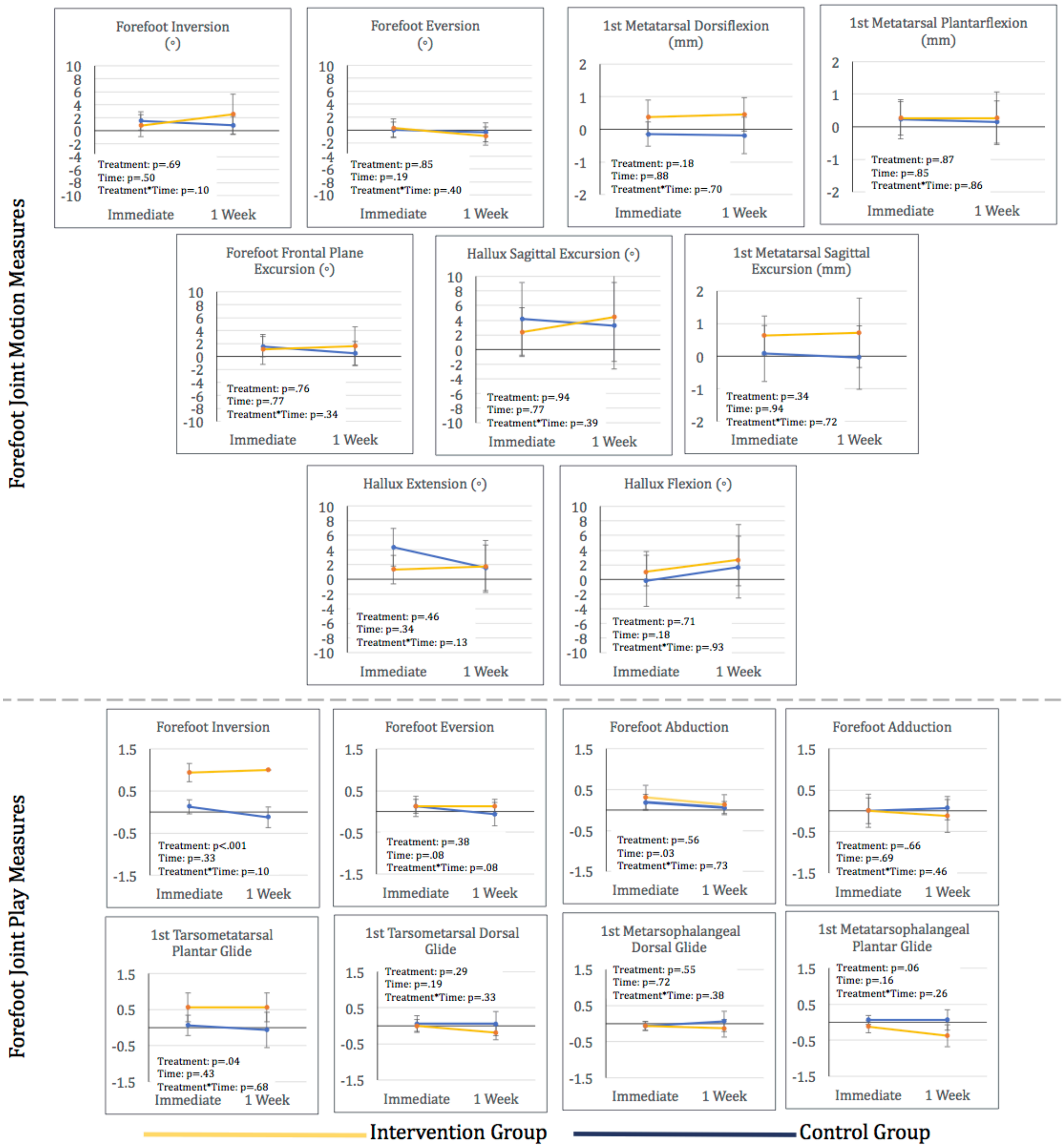


Figure 4. Forefoot joint motion and play change measures.

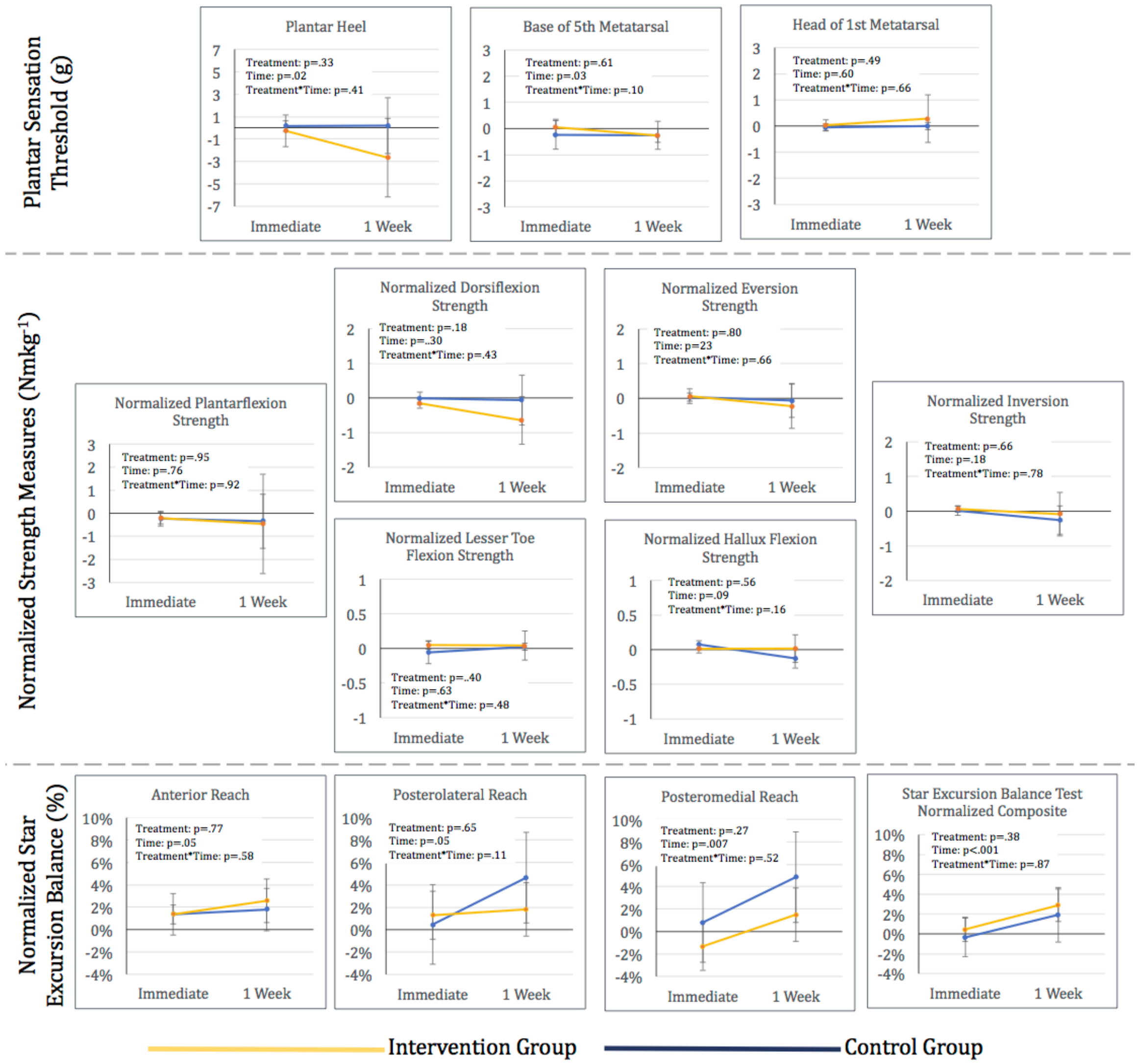


Figure 5. Sensorimotor function and dynamic balance change measures.

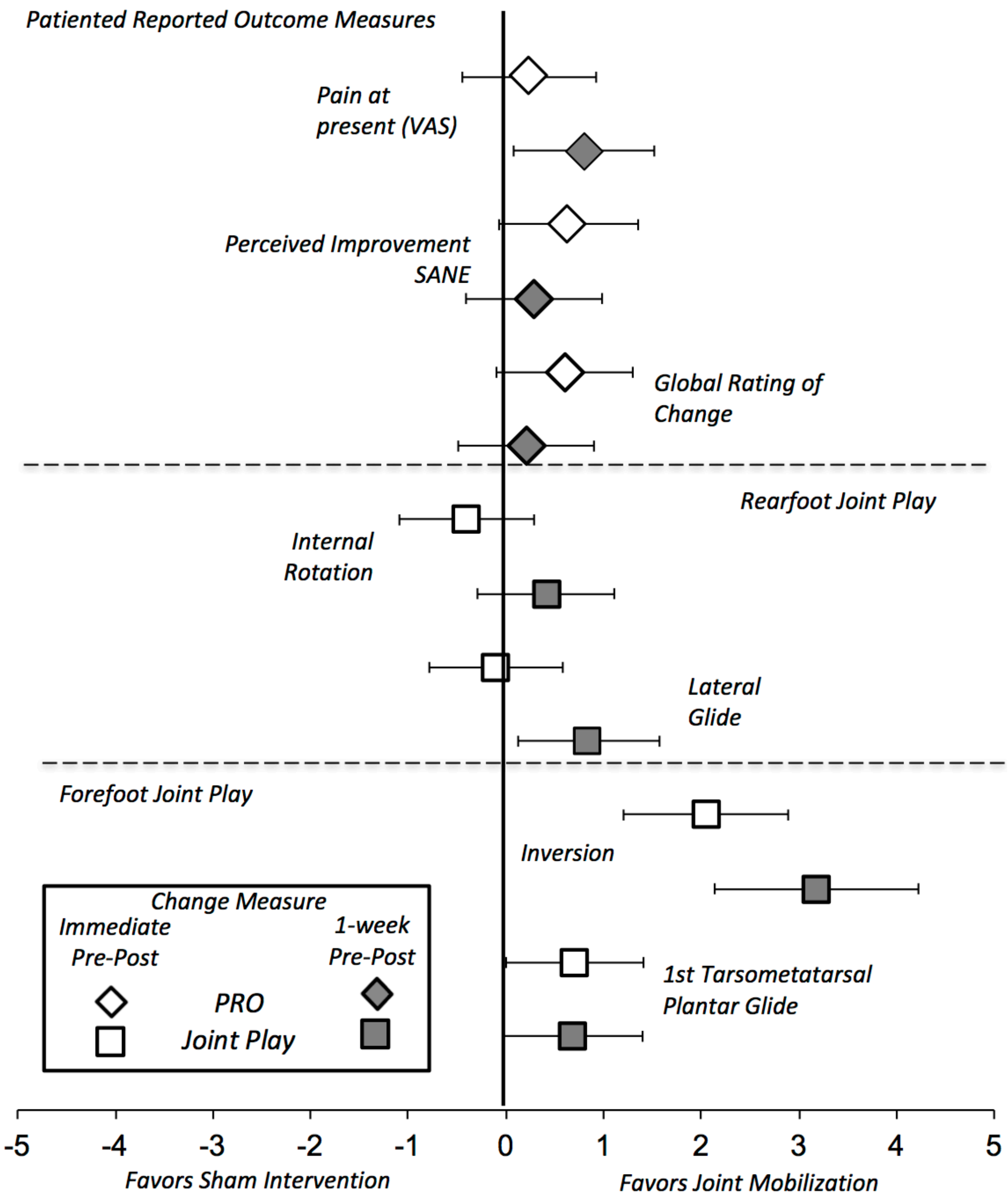


Figure 6. Effect size estimates and 95% confidence intervals comparing joint mobilization to sham treatment.

Figure 7. Summary of effects of midfoot joint mobilization compared to sham on clinical outcomes.

SECTION III: APPENDIX A

LITERATURE REVIEW

IJSPT

CLINICAL COMMENTARY

MIDFOOT AND FOREFOOT INVOLVEMENT IN LATERAL ANKLE SPRAINS AND CHRONIC ANKLE INSTABILITY. PART 1: ANATOMY AND BIOMECHANICS

John J. Fraser, PT, MS, OCS[1,2]
Mark A. Feger, Ph.D., ATC[3]
Jay Hertel, Ph.D., ATC[1]

ABSTRACT

The modern human foot is the culmination of more than five million years of evolution. The ankle-foot complex absorbs forces during loading, accommodates uneven surfaces, and acts as a lever for efficient propulsion. The ankle-foot complex has six independent functional segments that should be understood for proper assessment and treatment of foot and ankle injuries: the shank, rearfoot, midfoot, lateral forefoot, and the medial forefoot. The compliance of the individual segments of the foot is dependent on velocity, task, and active and passive coupling mechanisms within each of the foot segments. It is also important to understand the passive, active, and neural subsystems that are functionally intertwined to provide structure and control to the multisegmented foot. The purpose of the first part of this clinical commentary and current concepts review was to examine foot and ankle anatomy, detail the roles of the intrinsic and extrinsic foot and ankle musculature from a multisegmented foot perspective, and discuss the biomechanics of the ankle-foot complex during function. The interplay of segmental joint mobility, afferent and efferent sensorimotor function, and movement and stabilization provided by the extrinsic and intrinsic musculature is required to coordinate and execute the complex kinematic movements in the ankle-foot complex during propulsion.

Key Words: intrinsic foot muscles, gait, joint mobility, kinematics, ambulation

Level of Evidence: 5

[1] Department of Kinesiology, University of Virginia, Charlottesville, VA, USA
[2] US Navy Medicine Professional Development Center, Bethesda, MD, USA
[3] Virginia Commonwealth University School of Medicine, Richmond, VA, USA

Conflicts of Interest: None

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CORRESPONDING AUTHOR
John J Fraser
PO Box 400407
Memorial Gymnasium, Charlottesville, VA 22904-4407
Phone: 757-438-0390
E-mail: jjf5ac@virginia.edu

BACKGROUND AND PURPOSE

The modern human foot is the culmination of more than 5-million years of evolution.[1] Our ancient hominine ancestors evolved from arboreal to terrestrial living and the morphology and function of the foot adapted accordingly and transitioned from primarily climbing tasks to bipedal locomotion.[1–5] The ankle-foot complex absorbs forces during loading, accommodates uneven surfaces, and acts as a lever for efficient propulsion.[6] The six independent functional segments that comprise the ankle-foot complex should be understood for proper assessment and treatment of foot and ankle injuries: the shank, rearfoot, midfoot, lateral forefoot, and the medial forefoot (first ray and hallux).[7] Compliance of the individual segments of the foot is dependent on velocity, task, and active and passive coupling mechanisms within each of the foot segments. It is also important to understand the passive, active, and neural subsystems that are functionally intertwined to provide structure and control to the multisegmented foot.[8,9]

The purpose of the first part of this clinical commentary and current concepts review was to examine foot and ankle anatomy, detail the roles of the intrinsic and extrinsic foot and ankle musculature from a multisegmented foot perspective, and discuss the biomechanics of the ankle-foot complex during function. The companion paper to this commentary will examine the contribution of midfoot and forefoot impairment in lateral ankle sprains and chronic ankle instability in order to increase clinician's awareness and to facilitate future research in this area.[10] The importance of multisegmented foot and ankle assessment will also be discussed from a clinical and research perspective.

ANATOMY AND FUNCTION OF THE ANKLE – FOOT COMPLEX

Shank

The shank (tibia and fibula) begins at the knee where the tibia articulates with the distal femur and the fibular head articulates with the lateral tibial condyle. The tibia and fibula are supported by the anterior and posterior ligaments of the fibula head proximally, by the interosseous ligament along the diaphysis, and the anterior and posterior tibiofibular ligaments distally. The shank forms a distal mortise joint that serves as the proximal segment of the talocrural articulation. During gait, the shank functions like the distal aspect of a pendulum during swing phase and fulcrums over the talus during periods of single support.[11] In stance, the fibula shares approximately 10% to 30% of the burden during axial loading of the shank.[12] The shank is coupled to ankle motion with tibial internal rotation coupled to rearfoot pronation[13,14] and talocrural dorsiflexion/plantarflexion coupled to fibular translation and rotation in all cardinal planes.[15]

Talocrural Articulation

The talocrural articulation is a "mortise and tenon" joint comprised of the shank proximally and the talus distally. Dorsiflexion and plantarflexion are the primary osteokinematic motions of the talocrural joint, with an oblique axis of rotation that travels through the medial malleolus, the talar head, and the lateral malleolus.[16–18] The oblique axis of rotation results in component eversion and adduction accompanying dorsiflexion and inversion and abduction accompanying plantarflexion.[16,18] The talocrural joint is statically supported by the joint capsule, the deltoid ligament (medially), and the anterior talofibular, calcaneofibular, and posterior talofibular ligaments (laterally).

Rearfoot and Subtalar Joint

The rearfoot, also known as the hindfoot, is comprised of the talus (proximally), the subtalar joint, and the calcaneous (distally). The subtalar joint is comprised of anterior (talocalcaneonavicular) and posterior (talocalcaneal) articulations that are separated by the tarsal canal. The joint capsules and the cervical, interosseous talocalcaneal, posterior talocalcaneal, lateral talocalcaneal, calcaneofibular, and fibular-talocalcaneal ligaments support the subtalar joint. The axis of rotation is oriented anterior-superomedial to posterior-inferolateral and transects the three cardinal planes. Primary osteokinematic motions of the subtalar joint are supination and pronation. Similar to what is observed with the oblique axis of rotation in the talocrural joint, subtalar pronation is accompanied by dorsiflexion and abduction and subtalar inversion is accompanied by plantarflexion and adduction.[16,18,19] The subtalar joint is often described as a "mitered hinge" and its triplanar orientation allows for the coupling of shank rotation and rearfoot supination/pronation.

Transverse Tarsal (Chopart or Midtarsal) Articulation

The transverse tarsal articulation is comprised of the talus and navicular (medially) and the calcaneus and cuboid (laterally). The bifurcate (calcaneocuboid and calcaneonavicular ligaments), dorsal calcaneocuboid, dorsal talonavicular, interosseous talocalcaneal, deltoid (tibionavicular part), spring, and plantar cuboideonavicular ligaments statically support the transverse tarsal joint.

Motion between the forefoot and rearfoot occurs in the transverse tarsal joint through two separate axes of rotation; one being supination and pronation of the cuboid on the calcaneus about the longitudinal axis and the other being oblique to the foot as the cuboid translates on the calcaneus.[20] The axes vary by task and change based on the congruency of the calcaneocuboid joint.[21] The longitudinal axis of the transverse tarsal joint allows for the forefoot to rotate opposite of the midfoot in the transverse plane.[20] Arthrokinematic movement about the oblique axis plus dorsiflexion and plantarflexion of the transverse tarsal produces deformation of the longitudinal arches.[20] The review conducted by Tweed and colleagues[22] is recommended for additional information on the function of the transverse tarsal joint.

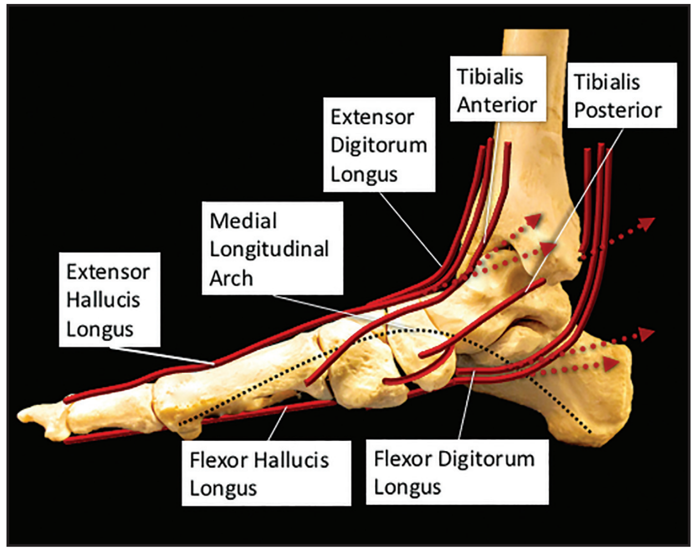

Figure 1. *Morphology and Extrinsic Dynamic Support of the Medial Longitudinal Arch*

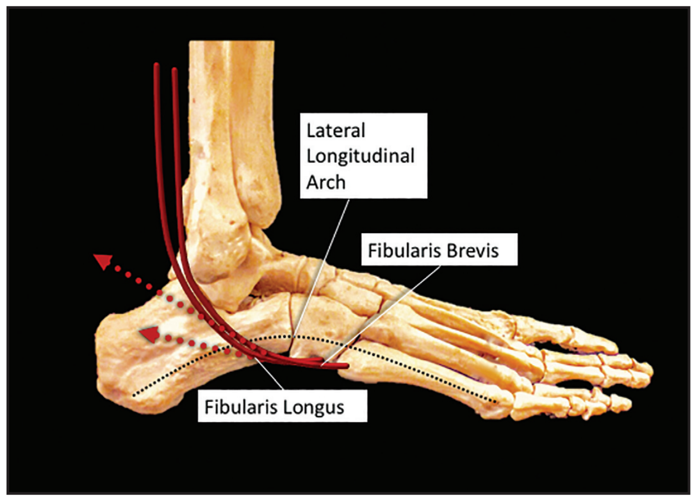

Figure 2. *Morphology and Extrinsic Dynamic Support of the Lateral Longitudinal Arch*

Midfoot

The midfoot is comprised of the navicular, medial, intermediate and lateral cuneiforms, and the cuboid. The bones of the midfoot form the medial longitudinal (Figure 1), the lateral longitudinal, (Figure 2) and the transverse arches (Figure 3), which together comprise a half dome.[23] The function of the midfoot is to transmit and attenuate force and allow the foot to accommodate to the variable surface of the ground.[23] The arches are supported and controlled by a combination of bony congruency and static and dynamic extrinsic and intrinsic stabilizers.[24,25] The primary stabilizers of the midfoot are evolutionary adaptations favorable for bipedal locomotion and consist of the osseous, muscular, and ligamentous structures that support the longitudinal arches, calcaneocuboid, and tarsometatarsal articulations.[2–5] The adaptations found in the human foot allow for various degrees of mechanical coupling of the forefoot to the rearfoot during gait (midtarsal locking) and control of dorsiflexion of the lateral tarsometatarsal joints (midtarsal break) during the stance phase.[4,5,26,27] Table 1 provides a comprehensive overview of the stance phase of gait and details the multisegmented ankle-foot motions and the relevant muscle actions that occur from initial contact to pre-swing. During lower velocity locomotion, the foot is lengthened and the medial longitudinal arch is flattened, increasing the compliance of the foot

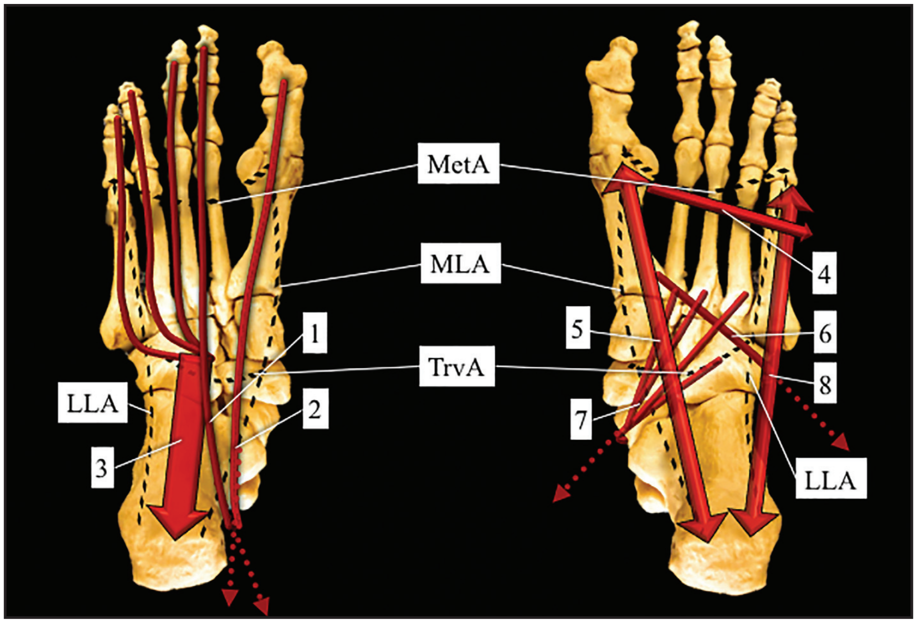

Figure 3. *Morphology and Dynamic Support of the Longitudinal and Transverse Arches (Plantar Aspect). 1 = Flexor Digitorum Longus, 2 = Flexor Hallucis Longus, 3 = Quadratus Plantae, 4 = Adductor Hallucis, 5 = Abductor Hallucis, 6 =* Fibularis *Longus, 7 = Tibialis Posterior, 8 = Abductor Digiti Minimi, MLA = Medial Longitudinal Arches, MetA =Metatarsal Arches, LLA = Lateral Longitudinal Arches, TrvA = Transverse Arch*

Table 1. *Summary of multisegmented foot and ankle kinematics and muscle actions during stance phases of gait. L = Lateral, M = Medial, FHL = Flexor Hallucis Longus, FDL = Flexor Digitorum Longus.*

	Initial Contact	Loading	Midstance	Terminal Stance (heel off)	Pre-swing (toe off)
Goal of Phase	Begin lowering forefoot to ground while maintaining proper frontal plane alignment	Dissipate ground reaction forces while accommodating terrain	Transfer momentum over foot and ankle complex with efficient transfer from deceleration to acceleration	Accelerate mass for forward propulsion	Finish forward propulsion into initial swing
Relevant Multi-segmented Ankle-Foot Kinematics	**Rearfoot:** Neutral Sagittal, Pronated, Abducted **Midfoot:** Supinated **L. Forefoot:** Plantarflexed, Supinated, Abducted **M. Forefoot:** Dorsiflexed, Everted, Adducted	**Rearfoot:** Plantarflexed, Pronated, Adducted **Midfoot:** Dorsiflexed, Pronated, Adducted **L. Forefoot:** Plantarflexed, Pronated, Abducted **M. Forefoot:** Dorsiflexed, Everted	**Rearfoot:** Dorsiflexed, Pronated, Abducted **Midfoot:** Neutral Sagittal, Pronated, Abducted **L. Forefoot:** Dorsiflexed, Supinated **M. Forefoot:** Dorsiflexed, Everted	**Rearfoot:** Plantarflexed, Supinated **Midfoot:** Plantarflexed, Supinated, Abducted **L. Forefoot:** Dorsiflexed, Supinated **M. Forefoot:** Dorsiflexed, Inverted, Adducted	**Rearfoot:** Plantarflexed, Supinated **Midfoot:** Plantarflexed, Supinated, Abducted **L. Forefoot:** Plantarflexed, Supinated **M. Forefoot:** Dorsiflexed, Inverted, Adducted
Relevant Ankle-Foot Muscle Actions	**Tibialis Anterior:** Maintains frontal plane alignment and eccentrically dorsiflexes foot **Fibularis Longus:** Maintains frontal plane alignment prior to initial contact **Tibialis Posterior:** Stabilizes rearfoot	**Tibialis Anterior:** Maintains frontal plane alignment and eccentrically dorsiflexes foot **FHL/FDL:** Isometrically stabilizes longitudinal arches **Tibialis Posterior:** Isometrically stabilizes medial longitudinal arch **Triceps Surae:** Tenses plantar aponeurosis **Plantar Intrinsics:** Accommodates terrain, stabilizes midfoot, and attenuates force	**Fibularis Longus:** Plantarflexes 1st ray **FHL/FDL:** Isometrically stabilizes longitudinal arches **Plantar Intrinsics:** Accommodates terrain, stabilizes midfoot, and attenuates force	**Fibularis Longus:** Isometrically stabilizes longitudinal and transverse arches **Triceps Surae:** Generates plantarflexion propulsion force	**Fibularis Longus:** Maintains 1st ray on ground during propulsion **Triceps Surae:** Generates plantarflexion propulsion force

for accommodation of uneven terrain and to maximize balance control.[28] During higher velocity locomotion, the medial longitudinal arch angle increases and the foot shortens as a means of optimizing the lever arm during pushoff.[28]

Tarsometatarsal (Lisfranc) Joint
The tarsometatarsal (TMT) joint is the articulation between mid and forefoot segments and consists of the medial and lateral columns of the foot. The medial column is formed by the articulation of the medial, middle, and lateral cuneiforms with the proximal first, second, and third metatarsals, respectively (Fig 1). Within the medial column, the first cuneiform, metatarsal, and the first TMT articulation form the first ray. The lateral column is comprised of the cuboid, the proximal fourth and fifth metatarsals and the lateral aspect of the TMT (Figure 2). The TMT joint complex is structurally stabilized morphologically in a "Roman Arch" configuration and supported by extensive dorsal, plantar, and interosseous ligamentous network.[29] During locomotion, the degree in which the forefoot couples with the rearfoot varies dependent on velocity and the cardinal plane in which forefoot motion occurs.[30]

First Ray & Hallux
The first ray, also referred to as the medial forefoot, is comprised of the first metatarsal, cuneiform, and the TMT joint. The first ray functions as a pillar and forms the distal truss of the medial longitudinal arch.[31] The joint capsule and the dorsal tarsometatarsal, plantar tarsometatarsal, and plantar metatarsal ligaments provide passive stability to the TMT articulation. The hallux is comprised of the first proximal and distal phalanx and the interphalangeal joint. The medial collateral, lateral collateral, and plantar ligaments and the joint capsules provide stability to the first metatarsophalangeal and interphalangeal joints.

Lateral Forefoot
The lateral forefoot is comprised of the metatarsals and phalanges of the lateral four digits. The joint capsules and the medial collateral, and lateral collateral ligaments provide stability for each of the metatarsophalangeal and interphalangeal joints. A deep transverse and plantar metatarsal ligament supports the intermetatarsal articulations. Together with the first ray, the metatarsals of the lateral forefoot form a metatarsal arch (Figure 3).

Extrinsic Control of the Ankle – Foot Complex
Traditionally, the extrinsic foot and ankle muscles are described as 'prime movers' based on the osteokinematic motion they cause when the foot is treated as a rigid segment. However, the authors aim to describe the functional roles of the extrinsic foot and ankle muscles in the context of a multisegmented foot and ankle complex. Collectively, the extrinsic and intrinsic foot and ankle musculature support, stabilize, dissipate force, and move the multiple articulations of the ankle and foot. Please refer to Figures 1-4 for illustrations of the extrinsic muscle tendons and their insertions.

LATERAL COMPARTMENT
The lateral compartment contains the fibularis longus and brevis, both of which are innervated by the superficial fibular nerve. The fibularis longus plays an important role in stabilization of the lateral midfoot and the first ray and is the primary evertor of the forefoot. Originating in the lateral compartment, the tendon courses around a series of pulleys formed by the lateral malleolus, the peroneal tubercle, and the cuboid.[27,32] The tendon exerts a compressive stabilizing force on the cuboid and contributes to midtarsal locking and prevention of midtarsal break.[27] The tendon continues from the cuboid in an anteromedial direction to the lateral plantar base of the first metatarsal. Functionally during stance, the fibularis longus stabilizes the medial column by everting the first ray and mechanically coupling the tarsometarsal and naviculocuneiform joints through a torsion of the articular ligamentous and capsular tissues.[32] The fibularis longus is the primary plantarflexor of the first ray[32,33] and assists in the support of the medial longitudinal arch.[33] The fibularis longus contributes important afferent feedback in regards to ankle position. In a study investigating proprioception, balance, and reaction time in individuals who received a regional nerve block to the foot and ankle, it was concluded that the fibularis longus is a primary afferent input to the brain in maintaining balance even more so than the ligamentous structures of the

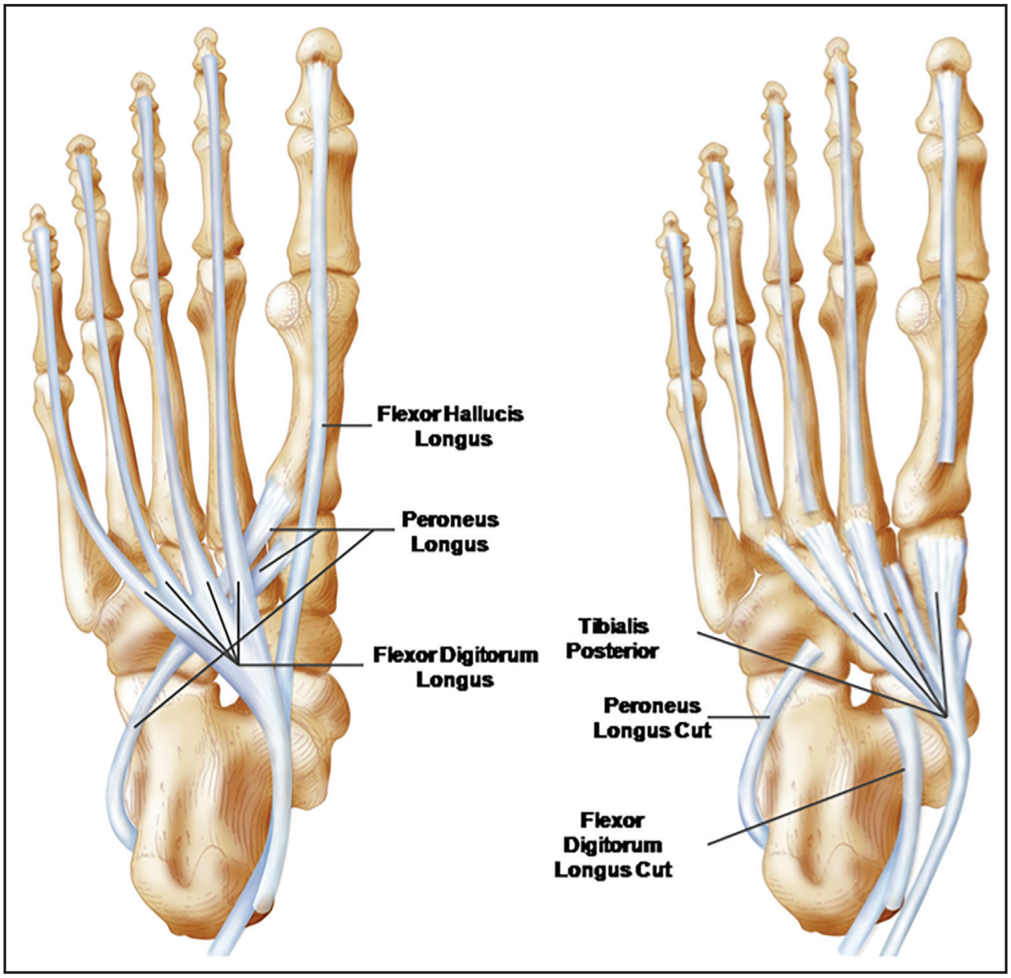

Figure 4. *Extrinsic muscle tendons and insertions. Adapted from McKeon PO, Hertel J, Bramble D, Davis I. The foot core system: a new paradigm for understanding intrinsic foot muscle function. Br. J. Sports Med. 2014. Used with permission of the publisher.*

ankle.[34] The fibularis longus, tibialis posterior, and the flexor digitorum longus tendons are oriented in a cross configuration and may contribute to the support and function of the longitudinal and transverse arches. Each tendon courses the span of both arches, with the fibularis longus traversing posterolateral to anteromedial and the flexor digitorum and posterior tibialis coursing posteromedial to anterolateral. It is plausible that synergistic concentric contraction of these muscles would contribute to approximation of opposing voussoirs and increase the rise of the longitudinal and transverse arches. It is also conceivable that like the long toe flexors, isometric or eccentric co-contraction of these muscles may contribute to stabilization and force attenuation of the foot arches.

The fibularis brevis originates in the lateral compartment of the leg and inserts on the styloid process of the fifth metatarsal. The fibularis longus is the primary evertor of the forefoot and similarly, the fibularis brevis and fibularis tertius (of the anterior compartment) are the primary evertors of the rearfoot and midfoot. In a study investigating the contribution of the fibularis longus and brevis to ankle and foot movement during a simulated early heel rise during the stance phase of gait, the fibularis brevis was found to be more effective in everting the talonavicular and subtalar joints than the fibularis longus.[35]

ANTERIOR COMPARTMENT

The fibularis tertius, tibialis anterior, extensor digitorum longus, and extensor hallucis longus originate in the anterior compartment and are innervated by the deep fibular nerve. The fibularis tertius, which functions synergistically with the two lateral compartment muscles and was discussed in the previous section, inserts on the dorsal base of the fifth metatarsal. The tibialis anterior, extensor hallucis longus and the extensor digitorum longus course from the anterior compartment distally to the extensor retinaculum. The tibialis anterior tendon continues and inserts on the inferomedial aspect of medial cuneiform and the base of first metatarsal. During gait, the tibialis anterior is thought to have an important function in maintaining balance during the first quarter of stance.[36] The extensor hallucis and digitorum longus insert into the extensor apparatus of the great toe and the second through fifth toes, respectively.[37] The toe extensors, with the anterior tibialis, activate to lift the toes from the ground at terminal stance of gait.[38] They also assist in the stabilization of the talocrural and the tarsal bones during loading of the foot.[38] Afferent information provided from the muscles of the anterior compartment, in conjunction with lateral compartment muscles and cutaneous receptors, have been suggested to have an important role in ankle kinesthesia[39] and modulation of the soleus during the stance phase of gait.[40]

SUPERFICIAL POSTERIOR COMPARTMENT

The gastrocnemius and soleus, collectively known as the triceps surae, innervated by the tibial nerve, originate in the posterior compartment and insert on the calcaneal tuberosity. During stance phase, the triceps surae controls the forward progression of the shank on the talus[38,41] and assists in providing a flexion moment at the knee.[38] Additionally, the triceps surae is able to mechanically influence the rearfoot, midfoot, and forefoot through its insertion on the calcaneus and ability to tension the plantar aponeurosis (PA), otherwise known as the plantar fascia (Figure 5). During gait, the PA is tensioned at 30% of stance until midstance, when elongation increases sharply.[42] Peak elongation of the PA occurs at 80% of stance when the triceps surae exerts a plantarflexion moment on the calcaneus and the metatarsophalangeal joints of the toes are extended.[42] The elongation of the PA elevates the medial longitudinal arch and inverts the midfoot and rearfoot via a shift in the calcaneal tendon medial to the axis of rotation of the subtalar joint.[43] Contraction of the triceps surae during weight bearing creates a plantarflexion moment in the rearfoot, tensions the PA, and increases the dorsiflexion moment and ground reaction force and in the midtarsal, cuneonavicular, and tarsometatarsal articulations.[44] An analysis using computer 3-D modeling of forefoot force transmission in the presence of impaired triceps surae strength found that contact area increased in the midfoot and plantar pressures

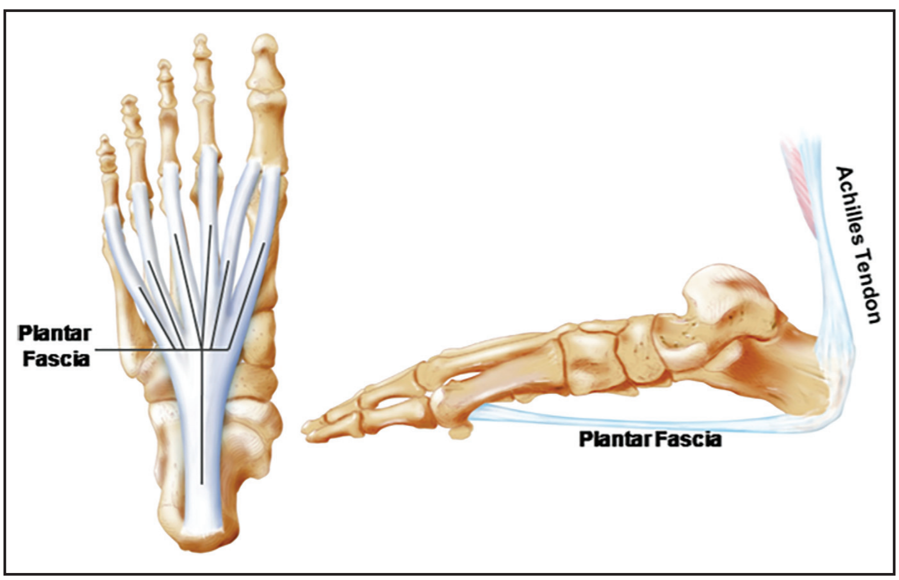

Figure 5. *The windlass mechanism. The triceps surae forms a coupled relationship with the plantar fascia through the proximal attachment on the calcaneus and action on the rearfoot. Adapted from McKeon PO, Hertel J, Bramble D, Davis I. The foot core system: a new paradigm for understanding intrinsic foot muscle function. Br. J. Sports Med. 2014. Used with permission of the publisher.*

decreased in the forefoot during terminal stance.[45] The triceps surae also has an important function as a proximal stabilizer of the calcaneus and in intrinsic foot muscle function. This was shown in patients with poliomyelitis who had impaired plantar flexor strength and unopposed intrinsic foot flexor function.[46] A foot deformity, coined the "calcaneus foot," was a sequela of triceps surae strength impairment and was characterized by rearfoot dorsiflexion, forefoot plantarflexion, and clawing of the toes.[46]

DEEP POSTERIOR COMPARTMENT

The flexor hallucis longus (FHL) and the flexor digitorum longus (FDL) tendons are innervated by the tibial nerve and traverse from the deep posterior compartment, through the flexor retinaculum, into the plantar aspect of the foot. The FHL is oriented longitudinally along the medial aspect of the foot. The FDL has a more oblique orientation from posteromedial to anterolateral. The FDL tendon is the proximal attachment for the lumbricals and the distal attachment for the quadratus plantae (flexor digitorum accessorius). While inserting distally and causing toe flexion, the FHL and FDL tendons also cross the transverse tarsal and TMT joints. During stance, the long toe flexors have been shown to contract isometrically to support and stabilize the longitudinal arches,[33,47] provide afferent feedback,[47] and dissipate force during loading.[47,48]

The tibialis posterior originates in the deep posterior compartment and courses deep to the flexor retinaculum.[49] It supports the medial longitudinal arch through its multiple insertions to the navicular tubercle, each tarsal bone, metatarsals two through four, and the flexor hallucis brevis muscle.[49] During barefoot walking, the tibialis posterior contracts to resist eversion and peroneal contraction and assists in stabilization of the rearfoot during initial contact (IC) and midstance.[50]

Intrinsic Control of the Ankle – Foot Complex

Ten muscles in the plantar foot and two in the dorsal foot provide intrinsic control of the foot (Figure 6). The plantar intrinsic muscles are organized into four layers and are innervated by the medial and lateral plantar nerves, which branch from the tibial nerve. The dorsal intrinsic muscles are innervated by the deep fibular nerve (extensor digitorum brevis) and the lateral plantar nerve (dorsal interossei muscles). During gait, the intrinsic foot muscles function both in open kinetic chain to shape the foot and toes in preparation for contact with the ground and in closed kinetic chain to accommodate the terrain and during force attenuation and transmission.

FIRST PLANTAR LAYER

The superficial layer is comprised of the abductor hallucis, flexor digitorum brevis, and the abductor digiti minimi. The abductor hallucis inserts proximally on the medial tubercle of the calcaneus, courses proximal to distal on the medial foot, and inserts distally on the medial base of the first proximal phalanx. The flexor digitorum brevis inserts proximally on the medial tubercle of the calcaneus, courses proximal to distal in the center of the plantar foot, and inserts distally on the middle phalanx of digits 2-5. The abductor digiti minimi inserts proximally on the medial and lateral tubercles of the calcaneus, courses proximal to distal on the lateral foot, and inserts distally on the lateral base of the fifth proximal phalanx. These muscles abduct the hallux, flex toes 2-5, and abduct the little toe when functioning in open kinetic chain, respectfully. During the stance phase of gait, the orientation and location of the abductor hallucis and abductor digiti minimi in relation to the medial and lateral longitudinal arches position these muscles to contribute to stabilization and eccentric control of arch descent during loading. The flexor digitorum brevis is analogous to the flexor digitorum profundus in the upper extremity based on morphology, insertion, and relationship to the long digit flexor. While speculative, it is likely that the flexor digitorum brevis contributes to eccentric control of metatarsophalangeal extension from mid-stance to pre-swing phase of gait.

SECOND PLANTAR LAYER

The second layer is comprised of the quadratus plantae (flexor digitorum accessorius) and the lumbrical muscles, all of which attach to and function with the flexor digitorum longus. The quadratus plantae originates on the plantar calcaneus and courses proximal to distal to insert on the flexor digitorum longus tendon. The four lumbrical muscles originate on the flexor digitorum longus tendon proximally and course

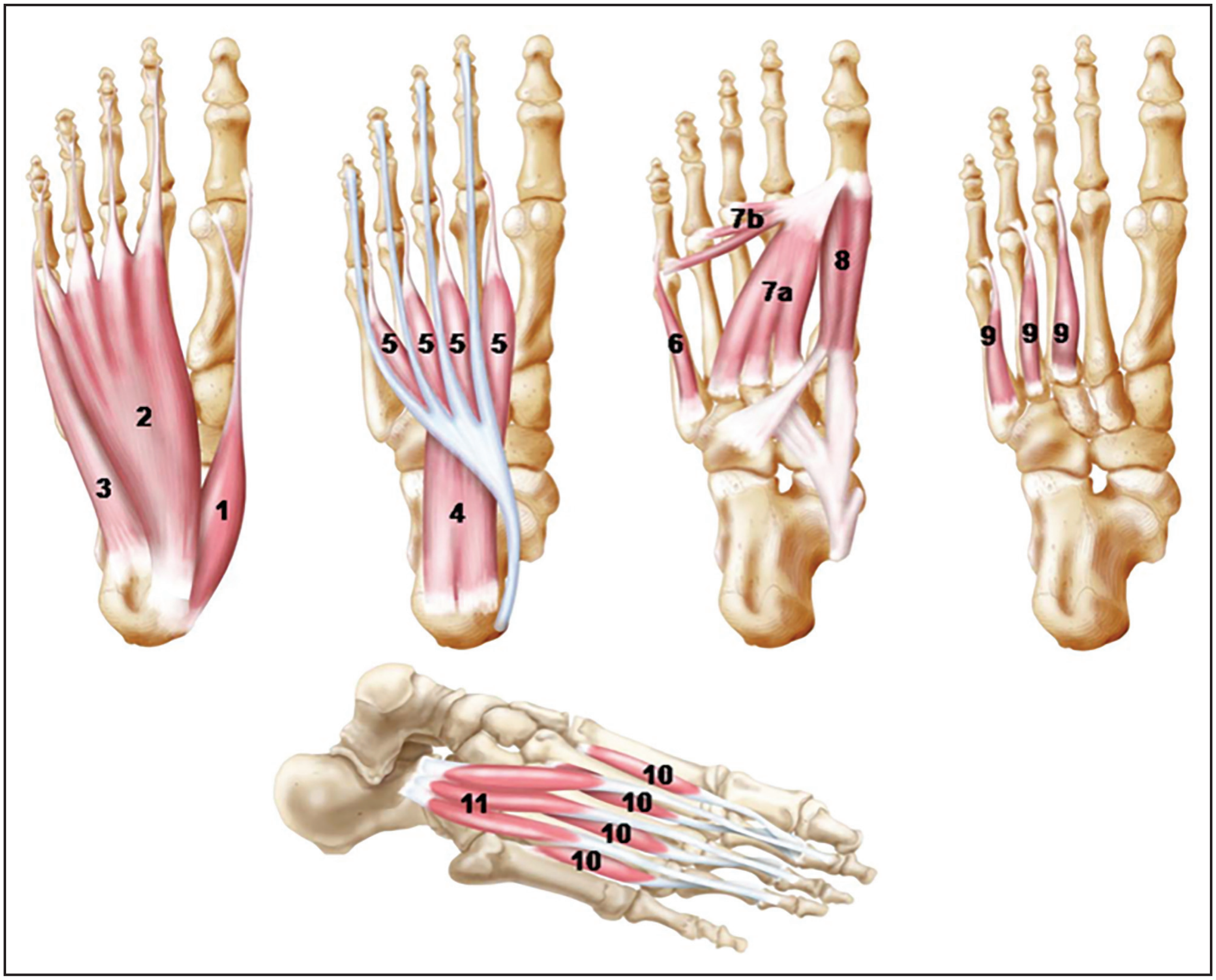

Figure 6. *Intrinsic muscles of the foot. Plantar intrinsics: Layer 1: 1 = abductor hallucis, 2 = flexor digitorum brevis, 3 = abductor digiti minimi; Layer 2: 4 = quadratus plantae, 5 = lumbricals 1-4; Layer 3: 6 = flexor digiti minimi, 7a = adductor hallucis oblique head, 7b = adductor hallucis transverse head, 8 = flexor hallucis brevis; Layer 4: Dorsal Interossei. Dorsal Intrinsics: 10 = dorsal interossei, 11 = extensor digitorum brevis. Adapted from McKeon PO, Hertel J, Bramble D, Davis I. The foot core system: a new paradigm for understanding intrinsic foot muscle function. Br. J. Sports Med. 2014. Used with permission of the publisher.*

distally to insert on the digital extensor expansions. In open kinetic chain, the quadratus plantae assists in long toe flexion and the lumbricals perform metatarsophalangeal flexion and interphalangeal extension. The proximodistal orientation of the quadratus plantae in relationship to the flexor digitorum longus allows for a change in force vectoring of the long toe flexor tendon from a proximomedial-distolateral angle to a more longitudinal vector. During gait, the lumbricals likely contribute to eccentric control of metatarsophalangeal extension while extending the interphalangeal joints during toe-break. It is also plausible that the lumbricals function by pulling the flexor digitorum longus tendons distally when the ankle is plantarflexed to optimize length-tension and prevent active insufficiency during toe flexion.

THIRD PLANTAR LAYER

The third plantar layer is comprised of the flexor digiti minimi, the adductor hallucis, and the flexor hallucis brevis. The flexor digiti minimi inserts proximally on the base of the fifth metatarsal and travels distally to insert on the base of the fifth proximal phalanx. The adductor hallucis has two heads, an oblique and transverse head. The oblique head inserts proximally on the base of the second through fourth metatarsals and traverses distal medial to insert on the base of the first proximal phalanx. The transverse head inserts laterally on the plantar metatarsophalangeal ligaments and travels medially to insert with the oblique head on the base of the first proximal phalanx. The flexor hallucis brevis inserts proximally on the cuboid, lateral cuneiform, and the middle and medial cuneiform by way of the tibialis posterior tendon and travels distally to insert on the base of the first proximal phalanx. In open kinetic chain, these muscles flex the little toe, adduct the hallux, and flex the hallux, respectively. During the stance phase of gait, the flexor hallucis brevis and the flexor digiti minimi likely contribute to eccentric control of toe extension from midstance to preswing. The adductor hallucis likely contributes to stabilization of the first ray during forefoot loading in the latter half of stance.

FOURTH PLANTAR LAYER

The fourth and deepest plantar layer is comprised of the three plantar interossei. The interossei insert proximally on the medial shafts of metatarsals 3-5 and traverses distally to insert on the bases of the proximal phalanges. These muscles adduct the toes in open kinetic chain and likely provide isometric or eccentric control of toe splay during forefoot loading in pre-swing phase of gait. It has also been speculated that these muscles stabilize the tarsometatarsal joints in conjunction with the dorsal interossei during late stance phase of gait.[51]

Dorsal Intrinsic Muscles

The two intrinsic muscles on the dorsal foot are the extensor digitorum brevis and the four dorsal interossei muscles. The medial head of the extensor digitorum brevis is sometimes treated as a separate muscle, the extensor hallucis brevis. For the purpose of this manuscript, the extensor hallucis brevis will be treated as integral with the extensor digitorum brevis. The extensor digitorum brevis inserts proximally on the calcaneus and courses distally to insert on the tendons of the extensor digitorum longus (toes 2-4) and the base of the first proximal phalanx. The dorsal interossei insert proximally on the shafts of the metatarsals one through five and traverse distally to insert on the proximal phalanges. In open kinetic chain, these muscles abduct and extend toes two through four, respectfully. The dorsal interossei also function with the palmar interossei to stabilize the forefoot in pre-swing phase of gait.[51]

In the sentinel study performed by Mann and Inman,[52] the intrinsic foot muscles were found to work synergistically as a functional unit during gait to provide stabilization of the midfoot, and that greater muscular activity was required to stabilize the foot in individuals who had excessive pronation observed during static standing. More recently, McKeon and colleagues[8] described a "foot core" system that is analogous to the lumbopelvic complex and comprised of active, passive, and neural subsystems. The intrinsic muscles play an important direct role in both active and neural subsystems and indirectly to the passive subsystem.[8] The flexor digitorum brevis, flexor hallucis brevis, oblique head of the adductor hallucis, and abductor digiti minimi are orientated longitudinally and run perpendicular to the transverse tarsal joint surface, making them prime stabilizers for this articulation and for the longitudinal arch.[52] The intrinsic muscles are stretched with deformation of the medial longitudinal arch during loading.[25] It is reasonable to assume that the stretch of the musculotendinous sensory organs provide afferent feedback during foot deformation, shaping, and force attenuation. Conversely, concentric contraction of the plantar intrinsic foot muscles produces calcaneal and metatarsal displacement resulting in decreased arch length and increased arch height.[25] This alteration of medial longitudinal arch morphology during IFM contraction forms the basis of the short foot exercise, an intervention utilized clinically to strengthen the foot core in the treatment of ankle-foot impairment.[8,9] It is thought that the intrinsic muscles, when functioning in conjunction with active extrinsic muscle contraction and the PA, contribute to buttressing of the foot during force attenuation and transmission.[25] Electromyographic analysis of muscle function during gait demonstrated coordinated activation of extrinsic and intrinsic toe flexors activity in the mid to terminal stance, sequentially followed by extrinsic and intrinsic toe extension activity in terminal stance to early swing phase.[53] The coordinated extrinsic and intrinsic activity observed in this study provides further evidence of the role of the intrinsic foot muscles during force attenuation and transmission in gait.

MULTISEGMENTED ANKLE-FOOT COMPLEX KINEMATICS DURING GAIT

Rearfoot

When referenced to the shank, the rearfoot is in a neutral sagittal, pronated, and abducted position at IC and transitions to a plantarflexed, pronated, and adducted position during early stance phase.[7] During midstance, the rearfoot is dorsiflexed, pronated, and abducted until 70% of stance when the rearfoot becomes plantarflexed and supinated at 90% of stance.[7] Total magnitude of rearfoot excursion is 10-15° in all three planes.[7]

Midfoot

When referenced to the rearfoot, the midfoot is supinated at IC and moves to a dorsiflexed, pronated, and adducted position post IC.[7] From 15% to 80% of stance, the midfoot is maintained in neutral in the sagittal plane, pronation, and abduction. The midfoot is plantarflexed, supinated, and continues into abduction in the last 20% of stance.[7] Total magnitude of midfoot range of motion is 5-8° in all three planes.[7]

Mann[54] described a coupling of the rearfoot and forefoot by way of the midfoot during mid to terminal stance when shank external rotation and rearfoot supination causes the longitudinal axes of talonavicular and calcaneocuboid to diverge, creating a more rigid lever for push off. Position and control of the medial longitudinal arch has been found to be contributory to rearfoot to forefoot coupling.[55,56] The transverse tarsal joint has been described to have two different modes of function which are dependent on mechanical demands of walking and running at various speeds, with different loads, on various surfaces, and whether the cuboid is locked by the fibularis longus.[21] The individual axes of the transverse tarsal joint have a corresponding parallel axis at the metatarsophalangeal joints.[21] During pushoff, the lever arm of the foot changes dependent on which axis the foot is functioning about.[21] In "low gear" dominated activity such as uphill walking with a load or the first steps of a sprint, pushoff occurs with the rearfoot adducted and plantarflexed while cuboid rotation occurs about the oblique axis in the transverse tarsal joint.[26] Plantar pressure progression is shifted to the lateral forefoot and results in a functionally shortened lever arm as toe break occurs about the axis formed by the lesser metatarsophalangeal joints.[21,26,57] With the foot adducted, ground contact during low gear push off is transmitted from the lateral heel to the lateral aspect of the first metatarsal head.[26] During pushoff in "high gear" dominated activity such as fast level walking and sprinting, the plantar aponeurosis (PA) is tensioned and the fibularis longus compresses and everts the calcaneocuboid joint to a closed pack position, mechanically coupling the rearfoot to forefoot to prevent midtarsal break.[26] With the foot neutral in the transverse plane, force is transmitted through the medial border of the first metatarsal head and hallux as push off occurs about the transverse metatarsophalangeal axis.[26] The ability of the foot to pushoff about two axes may contribute to balance and negotiation of uneven ground by allowing for alteration of forward progression in response to perturbation.[57] More recent kinematic studies using multisegmented foot models have found that individual foot segments remain compliant during ambulation.[58–60] During gait, forefoot inversion and eversion motion remains relatively uncoupled and independent from frontal plane motion in the rearfoot.[60] However, a coupling relationship has been found between rearfoot pronation and forefoot dorsiflexion in the first half of stance and forefoot plantarflexion and rearfoot supination in the latter half of stance, with vector coded mean excursions of 41-43°.[60] Additionally, there is a high degree of coupling (mean excursions 24-32°) between rearfoot frontal plane motion and forefoot transverse motion during walking in the first 20% of stance and again from midstance to preswing.[60]

Lateral Forefoot

The lateral forefoot is plantarflexed, slightly supinated, and abducted at IC, followed by plantarflexion, pronation, and abduction post IC relative to the midfoot.[7] Lateral forefoot pronation occurs in the latter half of IC until the forefoot contacts the ground.[7] The metatarsal arch deforms and widens in a metatarsal forming phase, with loading incurred in the lateral aspect of the forefoot.[61] From 15% to 70% of stance, the lateral forefoot remains dorsiflexed while slightly supinated.[7] Force distribution across the forefoot becomes more uniform during mid stance as the medial forefoot is progressively loaded.[61] From 70% to 90% of stance, the lateral forefoot supinates[7] and the metatarsal arch increases to its maximal height[61]. Despite direct loading of the metatarsal arch in the last 25% of stance, forefoot width decreases and tightens as the foot prepares to pushoff.[61] It is speculated that the paradoxical increase in metatarsal arch height during maximal loading is resultant from the engagement of connective tissues (such as the PA) and contractile support mechanisms of the arch.[61] Total lateral forefoot excursion is approximately 10° in each plane.[7]

There are two axes of rotation formed by the metatarsal heads that parallel the axes of transverse tarsal joint.[21,26,57,62,63] The axis that the body employs during propulsion is dependent on requirements of force generation or balance requirements and is dictated by midfoot function.[21,26,57,62,63] The three major functions for the metatarsal heads include adaptation to changing gravitational axes in balance, transfer of weight from rearfoot to the forefoot prior to terminal stance, and function as a lever for propulsion in terminal stance.[62] Of these functions, the role of the metatarsal heads in providing fine adjusting movements of the foot has been described as the most important in maintaining balance during standing and walking.[62] Impaired ability of the metatarsals to perform fine adjusting movements would shift the burden of balance to the subtalar joint and result in maximal impairment,[62] a scenario likely to be observed clinically when tarsometatarsal hypomobility or impaired neuromuscular function is a consequence post injury. During ambulation that occurs at lower velocity, is balance intensive, involves negotiating inclines, or includes carrying loads, the foot is adducted so pushoff may occur about the oblique axis that transects metatarsal heads 2-5 in the lateral forefoot.[21]

First Ray & Hallux (Medial Forefoot)

In relation to the midfoot, the first ray dorsiflexes, everts, and adducts at IC, abducts during early stance phase post IC, and remains dorsiflexed and everted until 75% of stance.[7] During the last quarter of stance, the first ray dorsiflexes, inverts, and adducts.[7] Total excursion in the first ray is 6-16° in all planes.[7] When referenced to the first ray, the hallux is dorsiflexed, supinated, and abducted at IC followed by slight pronation at 15% of stance that persists until the last quarter of stance.[7] The hallux dorsiflexes and abducts during the last 25% of stance.[7] Total hallux excursion is 55°, 50°, and 18° in the sagittal, transverse, and frontal planes, respectively.[7]

During higher velocity ambulation, running, and sprinting, the foot is neutral in the transverse plane so that pushoff may occur about the transverse metatarsal axis.[21,26] The transverse axis transects the metatarsal heads of digits 1 and 2 and parallels the transverse axis of the midtarsal joint.[21,26,57,62,63] When the forefoot is coupled to the rearfoot and the transverse metatarsal axis employed during pushoff, the moment arm is functionally lengthened by 20%.[21]

CONCLUSIONS

In summary, the multiple segments that comprise the ankle-foot complex function synergistically to transmit and attenuate force during propulsion, accommodate and conform with uneven terrain, and provide important afferent information and motor adjustment to maintain balance during standing and ambulation. The interplay of segmental joint mobility, sensorimotor function, and movement and stabilization provided by the extrinsic and intrinsic musculature is required to coordinate and execute the complex kinematics observed in the ankle-foot complex during propulsion. In part two of this clinical commentary, alterations in kinematics secondary to joint and neuromotor impairment incurred following lateral ankle sprain and in chronic ankle instability will be discussed.[10] Clinical assessment and treatment techniques for the ankle-foot complex will also be addressed.[10]

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CLINICAL COMMENTARY

CLINICAL COMMENTARY ON MIDFOOT AND FOREFOOT INVOLVEMENT IN LATERAL ANKLE SPRAINS AND CHRONIC ANKLE INSTABILITY. PART 2: CLINICAL CONSIDERATIONS

John J. Fraser, PT, MS, OCS[1, 2]
Mark A. Feger, PhD, ATC[3]
Jay Hertel, PhD, ATC[1]

ABSTRACT

Lateral ankle sprains (LAS) and chronic ankle instability (CAI) are common musculoskeletal injuries that are a result of inversion injury during sport. The midfoot and forefoot is frequently injured during a LAS, is often overlooked during clinical examination, and maybe contributory to the development of CAI. The purpose of part two of this clinical commentary and current concept review is to increase clinician's awareness of the contribution of midfoot and forefoot impairment to functional limitation and disability of individuals who experience LAS and CAI and to facilitate future research in this area. The importance of multisegmented foot and ankle assessment from a clinical and research perspective is stressed. Select physical assessment and manual therapeutic techniques are presented to assist the clinician in examination and treatment of the ankle-foot complex in patients with LAS and CAI.

Keywords: Gait, intrinsic foot muscles, joint mobilization, physical examination, rehabilitation

[1] Department of Kinesiology, University of Virginia, Charlottesville, VA, USA
[2] US Navy Medicine Professional Development Center, Bethesda, MD, USA
[3] Virginia Commonwealth University School of Medicine, Richmond, VA, USA

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CORRESPONDING AUTHOR
John J Fraser,
PO Box 400407,
Memorial Gymnasium, Charlottesville, VA
Phone: 757-438-0390
E-mail: jjf5ac@virginia.edu

BACKGROUND AND PURPOSE

In the first part of this clinical commentary and current concepts review, foot and ankle anatomy, the roles of the intrinsic and extrinsic foot and ankle musculature from a multisegmented foot perspective, and the biomechanics of the ankle-foot complex during function were examined.[1] In part two of this this commentary, the contribution of midfoot and forefoot impairment in lateral ankle sprains and chronic ankle instability will be discussed in order to increase clinician's awareness and to facilitate future research in this area. The importance of multisegmented foot and ankle assessment will also be discussed from a clinical and research perspective.

Lateral ankle sprains (LAS) are common musculoskeletal injuries that affect more than two million individuals annually in the United States.[2] Only 11% of LAS patients perform supervised physical therapy following their injury.[3] Improper management of LAS may manifest into the residual impairment seen in the 40% of LAS patients that develop chronic ankle instability (CAI).[4] CAI is a chronic condition that involves impaired neuromuscular control, residual instability, and chronic pain that collectively result in self-reported disability after LAS.[5–8] Kinematic analyses of acute LAS's sustained during sport demonstrate rotational velocities up to 2124°/second which leads to extremes of range of motion, including up to 52° of plantarflexion, 126° of inversion, and 99° of adduction.[9–13] Simulated ankle sprains have demonstrated external moments in excess of 23 Nm for inversion and 11 Nm for adduction in simulated Grade I sprains.[14] LAS commonly involves damage to the anterior talofibular and calcaneofibular ligaments, which can be strained to approximately 20% and 16% of their resting length, respectively.[14,15]

Søndergaard[16] demonstrated that both the midfoot and forefoot are frequently injured during inversion ankle sprains and this phenomenon may be underappreciated by many clinicians. A number of midfoot injuries share similar mechanics to those incurred during a LAS.[17–24] Figure 1 depicts the external adduction and inversion moments that create lateral midfoot adduction stress and rearfoot inversion stress incurred during an inversion injury. The occult presentation of mild to moderate midfoot injury is likely attributed to the synchronicity of lateral ankle and midfoot injury. Inversion injuries frequently cause damage to the soft tissue structures of both the ankle and midfoot, while pain is often localized to the talocrural or subtalar articulations.[16] Nevertheless, if a patient reports inverting or 'rolling' their ankle, a thorough assessment of the lateral ankle joint and foot should simultaneously be performed. A recent clinical practice guideline published by the Orthopaedic Section of the American Physical Therapy Association recommends assessing patients who sustain LAS for painful foot conditions that may be indicative of fracture, cuboid involvement, or midfoot disruption.[25]

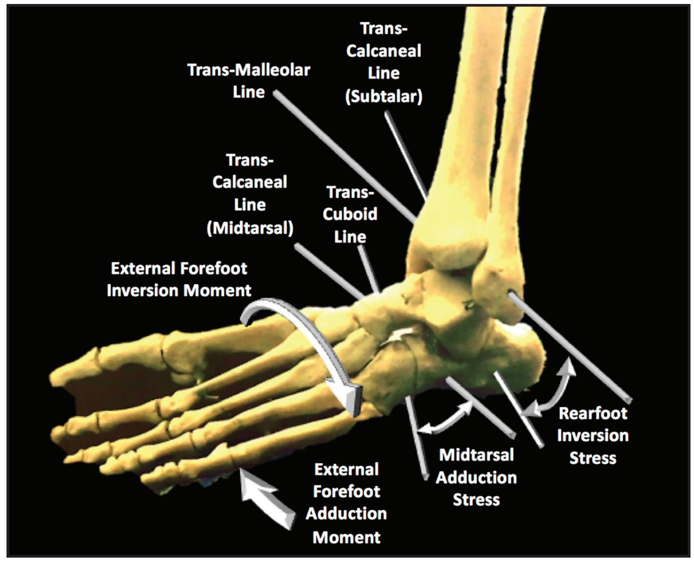


Figure 1. *Lateral midfoot stress due to external adduction and inversion moments during an inversion injury.*

Despite improved understanding of the pathomechanics and pathophysiology of LAS and CAI, there is no evidence that the rate of recurrent LAS or CAI is declining. There is a need for further examination of other potential contributors to the etiology of recurrent LAS and CAI. Consideration of midfoot and forefoot involvement after LAS may be of clinical importance and the purpose of Part 2 of this clinical commentary and current concepts review paper is to increase clinicians' awareness of the contribution of midfoot and forefoot impairment to activity limitation and participation restrictions of individuals who experience LAS and CAI and to facilitate future research in this area. To accomplish this, the importance of multisegmented foot and ankle assessment from a clinical and research perspective will be reviewed.

INJURIES INVOLVING THE MIDFOOT AND FOREFOOT

Midfoot Injury

Midfoot injuries may include fractures, dislocations, subluxations, ligamentous sprains, or a composite of one or more of these injuries and are named by mechanism vector of the injurious force.[26,27] Examination of the foot is indicated when there is an apparent osseous or ligamentous injury in the foot. Prudence may dictate that the foot is examined in conjunction with the ankle following inversion injury, even when the patient does not report symptoms. The mechanism of midfoot injuries are frequently a consequence of ankle and foot supination that result in deleterious dorsal translation/axial compression in the medial column and plantar translatory/tensile distractive forces in the lateral column.[28] These injurious forces may culminate in ligamentous tears and osseous avulsions at the attachments of the calcaneocuboid, talonavicular or bifurcate ligaments.[16]

Midfoot Injury in Lateral Ankle Sprains

In a prospective study of 711 patients who sustained an inversion sprain and were diagnosed in an urgent-care clinic, isolated midfoot sprains of either the bifurcate/dorsal calcaneocuboid ligament, talonavicular ligament, or both were found in 172 (26%) of the cases.[16] Additionally, midtarsal joint capsule involvement was found in 237 (33%) individuals who sustained LAS.[16] In another study investigating midfoot involvement in patients with history of LAS, damage to the bifurcate ligament was found in 40.5% of all cases.[29] Of these patients, 23% of the patients who had a diagnosis of "lateral ankle sprain," had isolated bifurcate ligament injury and an intact lateral ankle.[29] These findings illustrate that midtarsal joint injury is quite common, may mimic or contribute to lateral ankle signs and symptoms, and that the foot should be thoroughly examined following inversion ankle-foot injury. Because midtarsal joint injury may be misdiagnosed as a LAS, delay of care or improper clinical management may contribute to persistent activity limitation and participation restriction in these patients.

Cuboid Syndrome

Cuboid syndrome, a lateral midfoot injury as a result of minor disruption of the calcaneal-cuboid congruency, has been described as being caused by abnormal inversion forces acting on the rearfoot when the forefoot is loaded during weight bearing.[17] Newell and Woodle[30] and Marshall[31] have described cuboid syndrome as a partial dislocation of the cuboid with subsequent impairment in motion. Similar mechanics have been described in multiple case studies of cuboid dislocation, a related and clinically more severe disruption of the calcaneocuboid articulation.[18–24,32] Analyses of case history and post-injury imaging have supported that when the forefoot is supinated, insult incurred from a dorsolateral external moment directed to the lateral aspect of the midfoot creates a plantar-medial displacement of the cuboid on the calcaneus.[18–24,32] It has been theorized that cuboid syndrome results from a calcaneocuboid subluxation created by forceful fibularis longus contractions during inversion injury.[33] The cuboid is normally everted and compressed during contraction of the fibularis longus as it courses around the fibularis sulcus.[34] During the combination of rearfoot inversion during forefoot loading, a medial and dorsal force vector created by the fibularis longus exerted on a medially rotated cuboid causes an inferomedial subluxation[33] (Figure 2). The subsequent discomfort associated with cuboid syndrome is attributed to the malposition of the cuboid and subsequent irritation of the joint capsules, ligaments, and the fibularis longus tendon.[17]

Chronic Ankle Instability and the Multisegmented Foot

Many individuals who sustain LAS will subsequently develop persistent pathological gait kinematics[35–39]

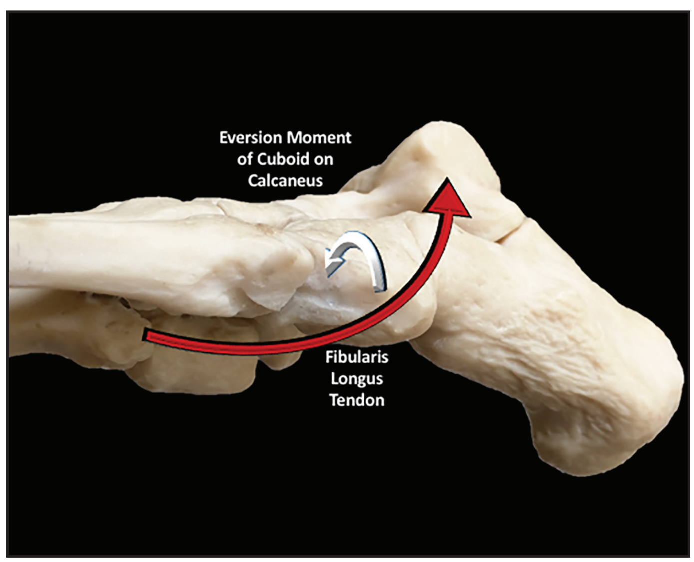


Figure 2. *Cuboid eversion with fibularis longus contraction.*

and altered motor strategies[37,40–42] associated with CAI. CAI occurs in individuals that have had at least one significant ankle sprain, have repeat episodes of giving way, feelings of instability, or recurrent ankle sprains, and self-reported disability as a result of the ankle injury.[5] Groups of patients with CAI have been observed to walk with a wider bases of support,[43] decreased stride to stride variability in shank-rearfoot coupling,[38] increased shank external rotation excursion,[39] a more plantarflexed[35] and supinated foot,[37,39] and a more lateral center of plantar pressure progression[41,42,44–46] when compared to healthy controls. They have greater electromyographic activity for longer period of time in the gluteus medius and medial gastrocnemius pre initial contact (IC),[42] fibularis longus immediately pre[36,37,41,42] and post[36,37,41] IC, and gluteus medius from 50% of stance phase to 25% of swing phase.[42] Evidence is conflicting regarding the electromyographic activity in the tibialis anterior during the stance phase of gait, with both increased[41] and decreased[42] activity reported. Impairment in the midfoot[47,48] and medial forefoot kinematics[49] have been suggested to be contributory in CAI. Interestingly in a study of 711 patients who sustained inversion injury isolated to either the lateral ankle (65% of sample) or the midtarsal joint (23% of sample), pain, swelling, perception of giving way, and subsequent inversion injury persisted at the same frequency at 6-12 months regardless of the site of injury.[16]

In order to make the case of suspected midfoot involvement in CAI, there are some recent studies in healthy subjects that may provide some contrast and relevance. A study of healthy individuals who were classified as having a large inversion forefoot angle at IC ($5.9 \pm 1.6^\circ$) were found to have a greater forefoot pronation excursion and remain everted for longer periods during stance when compared to a group who had a moderate forefoot angle ($2.6 \pm 1.1^\circ$) at IC.[50] Similarly, the findings of a kinematic study of the rearfoot coupling mechanism were that healthy midtarsal joints uncoupled from the rearfoot post IC and remained unlocked through terminal stance.[51] This finding challenges the notion that the midtarsal joint locks the rear and midfoot at terminal stance in order to provide a rigid lever required for efficient gait.

Groups of patients with CAI have been found to have up to 7° more inversion in the rearfoot prior to and following IC when compared to healthy controls, which has been suggested to be a contributing factor to this population's increase risk for reinjury.[36,37] Morphologically a group of patients with CAI who were scheduled for lateral ankle reconstruction were found on radiograph to have significantly higher mean talometatarsal and talocalcaneal angles, and lower mean calcaneal angles and tarsal indices when compared to healthy controls, indicating higher medial longitudinal arches and cavovarus.[52] It has been suggested that cavovarus in patients with CAI is a major contributing factor in the progression to ankle osteoarthritis and corrective calcaneal osteotomy should be considered in conjunction with ligamentous reconstruction to normalize forces about the ankle-foot complex.[53]

Changes in plantar pressure during walking have been found in patients with CAI when compared to healthy controls.[41,44–46,54] Nyska and collegues[45] found patients with CAI spend more time in the rear and midfoot during stance with a delay in transition to the central and lateral forefoot and toes, increased pressure in the midfoot and lateral forefoot, and decreased pressure in the heel and toes. Schmidt and colleagues[46] also found a delay in time to peak pressure of the medial and lateral rearfoot and the medial midfoot during early stance phase in patients with CAI. Patients with CAI have greater plantar pressure under the midfoot and lateral forefoot and decreased pressure in the heel and toes compared to healthy controls.[45,46] Nawata and colleagues[44] found that patients with CAI ambulated with a laterally deviated center of progression and an adducted/supinated foot during midstance. Hopkins and colleagues[41] observed similar findings with subjects with CAI walking with increased lateral center of pressure progressions between 20% to 90% of stance when compared to healthy matched controls. Koldenhoven and colleagues[42] found that patients with CAI have a more lateral center of pressure progression throughout the stance phase and have increased plantar pressure in the lateral forefoot for longer periods of time. Individuals with CAI also run with a lateral plantar pressure distribution during foot strike and the plantar progression starts more laterally during initial loading when compared to controls.[54]

The kinematic and kinetic findings found in patients with CAI may result from the impaired ability to uncouple the midfoot from the rearfoot due to mechanical or neurophysiologic constraints. Impaired joint mobility in any of the foot segments may impair the ability of the foot to decouple during lower velocity ambulation. A neurophysiologically constrained midfoot combined with a supinated rearfoot could plausibly contribute to the lateral shift in plantar center of pressure progression during the stance phase of gait. Joint mobility assessment and manipulation has been recommended in clinical cases of idiopathic cavovarus, especially when associated with gait abnormalities and clinical entities such as LAS and ankle instability.[55]

Hypomobility of the first ray may contribute to the lateral shift in plantar pressure seen in this patient population.[56] It is plausible that joint hypomobility could also affect the muscles acting on the first ray and may explain the findings of a recent study, where patients with CAI were found to have atrophy of the flexor hallucis brevis and flexor hallucis obliquus and hypertrophy of the flexor hallucis longus.

Neuromuscular adaptations in the foot such as co-contraction of the extrinsic and intrinsic antagonistic pairs may also be implicit in CAI. Increased muscle stiffness is thought to be beneficial in joint stability, especially when mechanical stability is impaired and the muscles play a larger role in mitigating destabilizing forces.[57] If there is mechanical disruption of the transverse tarsal, tarsometatarsal, or intertarsal ligamentous structures, it is plausible that stabilizing co-contraction in the foot may create a situation where the rearfoot, midfoot, and forefoot remain coupled throughout stance, creating a constrained system.

Impaired coupling in the foot may also occur in the CAI population due to neuromuscular dysfunction of the extrinsic and intrinsic musculature. In electrophysiological studies of 66 patients who sustained LAS, Nitz and colleagues[58] found decreased nerve conduction velocities in the peroneal (17% of patients with a Grade II LAS, 86% of patients with a Grade III LAS) and tibial (10% of patients with a Grade II LAS, 83% of patients with a Grade III LAS) nerves, as well as electromyographic evidence of denervation. Jazayeri and colleagues[59] also found increased peroneal and tibial nerve latencies during nerve conduction studies of football (soccer) players who sustained LAS. Impaired fibularis longus or intrinsic foot muscle function secondary to neuropraxia or traction axonotmesis/neurotmesis may be deleterious to intersegment coupling, foot shaping, intersegmental stability, force attenuation, and afferent feedback from the articular soft tissue and plantar cutaneous sensation. In the only study known to investigate individuals with CAI utilizing a multisegmented foot model during walking, the first ray was found to have a mean 9.4° more inversion from 87% to 98% of stance phase when compared to healthy controls.[49] Similar findings were observed in LAS copers, operationally defined as subjects who had sustained LAS in the previous two years but were not experiencing ankle instability, had a mean 7.4° difference from 10% to 83% of stance phase.[49]

The fibularis longus, besides being an extrinsic evertor of the foot, is a plantarflexor and evertor of the hallux, and stabilizes the medial column, medial longitudinal and transverse arches[60] and the calcaneocuboid joint.[34] Impaired peroneal function has been offered as a possible explanation for the supinated position of the hallux in patients with CAI.[49] Patients with CAI have been found to have decreased concentric and eccentric strength,[61] diminished mean activation time,[62] and increased latency and electromechanical delay[63] in the fibularis longus in the injured limb when compared to healthy controls. Due to the proximity of the fibularis longus to the cuboid, minor disruption in cuboid congruency or subluxation is thought to contribute to peroneal irritability[64] and may contribute to impaired function of this muscle. The cuboid functions as a pulley for the fibularis longus tendon and provides a more advantageous vector of pull to support the transverse arch, medial longitudinal arch, and the first ray.[60] More substantial disruption in stability or position of the calcaneus may have the potential to disrupt this pulley mechanism by altering tendon slack length or the vector of force. Patients with CAI have been found to walk at lower velocities[43] and with an adducted foot.[45] It is plausible that impaired ability to lock the midfoot due to ligamentous instability or neuromuscular impairment in the fibularis longus may force patients with CAI to employ a gait strategy where pushoff occurs about the oblique metatarsal axis. This may also explain some of the plantar pressure findings found in the lateral forefoot in patients with

Table 1. *Observational and Clinical Measures of Foot Morphology.*

Segment	Assessment	Summary
Multi-segmented	Foot Posture Index – 6 item	A composite measure of foot posture that is based on one palpation and five observations of foot morphology in standing.
Longitudinal Arch (Midfoot)	Change in Foot Length (NWB to FWB)	A measure of change of total foot length in both NWB and FWB conditions.
	Δ Arch Height Index (Navicular height/Foot Length, NWB to FWB)	A measure of change of navicular height normalized to foot length in both NWB and FWB conditions.
Longitudinal and Transverse Arches (Midfoot)	Δ Dorsal Arch Height (NWB to FWB)	A measure of change in vertical arch height between loading and unloading. The dorsal aspect foot is measured at 50% of total foot length in both NWB and FWB conditions.
	Δ Midfoot Width (NWB to FWB)	A measure of change of midfoot width between loading and unloading. The width of the foot is measured at 50% of total foot length in both NWB and FWB conditions.
	Foot Mobility Magnitude	$Foot\ Mobility\ Magnitude = \sqrt{(\Delta\, height)^2 + (\Delta\, width)^2}$ A composite measure derived from change of midfoot height and width. We posit that this may be an acceptable surrogate measure for the assessment of intrinsic/extrinsic muscular control of the foot across loading conditions.
	"Too Many Toes" sign	An observational assessment of the pronated foot during standing, when the lateral forefoot/lesser toes can be observed when viewing the foot from an posterior-anterior perspective
Subtalar (rearfoot)	"Peak-a-Boo" sign	An observational assessment of the supinated rearfoot during standing, when the medial calcaneus can be observed when viewing the foot from an anterior-posterior perspective

NWB= non-weight bearing, FWB= full weight bearing

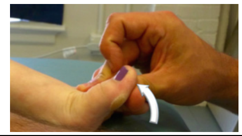
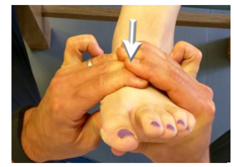
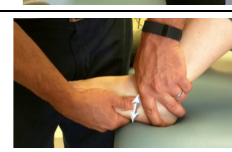
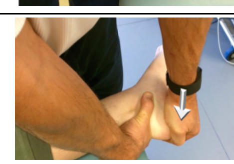
The Foot Posture Index is based on the work of Redmond AC, Crosbie J, Ouvrier RA. Development and validation of a novel rating system for scoring standing foot posture: The Foot Posture Index. Clinical Biomechanics. 2006;21(1):89-98.

CAI. This gait strategy may also be utilized to maximize balance in the presence of other neurophysiologic impairment.

CLINICAL IMPLICATIONS AND FUTURE DIRECTION

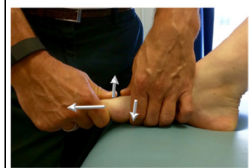
The midfoot plays an essential role in force transmission during gait, is commonly injured during inversion sprains, and is likely to contribute to the morbidity associated with LAS and CAI. Clinically, it is important to consider the midfoot and forefoot during examination and treatment of these patients. It has been previously suggested that the diagnostic scope should be widened to include the midfoot when assessing and treating common ankle sprains.[16] Based on the evidence presented in this paper, it is recommended that patients may benefit from examination of the midfoot and forefoot post inversion injury, even when the patient does not report pain symptoms in the region. If treating providers fail to assess the midfoot and forefoot following LAS, it is likely that important contributory impairment will be missed.

The authors recommend that clinicians take a holistic approach when examining and performing treatment in those who sustain LAS. A detailed clinical history that captures type and duration of symptoms, recurrence, mechanism of injury, timing and location of pain complaints, and current functional limitations will help guide the physical examination. Inquiry to factors, that when implemented have been shown to hypertrophy the intrinsic foot muscles and beneficially modify foot shape, such as minimalist footwear[65,66] time spent barefoot,[67–69] and the type of surface physical activity occurs (outdoors > indoors)[67] may provide the clinician insight regarding intrinsic foot strength. Observation of foot morphology, in both unloaded and loaded conditions, can provide information on the patient's ability to shape and stabilize the foot. Measurements of navicular height, dorsal arch height, foot length, and foot width in both loading conditions are expedient and clinically meaningful methods of assessing control of the longitudinal and transverse arches. Table 1 presents some suggested observational and clinical measures of foot morphology.

Table 2. *Joint Mobility Assessment of the Ankle-Foot Complex. Joints are graded as having normal mobility, hypermobility, or hypomobility*		
Assessment	**Procedure**	**Image**
1^{st} Metatarso-phalangeal Passive Mobility	The patient is positioned in hook lying with the toes cantilevered over the plinth edge. With the the distal 1^{st} metatarsal stabilized, the proximal phalanx is distracted and glided in a plantar vector parallel to the joint line until the end feel is noted. Assessment is repeated utilizing a dorsal glide. Annotate joint laxity using the passive mobility scale.	
Hallux Extension Excursion	The patient is positioned in hook lying with the feet flat on the plinth. With the 1^{st} metatarsal stabilized, the metatarsophalangeal joint is passively extended until the end feel is noted. Goniometric measurement and joint end feel is recorded.	
1st Tarso-metatarsal Plantar glide	The patient is positioned supine with the distal shank cantilevered over the plinth edge. The distal 1^{st} metatarsal is stabilized with the assessor's thumb pads. The pads of the assessor's middle and index fingers are placed on the distal segment of the dorsal first tarsometatarsal joint. Force is applied using the overlapped fingers from the assessor's opposite hand in a plantar vector parallel to the joint line. Annotate joint laxity using the passive mobility scale.	
1st Tarso-metatarsal excursion	The patient is positioned supine. The most distal aspect of the 1^{st} cuneiform is stabilized while the 1^{st} metatarsal is passively dorsiflexed until the end feel is noted. Goniometric measurement and joint end feel is recorded. The measure is repeated for plantarflexion.	
Forefoot and Midfoot Inversion/ Eversion Mobility	The patient is positioned supine with the distal shank cantilevered over the plinth edge. The stabilizing hand cradles the calcaneus to prevent rearfoot inversion/eversion. Utilizing a "C" grip, grasp the forefoot at the metatarsal heads. The forefoot is maximally inverted until terminal excursion is achieved. End feel and goniometric measurement is recorded. Repeat procedure for eversion.	
Midfoot Adduction passive mobility	An assessment of calcaneocuboid and calcaneonavicular ligamentous and capsular laxity/provocation. The patient is positioned supine with the distal shank cantilevered over the plinth edge. The stabilizing hand cradles the calcaneus to prevent rearfoot movement. An adduction force is exerted to the lateral forefoot. Annotate joint laxity using the passive mobility scale.	
Talonavicular passive mobility	The patient is positioned in hook lying with the feet flat on the plinth. With the dorsal rearfoot stabilized, the navicular is passively glided in a dorsal vector until the end feel is noted. Assessment is repeated utilizing a plantar glide. Annotate joint laxity using the passive mobility scale.	
Calcaneo-cuboid passive mobility	The patient is positioned in hook lying with the lateral foot cantilevered over the edge of the plinth. With the dorsal rearfoot stabilized, the cuboid is passively glided in a dorsal vector until the end feel is noted. Assessment is repeated utilizing a plantar glide. Annotate joint laxity using the passive mobility scale.	
Subtalar eversion passive mobility	The patient is positioned in a side lying position on the side that is to be assessed and cantilevered off the edge of the plinth. The shank and talus is stabilized. With the calcaneus cradled, a lateral force is exerted through the medial calcaneus. Annotate joint laxity using the passive mobility scale.	

Palpatory examination of the joints, ligaments, and muscles of the foot is important post inversion injury to assist in determining midfoot or forefoot involvement. Joint range of motion and accessory motion assessment in each segment and joint of the foot will often reveal intersegmental joint limitation and provide the clinician with a prime opportunity to render treatment such as joint mobilization or manipulation. Suggested manual therapeutic techniques for the ankle-foot complex are presented in

Table 3. *Joint Manipulation of the Midfoot and Medial Forefoot*

Segment	Intervention	Indication	Procedure	Picture
Medial Forefoot/ Hallux	Hallux (MTP) Dorsal Glide	Impaired dorsiflexion of the hallux	The patient is positioned supine in hook lying. The distal metatarsal is stabilized between the pad of the thumb and the proximal phalanx of the index finger (use of a piece of tubigrip of latex glove may assist in maintaining grip). The base of the proximal phalanx is gripped using a similar method. A grade III axial distractive force is exerted to achieve joint separation. A plantar force is exerted on the proximal segment while simultaneously exerting a dorsal counterforce on the distal segment to take up joint slack. Once at the end of the joint excursion, a high frequency, low amplitude oscillatory grade IV manipulation may be applied to the joint.	
	1st TMT Plantar Glide	Impaired dorsiflexion of the 1st metatarsal	The patient is positioned supine. The treating clinician will wrap the secondary hand around the lateral aspect of the foot perpendicular to the proximal 1st metatarsal. The pads of the middle and index finger will rest adjacent and just distal to 1st tarsometatarsal joint. The primary hand will wrap over the medial aspect of the foot and overlay the fingers of the secondary hand. A plantar direct force is exerted through the proximal metatarsal to take up joint slack and to introduce dorsiflexion. Once at the end of the joint excursion, a high frequency, low amplitude oscillatory grade IV manipulation may be applied to the joint.	
Midfoot	Dorsolateral Cuboid Glide with Forefoot Supination	Hypomobility or disrupted calcaneo-cuboid congruency	The patient is positioned supine. The heel is cupped and the plantar aspect of the cuboid blocked by the treating clinician's stabilizing hand. The clinician grips the forefoot across the metatarsal heads and exerts a supination force, taking up the slack of the multiple segments from the midfoot to forefoot. At terminal excursion, overpressure is applied to supination while providing a dorsolateral counter force to the cuboid.	
	Calcaneo-cuboid Squeeze		The patient is positioned prone with the knee flexed to 70º. The patient's foot is gripped with both hands and the pads of both thumbs contacting the plantar aspect of the cuboid. With constant dorsal pressure applied to the cuboid, the ankle is slowly stretched into terminal plantarflexion with the midfoot and toes maximally flexed.	
	Cuboid Whip		The patient is positioned prone with the knee flexed to 70-90º and the talocrural joint in neutral. The patient's foot is gripped with both hands and the pads of both thumbs contact the plantar aspect of the cuboid. With constant dorsal pressure applied to the cuboid, the knee is rapidly extended and the ankle rapidly plantarflexed.	
	Talonavicular Plantar and Dorsal Glides	Talo-navicular/ medial longitudinal arch hypomobility	The patient is positioned supine in hookl ying. The treating clinician will wrap the fingers of the stabilizing hand around the talus, distal to the malleoli. The mobilizing hand will grasp the navicular with the pad of the thumb in contact with the dorsal navicular. With the talus stabilized a plantar or dorsal force may be exerted to take up joint slack. Once at the end of the joint excursion, a high velocity, low amplitude force or a high frequency, low amplitude oscillatory grade IV manipulation may be applied to the joint.	

MTP=metatarsal phanlangeal, TMT= tarsometatarsal

Tables 3 and 4. In the cases of segmental instability, the plan of care can be modified to allow for protection, intervention such as taping/strapping, bracing, orthotic fitting, and foot core stabilization exercises, and/or referral to orthopedic surgery or podiatry for surgical consideration. Table 2 presents some suggested joint mobility assessment techniques that can be used in the clinical examination.

Assessment of intrinsic muscle function can be difficult without the use of laboratory equipment or imag-

Table 4. *Joint Manipulation of the Rearfoot and Shank*

Segment	Intervention	Indication	Procedure	Picture
Subtalar	Subtalar Lateral Glide	Impaired rearfoot eversion	The patient is positioned sidelying, on the side of the injured limb. The treating clinician will wrap the fingers of the stabilizing hand around the talus, distal to the malleoli. Using the thenar eminence of the manipulating hand as a contact to the medial calcaneus, the clinician will apply a downward force through the arm into the patient's medial calcaneus to take up any joint slack. Once at the end of the joint excursion, a high velocity, low amplitude force or a high frequency, low amplitude oscillatory grade IV manipulation is applied to the joint.	
Talo-crural	Talar Distraction Manipulation	Impaired talocrural dorsiflexion or plantarflexion	With the patient positioned supine, the treating clinician places both hands with the fingers intertwined on the most posterior aspect of the dorsal foot, closest to the axis as possible. Using the thumbs, the clinician will position and maintain the foot in 10º of plantarflexion. The clinician will take up the joint slack by applying a caudal distractive force to the foot. Once at the end of the joint excursion, a high velocity, low amplitude force is exerted.	
	Posterior Talar Glide Manipulation	Impaired talocrural dorsiflexion	The patient is positioned supine with the foot extended beyond the edge of the plinth. The treating clinician will use the soft tissue of the web space and the thenar eminence between the thumb and index finger of the manipulating hand to contact the anterior talus just distal of the malleoli. The clinician will position and maintain the foot in 10º of plantarflexion and a stabilizing force to the shank while applying an anterior-posterior force to the talus to take up the joint slack. Once at the end of the joint excursion, a high velocity, low amplitude force or a high frequency, low amplitude oscillatory grade IV manipulation is applied to the joint.	
Tibio-fibular (shank)	Proximal Tibiofibular Joint Manipulation	Impaired fibula translation during ankle dorsiflexion and eversion	The patient is positioned supine with the hip and knee flexed. The treating clinician wraps one hand around the lateral aspect of the proximal shank into the popliteal space, with palmar surface of the metatarsophalangeal joint of digits 1 & 2 contacting the patient's fibular head. The shank is externally rotated and the knee is flexed until joint slack is taken up at the proximal tibiofibular articulation. Once at the end of the joint excursion, a high velocity, low amplitude force is exerted at the distal end of the shank.	
	Distal Tibiofibular Joint Posterior Glide Manipulation		The patient is positioned supine with the heel cupped in the treating clinicians stabilizing hand. The clinician contacts the anterior lateral malleolus using the thenar eminence of the mobilizing hand and applies an anterior-posterior force to take any joint slack. A high frequency, low amplitude oscillatory grade IV mobilization is applied at the end of joint excursion.	

ing modalities that are either not feasible or accessible for regular clinical use. Equipment such as motion capture systems, electromyographic, or magnetic resonance imaging machines is expensive, take clinical space, or require time-consuming technical analysis. Clinically, there are strategies that practitioners may use to objectively collect surrogate measures of intrinsic muscle function. The intrinsic muscles have been found to have the ability to control deformation of the longitudinal arch.[70] Measurement of the navicular height, foot length, and width using a tape measure or caliper in both unloaded position and in standing is a time expedient and inexpensive method. Toe flexor strength has been found to be associated with cross sectional area of both the extrinsic and intrinsic foot muscles, with larger size of the medial plantar intrinsic foot muscles (flexor hallucis brevis, flexor digitorum brevis, quadratus plantae, lumbricals and abductor hallucis) being a major predictor of toe flexor strength.[71] Manual muscle testing of the toe flexors is an easy and quick assessment technique that may yield clinically relevant information about the intrinsic foot muscles. Testing the patient's ability to isolate great toe movements from the lateral forefoot (great toe abduction, great toe extension with flexion in toes 2-5, great toe flexion with extension in toes 2-5) and strength testing may yield pertinent information on intrinsic function.

Ultrasound imaging is a modality that has emerged in the literature for the assessment of intrinsic foot muscle size.[72–76] Many clinicians have access to ultrasound imaging units, which makes this imaging modality ideal for use in evaluation of patients with ankle-foot pathology. Clinicians may find ultrasound imaging useful as an outcome measure for tracking changes in resting muscle size to assess effectiveness of exercise intervention (hypertrophy) or atrophy following disuse or neuromuscular insult. There is also great potential for the use of this imaging modality for the assessment of neuromuscular function or as a bio-feedback instrument. Assessment of the intrinsic and extrinsic muscles of the ankle-foot during a state of contraction may provide a clinician great insight to neuromuscular function and motor control. Future research is needed to establish the measurement properties of ultrasonography for assessment of neuromuscular function of the intrinsic foot muscles.

Testing of extrinsic muscle function of the ankle-foot complex is a standard of care when treating patients with LAS or CAI. Commonly, assessment is comprised of manual muscle testing (MMT) or hand held dynamometry of the open kinetic chain motions of ankle dorsiflexion, plantarflexion, inversion, and eversion. While MMT is a convenient assessment technique that may reveal information about single segment, open kinetic chain function of the extrinsic muscles, they may not translate well to how these muscles function in relation to the multisegmented foot. It has been recommended that strength testing and training should be specific with consideration given to muscle group function and the joint segments the tendons cross.[77] A more clinically relevant assessment of both the extrinsic and intrinsic muscles may be accomplished by testing their function in foot shaping, stability, and force attenuation. For example, assessment of the patient's ability to maintain arches across loading conditions may yield more clinically relevant information on the synergy of the posterior tibialis and the intrinsic muscles to maintain the medial longitudinal arch in both conditions. MMT of first metatarsal plantarflexion and adduction may yield more pertinent information on fibularis longus function as opposed to standard testing of foot eversion. Once deficits are identified, treatment that is specific to the impairment may be implemented. Treatments such as strengthening exercises, neuromuscular stimulation, biofeedback, and gait training may be employed with progressive loading for isolation and integration of the intrinsic and extrinsic muscles.[78] Video of some intrinsic foot exercises can be accessed at https://goo.gl/ugffZ8.

CONCLUSIONS

In summary, the midfoot and forefoot are commonly injured and can be an insidious comorbidity in LAS and CAI. Overlooked physical impairment in the midfoot or forefoot may result in persistent limitation in function, disability, and/or impaired quality of life. It is clinically imperative for healthcare providers to assess and treat the ankle-foot complex as a whole, to include the midfoot and forefoot, even when symptoms are not manifest.

Examination and treatment of the midfoot and forefoot should complement the thorough examination and treatment of the proximal and distal tibiofibular, talocrural, and subtalar articulations typically performed following injury. Based on the prevalence, cost, morbidity and progression to CAI type symptoms develop at the same rate in isolated midfoot injury as it does in LAS,[16] the examination and treatment of the midfoot and forefoot may furnish additional pertinent information to the treating provider and allow for a more comprehensive plan of care. The midfoot may have a larger contribution to normal neurophysiologic and mechanical function than previously thought. Further research focused on investigating the role of multisegmented foot kinematics in individuals with LAS and CAI, development and validation of clinical tests of the midfoot and forefoot is suggested.

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SECTION III: APPENDIX B

ADDITIONAL METHODS

18550 flyer #1

Are you recreationally active?

The Exercise and Sports Injury Laboratory (EASIL) at the University of Virginia is seeking men and women aged 18-50 with

NO history of foot or ankle injury

OR

Who have had an ankle sprain greater than 1-year and have NO feelings of instability, giving way, or repeat sprains

- The purpose of this study is to investigate if strengthening exercises or joint mobilization treatment of the foot improve function
- The study will require one laboratory visit, lasting approximately 2-hours
- Subjects will not be compensated for participation in this study

For more information, please contact

John J Fraser, PT, MS, OCS

JJF5ac@virginia.edu

Or call the EASIL at (434) 924-6184

Principal Investigator: Jay Hertel, PhD, ATC

IRB-HSR # 18550

UVA IRB-HSR

Approval Date: 8/25/16

Foot Study: John Fraser
jjf5ac@virginia.edu
(434) 924-6184

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jjf5ac@virginia.edu
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(434) 924-6184

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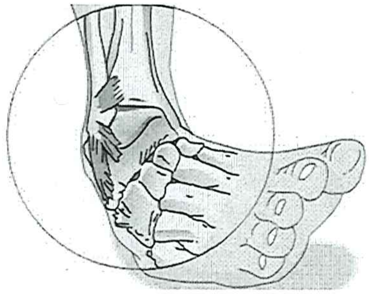
jjf5ac@virginia.edu
(434) 924-6184

18550 #2

Have you ever sprained your ankle?



The Exercise and Sports Injury Laboratory (EASIL) at the University of Virginia is seeking men and women aged 18-50 who sprained their ankle

For the first time in the past 8-weeks

OR

Greater than 1-year AND have continued feelings of instability, giving way, and/or repeat sprains

- The purpose of this study is to investigate if joint mobilization treatment of the foot will improve function
- The study will require three lab visits, lasting approximately 2-hours
- Subjects will be compensated $20 for participation in this study

For more information, please contact

John J Fraser, PT, MS, OCS

JJF5ac@virginia.edu

Or call the EASIL at (434) 924-6184

Principal Investigator: Jay Hertel, PhD, ATC

IRB-HSR # 18550

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jjf5ac@virginia.edu
(434) 924-6184

Consent of an Adult to Be in a Research Study
Joint Mobilization Arm – Healthy and Copers

In this form "you" means a person 18 years of age or older who is being asked to volunteer to participate in this study.

Participant's Name________________________________

Principal Investigator:	Jay Hertel, PhD ATC University of Virginia 210 Emmet St South Charlottesville, VA 22904 434-243-8673
Sponsor:	The Curry School of Education Foundation, Inc.

What is the purpose of this form?

This form will help you decide if you want to be in the research study. You need to be informed about the study, before you can decide if you want to be in it. You do not have to be in the study if you do not want to. You should have all your questions answered before you give your permission or consent to be in the study.

Please read this form carefully. If you want to be in the study, you will need to sign this form. You will get a copy of this form.

Who is funding this study?

This study is funded by a grant from the Curry School of Education Foundation, Inc.

Why is this research being done?

The purpose of this study is to determine if joint mobilization applied to the middle part of the foot will effect function in people who are healthy, have a history of lateral ankle sprains (LAS), or have chronic ankle instability (CAI) and have joint stiffness.

CAI is a condition where symptoms from an ankle sprain last longer than one year. These symptoms include a feeling of looseness, feeling that you may roll your ankle, or repeated ankle sprains. This study may help clinicians prescribe simple exercises at home to help treat CAI.

You are being asked to be in this study, because you are physically active (participate in some form of physical activity for at least 20 minutes per day, three days per week) and are not currently seeking medical treatment/therapy for your LAS/CAI.

IRB-HSR
APPROVAL DATE 10/5/16
EXPIRATION DATE 10/4/17

Up to 125 people will be in this study at UVA.

What will happen if you are in the study?

STUDY PROCEDURES

If you agree to participate, you will sign this consent form before any study related procedures take place.

VISIT 1 (will take about 2 hours to complete)

BASELINE MEASUREMENTS

Ankle Questionnaires:

- You will be asked to mark a line used to represent your current pain level
- A questionnaire asking about your general health as it relates to your ankle injury
- A questionnaire asking about your current physical activity level
- A questionnaire asking about your thoughts on your injury
- Two questionnaires asking about your ankle function

Foot Alignment:

- You will have your foot alignment measured in sitting and standing positions. The measurements will be recorded
- The shape of your foot will be observed and recorded

Range of motion:

- Your foot and ankle motion will be measured. These motions are: pulling your foot toward yourself, pointing your foot away from yourself, turning your foot inward, turning your foot outward, and how far up and down does your great toe move.
- You will be asked to stand on one leg and reach with your non-stance foot as far as possible in 3 directions

Balance

- You will be asked to stand on one leg and reach with your non-stance foot as far as possible in 3 directions

Foot and Ankle Laxity:

- You will have tests done that will determine how "loose" the joints of your ankles and feet are.

Ankle and Toe Strength:

- You will have your ankle and toes strength tested 3 times. The tester will use a device held in their hand that records how hard you can push using your ankle. These motions are: pulling your foot toward yourself, pointing your foot away from yourself, turning your foot inward, turning your foot outward, and curling your toes.

Standing Lunge, Heel Raise, and Walking Testing:

- You will have sensors attached to your skin with tape that will passively record how your bones move.

Joint Mobilization Arm – Healthy and Copers

- With the sensors on, your foot and ankle will be recorded during the following conditions
  - Standing lunge
  - While performing a heel raise on one foot, while touching the back of a chair to assist in balance
  - Walking across a 20-foot platform

Ultrasound Measurements of the Muscles of the Hip, Ankle and Foot

- Water-soluble ultrasound gel will be placed on your skin on your hip, lower leg and the bottom of your feet.
- The ultrasound probe will be placed on the skin where the gel was placed, and that will display the muscle thickness images on the ultrasound computer screen.

FOLLOWING BASELINE TESTING
Your participation in this study is complete. There will be no further testing or visits.

What are your responsibilities in the study?

You have certain responsibilities to help ensure your safety.

These responsibilities are listed below:

- You must come to each study visit.
- You must be completely truthful about your health history.
- Follow all instructions given.
- You should tell the study doctor or study staff about any changes in your health or the way you feel.
- Answer all of the study-related questions completely.

How long will this study take?

Experimental Group: Your participation in this study will require 3 separate visits over a 2 week period of time. Each visit will last about 2 hours.

Control Group and Participants without stiffness: Your participation in this study will require 2 separate visits over a 2 week period of time. Each visit will last about 2 hours.

If you want to know about the results before the study is done:

During the study you are having an investigational test done. The purpose of the test is not to diagnose any disease or abnormality you may have. Because the test is investigational there is no way for the study leader to understand if the results are "normal" or "abnormal". However, if any test results are concerning, your study leader will let you know.

In addition, as the research moves forward, your study leader will keep you informed of any new findings about the research itself that may be important for your health or may help you decide if you want to continue in the study. The final results of the research will not be known until all the information from everyone is combined and reviewed. At that time, you can ask for more information about the study results.

What are the risks of being in this study?

Risks and side effects related to the procedures and interventions include:

<u>Likely</u>
- Mild joint soreness associated with the mobilization intervention
- Mild muscle soreness of associated with the exercises

There is a small risk that breaches of privacy and/or confidentiality might occur. The risk of violation of subject privacy and confidentiality is minimal due to the requirements of the privacy plan in this protocol.

<u>Other unexpected risks:</u>
You may have side effects that we do not expect or know to watch for now. Call the study leader if you have any symptoms or problems.

Could you be helped by being in this study?
We cannot promise that you will be helped by being in this study. You may benefit from being in this study. Possible benefits include: decreased symptoms, improved mechanics, and restoration of joint motion. In addition, information researchers get from this study may help others in the future.

What are your other choices if you do not join this study?
The only choice is not to be in this study. If you are a patient at UVa your usual care will not be affected if you decide not to participate in this study. If you are an employee of UVa your job will not be affected if you decide not to participate in this study. If you are a student at UVa, your grades will not be affected if you decide not to participate in this study.

Will you be paid for being in this study?
You will not be paid for this study.

Will being in this study cost you any money?
All of the procedures in this study will be provided at no cost to you or your health insurance. You will be responsible for the cost of travel to come to any study visit and for any parking costs.

What if you are hurt in this study?

If you are hurt as a result of being in this study, there are no plans to pay you for medical expenses, lost wages, disability, or discomfort. The charges for any medical treatment you receive will be billed to your insurance. You will be responsible for any amount your insurance does not cover. You do not give up any legal rights, such as seeking compensation for injury, by signing this form.

What happens if you leave the study early?

You can change your mind about being in the study any time. You can agree to be in the study now and change your mind later. If you decide to stop, please tell us right away. You do not have to be in this study to get services you can normally get at the University of Virginia.

Even if you do not change your mind, the study leader can take you out of the study. Some of the reasons for doing so may include

a) You become injured and can no longer participate in the study
b) The principal investigator closes the study for safety, administrative or other reasons

How will your personal information be shared?

The UVa researchers are asking for your permission to gather, use and share information about you for this study. If you decide not to give your permission, you cannot be in this study, but you can continue to receive regular medical care at UVA.

If you sign this form, we may collect any or all of the following information about you:

- Personal information such as name, address and date of birth

Who will see your private information?

- The researchers to make sure they can conduct the study the right way, observe the effects of the study and understand its results
- People or groups that oversee the study to make sure it is done correctly

Some of the people outside of UVa who will see your information may not have to follow the same privacy laws that we follow. They may release your information to others, and it may no longer be protected by those laws.

The information collected from you might be published in a medical journal. This would be done in a way that protects your privacy. No one will be able to find out from the article that you were in the study.

What if you sign the form but then decide you don't want your private information shared?

You can change your mind at any time. Your permission does not end unless you cancel it. To cancel it, please send a letter to the researchers listed on this form. Then you will no longer be in the study. The researchers will still use information about you that was collected before you ended your participation.

Please contact the researchers listed below to:

- Obtain more information about the study
- Ask a question about the study procedures or treatments
- Report an illness, injury, or other problem (you may also need to tell your regular doctors)
- Leave the study before it is finished
- Express a concern about the study

Jay Hertel, PhD ATC
University of Virginia
210 Emmet St South
Charlottesville, VA 22904
434-243-8673

What if you have a concern about a study?

You may also report a concern about a study or ask questions about your rights as a research subject by contacting the Institutional Review Board listed below.

University of Virginia Institutional Review Board for Health Sciences Research
PO Box 800483
Charlottesville, Virginia 22908
Telephone: 434-924-9634

When you call or write about a concern, please give as much information as you can. Include the name of the study leader, the IRB-HSR Number (at the top of this form), and details about the problem. This will help officials look into your concern. When reporting a concern, you do not have to give your name

Signatures

What does your signature mean?

Before you sign this form, please ask questions about any part of this study that is not clear to you. Your signature below means that you have received this information and all your questions have been answered. If you sign the form it means that you agree to join the study. You will receive a copy of this signed document.

Consent From Adult

______________________	______________________	________
PARTICIPANT (SIGNATURE)	PARTICIPANT (PRINT)	DATE

Consent From Impartial Witness

I agree the information in this informed consent form was presented orally in my presence to the subject and the subject had the opportunity to ask any questions he/she had about the study. I also agree that the subject freely gave their informed consent to participate in this trial.

IMPARTIAL WITNESS (SIGNATURE)	IMPARTIAL WITNESS (PRINT)	DATE

Person Obtaining Consent

By signing below you confirm that you have fully explained this study to the potential subject, allowed them time to read the consent or have the consent read to them, and have answered all their questions.

PERSON OBTAINING CONSENT (SIGNATURE)	PERSON OBTAINING CONSENT (PRINT)	DATE

Consent of an Adult to Be in a Research Study
Joint Mobilization Arm – Ankle Sprain and Chronic Ankle Instability

In this form "you" means a person 18 years of age or older who is being asked to volunteer to participate in this study.

Participant's Name______________________________

Principal Investigator:	Jay Hertel, PhD ATC University of Virginia 210 Emmet St South Charlottesville, VA 22904 434-243-8673
Sponsor:	The Curry School of Education Foundation, Inc.

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CAI is a condition where symptoms from an ankle sprain last longer than one year. These symptoms include a feeling of looseness, feeling that you may roll your ankle, or repeated ankle sprains. This study may help clinicians prescribe simple exercises at home to help treat CAI.

IRB-HSR
APPROVAL DATE 10/5/16
EXPIRATION DATE 10/4/17

You are being asked to be in this study, because you are physically active (participate in some form of physical activity for at least 20 minutes per day, three days per week) and are not currently seeking medical treatment/therapy for your LAS/CAI.

Up to 125 people will be in this study at UVA.

What will happen if you are in the study?

STUDY PROCEDURES

If you agree to participate, you will sign this consent form before any study related procedures take place.

VISIT 1 (will take about 2 hours to complete)

BASELINE MEASUREMENTS

Ankle Questionnaires:

- You will be asked to mark a line used to represent your current pain level
- A questionnaire asking about your general health as it relates to your ankle injury
- A questionnaire asking about your current physical activity level
- A questionnaire asking about your thoughts on your injury
- Two questionnaires asking about your ankle function

Foot Alignment:

- You will have your foot alignment measured in sitting and standing positions. The measurements will be recorded
- The shape of your foot will be observed and recorded

Range of motion:

- Your foot and ankle motion will be measured. These motions are: pulling your foot toward yourself, pointing your foot away from yourself, turning your foot inward, turning your foot outward, and how far up and down does your great toe move.
- You will be asked to stand on one leg and reach with your non-stance foot as far as possible in 3 directions

Balance

- You will be asked to stand on one leg and reach with your non-stance foot as far as possible in 3 directions

Foot and Ankle Laxity:

- You will have tests done that will determine how "loose" the joints of your ankles and feet are.

Ankle and Toe Strength:

- You will have your ankle and toes strength tested 3 times. The tester will use a device held in their hand that records how hard you can push using your ankle. These motions are: pulling your foot toward yourself, pointing your foot away from yourself, turning your foot inward, turning your foot outward, and curling your toes.

Joint Mobilization Arm – Ankle Sprain and Chronic Ankle Instability

Standing Lunge, Heel Raise, and Walking Testing:

- You will have sensors attached to your skin with tape that will passively record how your bones move.
- With the sensors on, your foot and ankle will be recorded during the following conditions
    - Standing lunge
    - While performing a heel raise on one foot, while touching the back of a chair to assist in balance
    - Walking across a 20-foot platform
    -

Ultrasound Measurements of the Muscles of the Hip, Ankle and Foot

- Water-soluble ultrasound gel will be placed on your skin on your hip, lower leg and the bottom of your feet.
- The ultrasound transducer will be placed on the skin where the gel was placed, and that will display the muscle thickness images on the ultrasound computer screen.

TREATMENT 1

Following baseline measurements, a separate researcher who is a board certified orthopaedic physical therapist with 14 years of experience and unaware of your baseline measurements will perform a clinical assessment of your foot. If you are found to have joint stiffness on clinical exam, you will be randomly assigned (like the flip of a coin) to 1 of 2 study treatment groups. You have an equal chance of being assigned to any one of the groups. You cannot choose which treatment you are assigned.

If you do not have joint stiffness, will be instructed in a home exercise program consisting of single limb balancing, foot and calf stretches that we will ask you to perform daily, three times throughout the day. You will be asked to return in 14 days for follow up measurements which is described under VISIT 3 on this consent form.

GROUP 1: Experimental group
GROUP 2: Control group

Experimental Group:

The experimental group will receive two joint mobilizations, a commonly used treatment to increase motion and decrease stiffness, to the midfoot. Following the joint mobilization, you will be instructed in a home exercise program consisting of single limb balancing, foot and calf stretches that we will ask you to perform three times throughout the day. You will be asked to come back 7-10 days later for a second treatment consisting of the same joint mobilizations. The home exercises will be reviewed as well to ensure technique is performed correctly.

Control Group:

The control group will be instructed in a home exercise program consisting of single limb balancing, foot and calf stretches that we will ask you to perform three times throughout the day.

IMMEDIATELY FOLLOWING TREATMENT 1

Following treatment and/or instruction in the home exercises, both groups will be asked by the researcher to mark a line with your current pain. Additionally, you will be asked to rate the change (if any) of your symptoms on a scale of 0 to 100 following the treatment.

Both groups will undergo all of the baseline measurements once more.
Both groups are asked to return in 7-10 days for a second visit.

VISIT 2 (will take about 2 hours to complete)

BASELINE MEASUREMENTS (Experimental and Control Groups)

Ankle Questionnaires:

- You will be asked to mark a line used to represent your current pain level
- A questionnaire asking about your general health as it relates to your ankle injury
- A questionnaire asking about your current physical activity level
- Two questionnaires asking about your ankle function
- A questionnaire asking about changes in your symptoms

Foot Alignment:

- You will have your foot alignment measured in sitting and standing positions. The measurements will be recorded
- The shape of your foot will be observed and recorded

Range of motion:

- Your foot and ankle motion will be measured. These motions are: pulling your foot toward yourself, pointing your foot away from yourself, turning your foot inward, turning your foot outward, and how far up and down does your great toe move.

Balance

- You will be asked to stand on one leg and reach with your non-stance foot as far as possible in 3 directions

Foot and Ankle Laxity:

- You will have tests done that will determine how "loose" the joints of your ankles and feet are.

Ankle and Toe Strength:

- You will have your ankle and toes strength tested 3 times. The tester will use a device held in their hand that records how hard you can push using your ankle. These motions are: pulling your foot toward yourself, pointing your foot away from yourself, turning your foot inward, turning your foot outward, and curling your toes.

Joint Mobilization Arm – Ankle Sprain and Chronic Ankle Instability

Standing Lunge, Heel Raise, and Walking Testing:

- You will have sensors attached to your skin that will passively record how your bones move.
- With the sensors on, your foot and ankle will be recorded during the following conditions
  - Standing lunge
  - While performing a heel raise on one foot, while touching the back of a chair to assist in balance
  - Walking across a 20-foot platform

Ultrasound Measurements of the Muscles of the Hip, Ankle and Foot

- Water-soluble ultrasound gel will be placed on your skin on your hip, lower leg and the bottom of your feet.
- The ultrasound transducer will be placed on the skin where the gel was placed, and that will display the muscle thickness images on the ultrasound computer screen.

FOLLOWING BASELINE MEASUREMENTS (Control Group only)

The control group's participation in this study is complete. No further visits or procedure will take place.

TREATMENT 2 (Experimental Group only)

Following baseline measurements, a separate researcher who is a board certified orthopaedic physical therapist with 14 years of experience and unaware of your baseline measurements will repeat the same two joint mobilizations performed on visit 1. Following the joint mobilization, we will review the home exercise program to ensure technique is performed correctly.

Following treatment and review of the home exercises, you will be asked by the researcher to mark a line with your current pain. Additionally, you will be asked to rate the change (if any) of your symptoms on a scale of 0 to 100 following the treatment.

You will complete the same baseline measurements as before treatment once more.
You will be asked to return in 7-10 days for the final visit.

VISIT 3 (will take about 1.5 hours to complete)

BASELINE (Experimental Group and Participants from VISIT 1 who did not have stiffness)

Ankle Questionnaires:

- You will be asked to mark a line used to represent your current pain level
- A questionnaire asking about your general health as it relates to your ankle injury
- A questionnaire asking about your current physical activity level
- A questionnaire asking about your thoughts on your injury
- Two questionnaires asking about your ankle function
- A questionnaire asking about changes in your symptoms

Joint Mobilization Arm – Ankle Sprain and Chronic Ankle Instability

Foot Alignment:

- You will have your foot alignment measured in sitting and standing positions. The measurements will be recorded
- The shape of your foot will be observed and recorded

Range of motion:

- Your foot and ankle motion will be measured. These motions are: pulling your foot toward yourself, pointing your foot away from yourself, turning your foot inward, turning your foot outward, and how how far up and down does your great toe move.

Balance

- You will be asked to stand on one leg and reach with your non-stance foot as far as possible in 3 directions

Foot and Ankle Laxity:

- You will have tests done that will determine how "loose" the joints of your ankles and feet are.

Ankle and Toe Strength:

- You will have your ankle and toes strength tested 3 times. The tester will use a device held in their hand that records how hard you can push using your ankle. These motions are: pulling your foot toward yourself, pointing your foot away from yourself, turning your foot inward, turning your foot outward, and curling your toes.

Standing Lunge, Heel Raise, and Walking Testing:

- You will have sensors attached to your skin that will passively record how your bones move.
- With the sensors on, your foot and ankle will be recorded during the following conditions
    - Standing lunge
    - While performing a heel raise on one foot, while touching the back of a chair to assist in balance
    - Walking across a 20-foot platform

Ultrasound Measurements of the Muscles of the Hip, Ankle and Foot

- Water-soluble ultrasound gel will be placed on your skin on your hip, lower leg and the bottom of your feet.
- The ultrasound transducer will be placed on the skin where the gel was placed, and that will display the muscle thickness images on the ultrasound computer screen.

FOLLOWING BASELINE TESTING

Your participation in this study is complete. There will be no further testing or visits.

What are your responsibilities in the study?

You have certain responsibilities to help ensure your safety.

These responsibilities are listed below:

- You must come to each study visit.
- You must be completely truthful about your health history.
- Follow all instructions given.
- You should tell the study doctor or study staff about any changes in your health or the way you feel.
- Answer all of the study-related questions completely.

How long will this study take?

Experimental Group: Your participation in this study will require 3 separate visits over a 2 week period of time. Each visit will last about 2 hours.

Control Group and Participants without stiffness: Your participation in this study will require 2 separate visits over a 2 week period of time. Each visit will last about 2 hours.

If you want to know about the results before the study is done:

During the study you are having an investigational test done. The purpose of the test is not to diagnose any disease or abnormality you may have. Because the test is investigational there is no way for the study leader to understand if the results are "normal" or "abnormal". However, if any test results are concerning, your study leader will let you know.

In addition, as the research moves forward, your study leader will keep you informed of any new findings about the research itself that may be important for your health or may help you decide if you want to continue in the study. The final results of the research will not be known until all the information from everyone is combined and reviewed. At that time, you can ask for more information about the study results.

What are the risks of being in this study?

Risks and side effects related to the procedures and interventions include:

Likely

- Mild joint soreness associated with the mobilization intervention
- Mild muscle soreness of associated with the exercises

There is a small risk that breaches of privacy and/or confidentiality might occur. The risk of violation of subject privacy and confidentiality is minimal due to the requirements of the privacy plan in this protocol.

Other unexpected risks:

You may have side effects that we do not expect or know to watch for now. Call the study leader if you have any symptoms or problems.

Could you be helped by being in this study?

We cannot promise that you will be helped by being in this study. You may benefit from being in this study. Possible benefits include: decreased symptoms, improved mechanics, and restoration of joint motion. In addition, information researchers get from this study may help others in the future.

What are your other choices if you do not join this study?

The only choice is not to be in this study. If you are a patient at UVa your usual care will not be affected if you decide not to participate in this study. If you are an employee of UVa your job will not be affected if you decide not to participate in this study. If you are a student at UVa, your grades will not be affected if you decide not to participate in this study.

Will you be paid for being in this study?

Payment for participation will be paid a total of $20 at study completion.

You should receive payment about 2-6 weeks following the final visit of your participation. The payment for participation is reportable to the IRS as income.

If you owe money to the University of Virginia or the University of Virginia Medical Center, the money to be paid to you in this study can be withheld to pay what you owe. If a court has issued a judgment against you, the money may also be withheld to pay the judgment creditor for such things as taxes, fines, or child support that you owe.

Will being in this study cost you any money?

All of the procedures in this study will be provided at no cost to you or your health insurance. You will be responsible for the cost of travel to come to any study visit and for any parking costs.

What if you are hurt in this study?

If you are hurt as a result of being in this study, there are no plans to pay you for medical expenses, lost wages, disability, or discomfort. The charges for any medical treatment you receive will be billed to your insurance. You will be responsible for any amount your insurance does not cover. You do not give up any legal rights, such as seeking compensation for injury, by signing this form.

What happens if you leave the study early?

You can change your mind about being in the study any time. You can agree to be in the study now and change your mind later. If you decide to stop, please tell us right away. You do not have to be in this study to get services you can normally get at the University of Virginia.

Even if you do not change your mind, the study leader can take you out of the study. Some of the reasons for doing so may include

a) You become injured and can no longer participate in the study
b) The principal investigator closes the study for safety, administrative or other reasons

How will your personal information be shared?

The UVa researchers are asking for your permission to gather, use and share information about you for this study. If you decide not to give your permission, you cannot be in this study, but you can continue to receive regular medical care at UVA.

If you sign this form, we may collect any or all of the following information about you:

- Personal information such as name, address and date of birth

Who will see your private information?

- The researchers to make sure they can conduct the study the right way, observe the effects of the study and understand its results
- People or groups that oversee the study to make sure it is done correctly

Some of the people outside of UVa who will see your information may not have to follow the same privacy laws that we follow. They may release your information to others, and it may no longer be protected by those laws.

The information collected from you might be published in a medical journal. This would be done in a way that protects your privacy. No one will be able to find out from the article that you were in the study.

What if you sign the form but then decide you don't want your private information shared?

You can change your mind at any time. Your permission does not end unless you cancel it. To cancel it, please send a letter to the researchers listed on this form. Then you will no longer be in the study. The researchers will still use information about you that was collected before you ended your participation.

Please contact the researchers listed below to:

- Obtain more information about the study
- Ask a question about the study procedures or treatments
- Report an illness, injury, or other problem (you may also need to tell your regular doctors)
- Leave the study before it is finished
- Express a concern about the study

Jay Hertel, PhD ATC
University of Virginia
210 Emmet St South
Charlottesville, VA 22904
434-243-8673

What if you have a concern about a study?

You may also report a concern about a study or ask questions about your rights as a research subject by contacting the Institutional Review Board listed below.

University of Virginia Institutional Review Board for Health Sciences Research
PO Box 800483
Charlottesville, Virginia 22908
Telephone: 434-924-9634

When you call or write about a concern, please give as much information as you can. Include the name of the study leader, the IRB-HSR Number (at the top of this form), and details about the problem. This will help officials look into your concern. When reporting a concern, you do not have to give your name

Signatures

What does your signature mean?

Before you sign this form, please ask questions about any part of this study that is not clear to you. Your signature below means that you have received this information and all your questions have been answered. If you sign the form it means that you agree to join the study. You will receive a copy of this signed document.

Consent From Adult

____________________	____________________	________
PARTICIPANT (SIGNATURE)	PARTICIPANT (PRINT)	DATE

Consent From Impartial Witness

I agree the information in this informed consent form was presented orally in my presence to the subject and the subject had the opportunity to ask any questions he/she had about the study. I also agree that the subject freely gave their informed consent to participate in this trial.

____________________	____________________	________
IMPARTIAL WITNESS (SIGNATURE)	IMPARTIAL WITNESS (PRINT)	DATE

Joint Mobilization Arm – Ankle Sprain and Chronic Ankle Instability

Person Obtaining Consent

By signing below you confirm that you have fully explained this study to the potential subject, allowed them time to read the consent or have the consent read to them, and have answered all their questions.

______________________	______________________	________
PERSON OBTAINING CONSENT (SIGNATURE)	PERSON OBTAINING CONSENT (PRINT)	DATE

Global Health

Please respond to each item by marking one box per row.

		Excellent	Very good	Good	Fair	Poor
Global01	In general, would you say your health is:	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
Global02	In general, would you say your quality of life is:	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
Global03	In general, how would you rate your physical health?	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
Global04	In general, how would you rate your mental health, including your mood and your ability to think?..	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
Global05	In general, how would you rate your satisfaction with your social activities and relationships?	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1
Global09	In general, please rate how well you carry out your usual social activities and roles. (This includes activities at home, at work and in your community, and responsibilities as a parent, child, spouse, employee, friend, etc.)..................	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

		Completely	Mostly	Moderately	A little	Not at all
Global06	To what extent are you able to carry out your everyday physical activities such as walking, climbing stairs, carrying groceries, or moving a chair?...	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

In the past 7 days…

		Never	Rarely	Sometimes	Often	Always
Global10	How often have you been bothered by emotional problems such as feeling anxious, depressed or irritable?	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

		None	Mild	Moderate	Severe	Very severe
Global08	How would you rate your fatigue on average?	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

Global07	How would you rate your pain on average?	☐ 0 No pain	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	☐ 6	☐ 7	☐ 8	☐ 9	☐ 10 Worst imaginable pain

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

Tampa Scale of Kinesiophobia (TSK-11)

For each of the statements below, please indicate how much you agree or disagree in regards to your current injury. Please use the following scale:

1	2	3	4
Strongly disagree	Somewhat disagree	Somewhat agree	Strongly agree

I'm afraid that I might injure myself if I exercise	1	2	3	4
If I were to overcome it, my pain would increase	1	2	3	4
My body is telling me I have something dangerously wrong	1	2	3	4
People aren't taking my medical condition seriously enough	1	2	3	4
My accident has put my body at risk for the rest of my life	1	2	3	4
Pain always means I have injured my body	1	2	3	4
Simply being careful that I do not make any unnecessary movements is the safest thing I can do to prevent my pain from worsening	1	2	3	4
I wouldn't have this much pain if there wasn't something potentially dangerous going on in my body	1	2	3	4
Pain lets me know when to stop exercising so that I don't injure myself	1	2	3	4
I can't do all the things normal people do because it's too easy for me to get injured	1	2	3	4
No one should have to exercise when he/she is in pain	1	2	3	4

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. ☐

Foot and Ankle Ability Measure (FAAM)

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

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

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

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

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

☐☐☐.0 %

FAAM Sports Scale

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

	No difficulty at all	Slight difficulty	Moderate difficulty	Extreme difficulty	Unable to do	N/A
Running	□	□	□	□	□	□
Jumping	□	□	□	□	□	□
Landing	□	□	□	□	□	□
Starting and stopping quickly	□	□	□	□	□	□
Cutting/lateral movements	□	□	□	□	□	□
Low impact activities	□	□	□	□	□	□
Ability to perform activity with your normal technique	□	□	□	□	□	□
Ability to participate in your desired sport as long as you would like	□	□	□	□	□	□

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

□□□.0 %

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

□ Normal □ Nearly normal □ Abnormal □ Severely abnormal

Healthy & Coper Participant Inclusion Checklist

	YES	NO	
Is the participant between the age of 18-50?			
Does the participant perform some form of physical activity for at least 20 min per day, three times per week?			Godin __________
Do they have a history of ankle or foot injury?			FAAM ADL ≥ 99 Sport ≥97 IdFAI ________________
If they have had a ankle or foot injury, has it been longer than one year?			
Do they have a self-reported disability due to lower extremity pathology that may adversely affect neuromuscular function?			
Do they have a history of ankle or foot fracture?			
Do they have a history of a prior ankle or foot surgery?			
Do they have a Neurological or vestibular disorders affecting balance?			
Do they have diabetes mellitus?			
Do they have Lumbosacral radiculopathy?			
Is the participant pregnant?			(Females only)
Do they have a Soft tissue disorders including Marfan's syndrome and Ehlers-Dandros syndrome?			
Do they have any absolute contraindications to manual therapy?			

LAS/CAI Inclusion Checklist

	YES	NO		
Is the participant between the age of 18-50?				
Does the participant perform some form of physical activity for at least 20 min per day, three times per week?			Godin __________	
Do they have a history of ankle or foot injury?				
How long ago was their last sprain?	2-6wks	1yr+		
Do they have lingering symptoms?			IdFAI ________ FAAM ADL __________ Sport _________	CAI if: IdFAI > 10 FAAM ≤ 90% FAAM-S ≤ 85%
Do they have a self-reported disability due to lower extremity pathology that may adversely affect neuromuscular function?				
Is the participant currently receiving care from Orthopaedics, Physical Therapy, or Sports Medicine?				
Do they have a history of a prior ankle or foot surgery?				
Do they have a history of ankle or foot fracture?				
Do they have a Neurological or vestibular disorders affecting balance?				
Do they have diabetes mellitus?				
Do they have Lumbosacral radiculopathy?				
Is the participant pregnant?			(Females only)	
Do they have a Soft tissue disorders including Marfan's syndrome and Ehlers-Dandros syndrome?				
Do they have any absolute contraindications to manual therapy?				

Subject ID _____________ Tester ID ______ Date ___________ Limb Assessed **RT** _____ **LT**______

Checklist (Arm 2, Visit 1)

Step		PreTx	PostTx
1	**Pre Screening**		
2	**Consent**		
3	**Self Reported Questionnaires** • PROMIS • Godin • TSK-11 • IdFAI • FAAM-ADL • FAAM-Sport		
4	**Healthy Participant Inclusion Checklist**		
5	**Demographic/Intake Sheet**		
6, 13	**Data Collection – Clinical Measures**		
7, 12	**Data Collection – Ultrasound Measures** Abductor Hallucis, Flexor Digitorum Brevis, Flexor Hallucis Brevis, Fibularis Longus/Brevis, Gluteus Medius Cross Section Measurements • Resting • Active • Resisted		
9, 11	**Data Collection – Motion Capture (10 trials)** • Standing lunge • Heel Raise • Gait		

10	**Manipulation Checklist** • Tx rendered • HEP instructed	

Subject ID ______________ Tester ID ______ Date ____________ Limb Assessed **RT** _____ **LT**______

Checklist [Arm 2, Visit 2 (7 days)]

Step		PreTx	PostTx
1	**Self Reported Questionnaires** • PROMIS • Godin • FAAM-ADL • FAAM-Sport • GROC		
2, 8	**Data Collection – Clinical Measures**		
3, 7	**Data Collection – Ultrasound Measures** Abductor Hallucis, Flexor Digitorum Brevis, Flexor Hallucis Brevis, Fibularis Longus/Brevis, Gluteus Medius Cross Section Measurements • Resting • Active • Resisted		
4, 6	**Data Collection – Motion Capture (10 trials)** • Standing lunge • Heel Raise • Gait		

5	**Manipulation Checklist** • Tx rendered • HEP instructed	

Subject ID ______________ Tester ID ______ Date ____________ Limb Assessed **RT** _____ **LT**______

Checklist [Arm 2, Final Reassessment (2 weeks)]

Step		
1	**Self-Reported Questionnaires** • PROMIS • Godin • TSK-11 • FAAM-ADL • FAAM-Sport • GROC **Single Assessment Numeric Evaluation (SANE)** "As a result of the treatment, do you feel better, worse or the same? With 0 being no change and 100% being full recovery, how much better/worse do you feel?" ___________%	
2	**Data Collection – Clinical Measures**	
3	**Data Collection – Ultrasound Measures** Abductor Hallucis, Flexor Digitorum Brevis, Flexor Hallucis Brevis, Fibularis Longus/Brevis, Gluteus Medius Cross Section Measurements • Resting • Active • Resisted	
4	**Data Collection – Motion Capture (10 trials)** • Standing lunge • Heel Raise • Gait	

Subject ID _____________ Tester ID ______ Date ___________ Limb Assessed **RT** _____ **LT**______

Checklist (Arm 2, Visit 1)

Step		PreTx	PostTx
1	**Pre Screening**		
2	**Consent**		
3	**Self Reported Questionnaires** • PROMIS • Godin • TSK-11 • IdFAI • FAAM-ADL • FAAM-Sport		
4	**Healthy Participant Inclusion Checklist**		
5	**Demographic/Intake Sheet**		
6, 13	**Data Collection – Clinical Measures**		
7, 12	**Data Collection – Ultrasound Measures** Abductor Hallucis, Flexor Digitorum Brevis, Flexor Hallucis Brevis, Fibularis Longus/Brevis, Gluteus Medius Cross Section Measurements • Resting • Active • Resisted		
9, 11	**Data Collection – Motion Capture (10 trials)** • Standing lunge • Heel Raise • Gait		

10	**Manipulation Checklist** • Tx rendered • HEP instructed	

Subject ID ______________ Tester ID ______ Date ____________ Limb Assessed **RT** _____ **LT**______

Checklist [Arm 2, Visit 2 (7 days)]

Step		PreTx	PostTx
1	**Self Reported Questionnaires** • PROMIS • Godin • FAAM-ADL • FAAM-Sport • GROC		
2, 8	**Data Collection – Clinical Measures**		
3, 7	**Data Collection – Ultrasound Measures** Abductor Hallucis, Flexor Digitorum Brevis, Flexor Hallucis Brevis, Fibularis Longus/Brevis, Gluteus Medius Cross Section Measurements • Resting • Active • Resisted		
4, 6	**Data Collection – Motion Capture (10 trials)** • Standing lunge • Heel Raise • Gait		

5	**Manipulation Checklist** • Tx rendered • HEP instructed	

Subject ID ______________ Tester ID ______ Date ___________ Limb Assessed **RT** _____ **LT**______

Checklist [Arm 2, Final Reassessment (2 weeks)]

<table>
<tr><td>Step</td><td></td><td></td></tr>
<tr><td>1</td><td>Self-Reported Questionnaires
PROMIS
Godin
TSK-11
FAAM-ADL
FAAM-Sport
GROC
<u>Single Assessment Numeric Evaluation (SANE)</u>

“As a result of the treatment, do you feel better, worse or the same? With 0 being no change

and 100% being full recovery, how much better/worse do you feel?” ___________%</td><td></td></tr>
<tr><td>2</td><td>Data Collection – Clinical Measures</td><td></td></tr>
<tr><td>3</td><td>Data Collection – Ultrasound Measures
Abductor Hallucis, Flexor Digitorum Brevis, Flexor Hallucis Brevis, Fibularis Longus/Brevis, Gluteus Medius

Cross Section Measurements
Resting
Active
Resisted</td><td></td></tr>
<tr><td>4</td><td>Data Collection – Motion Capture (10 trials)
Standing lunge
Heel Raise
Gait</td><td></td></tr>
</table>

Subject ID _____________ Tester ID ______ Date ___________ Limb Assessed **RT** _____ **LT**______

Pre Treatment Passive Joint Mobility Assessment

Is there hypomobility in the proximal tibiofibular joint during active dorsiflexion? Yes No

0 Ankylosed	1 Extremely Hypomobile	2 Slightly Hypomobile	3 Normal Mobility	4 Slightly Hypermobile	5 Extremely Hypermobile	6 Unstable

Distal tibiofibular	Posterior glide	
Talocrural (Rearfoot on shank)	Anterior glide	
	Posterior glide	
	External rotation	
	Internal rotation	
Subtalar (Rearfoot on shank)	Inversion	
	Eversion	
	Medial Glide	
	Lateral Glide	

Midfoot (Forefoot on Rearfoot)	Inversion	
	Eversion	
	ABDuction	
	ADDuction	
1st TMT (MT on Midfoot)	Dorsal glide	
	Plantar glide	
1st MTP (Hallux on MT)	Dorsal glide	
	Plantar glide	

Mobilization	**Forefoot Inversion**		**TMT 1**	
Was there hypomobility in the midfoot upon presentation?	Yes	No	Yes	No
Was a mobilization performed?	Yes	No	Yes	No
Was there a cavitation during the mobilization?	Yes	No	Yes	No
If no, was a repeat mobilization performed?	Yes	No	Yes	No
Was there a cavitation on the second mobilization?	Yes	No	Yes	No

Initial Visit

Was the patient instructed in the home exercise program? Yes No

Was the patient given a handout? Yes No

Was the patient able to verbalize or demonstrate understanding? Yes No

Follow-up

Was the patient able to demonstrate HEP using appropriate technique? Yes No

What percentage of the time did the patient report performing the HEP? ________%

Subject ID _____________ Tester ID ______ Date ___________ Limb Assessed **RT** _____ **LT**______

Single Assessment Numeric Evaluation (SANE)

"As a result of the treatment, do you feel better, worse or the same? With 0 being no change and 100% being full recovery, how much better/worse do you feel?" ___________%

Post-Treatment Passive Joint Mobility Assessment

Is there hypomobility in the proximal tibiofibular joint during active dorsiflexion? Yes No

0 Ankylosed	1 Extremely Hypomobile	2 Slightly Hypomobile	3 Normal Mobility	4 Slightly Hypermobile	5 Extremely Hypermobile	6 Unstable

Distal tibiofibular	Posterior glide	
Talocrural (Rearfoot on shank)	Anterior glide	
	Posterior glide	
	External rotation	
	Internal rotation	
Subtalar (Rearfoot on shank)	Inversion	
	Eversion	
	Medial Glide	
	Lateral Glide	

Midfoot (Forefoot on Rearfoot)	Inversion	
	Eversion	
	ABDuction	
	ADDuction	
1st TMT (MT on Midfoot)	Dorsal glide	
	Plantar glide	
1st MTP (Hallux on MT)	Dorsal glide	
	Plantar glide	

Subject ID ______________ Tester ID ______ Date ____________ Limb Assessed **RT** _____ **LT**______

Pre-Treatment

Intrinsic Foot Muscle Test

☐ **Satisfactory**:
Neutral navicular height without over-activity of the extrinsics **consistent** throughout the 30-sec trial

☐ **Fair**:
Unsteadiness of the neutral navicular height and/or over-activity of the extrinsics are **inconsistently** observed during the 30-sec

☐ **Poor**:
Unsteadiness of the neutral navicular height and/or over-activity of the extrinsics are **consistently** observed during the 30-sec

Intrinsic (+) Test

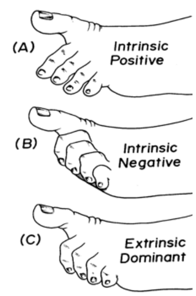
"While keeping the big toe straight, bend your lesser toes from the knuckle while keeping the tips straight."

☐

3 = Intrinsic (+) easily assumed and maintained

2 = Intrinsic (+) assumed with difficulty

1 = Demonstrates intrinsic (-) or extrinsic dominant pattern



Weight Bearing DF (cm) ☐

Star Excursion Balance Test

Anterior (cm)	1	
	2	
	3	
Posteromedial (cm)	1	
	2	
	3	
Posterolateral (cm)	1	
	2	
	3	

Goniometry (deg)

Ankle (On Shank)	DF	
	PF	
1st MTP	EXT	
	FLEX	
Calcaneal (On Shank)	INV	
	EV	

Inclinometry (deg)

		1	2	3
Forefoot (On Rearfoot)	INV			
	EV			

Linear Excursion (mm)

		1	2	3
1ST MT	DF			
	PF			

Handheld Dynamometry

	1	2	3
DF			
PF			
INV			
EV			
Lesser toe Flexion			
Great toe Flexion			

Dynamic Leap and Balance Test (DLBT)

_________ Errors

_________ sec Completion Time

VAS

How severe is your pain in the worst of the two ankles and/or feet at present?

Place a vertical mark on the line below to indicate how bad you feel your pain is at present.

No Pain ____ Very Severe Pain

How severe has your pain been in the worst of the two ankles and/or feet during the past week?

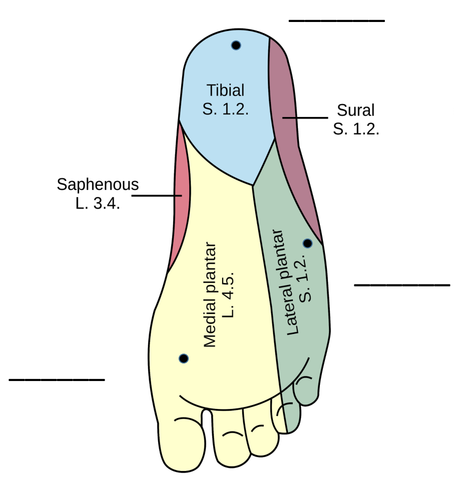
Place a vertical mark on the line below to indicate how bad you feel your pain has been during the past week.

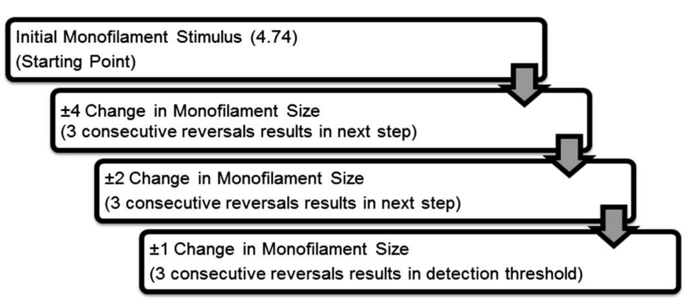
No Pain ____ Very Severe Pain

Palpation

	Yes	No
Pain to palpation of syndesmosis?		
If yes, how far proximal of the malleolar line does the pain extend (cm)?	cm	
Pain to palpation of the Deltoid ligament?		
Pain to palpation of ATFL?		
Pain to palpation of CFL?		
Pain to palpation of PTFL?		
Pain to palpation of Bifurcate ligament?		

Semmes-Weinstein Monofilament





Subject ID ______________ Tester ID ______ Date ____________ Limb Assessed **RT** _____ **LT**______

Post-Treatment

Foot Morphology Measures

	Unloaded	Loaded
Total Foot length (cm)		
Truncated Foot length (cm)		
Foot Width (mm)		
Dorsal Arch Height (50% total foot length, cm)		

Weight Bearing DF (cm) [ ]

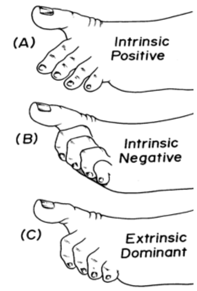
Intrinsic (+) Test

"While keeping the big toe straight, bend your lesser toes from the knuckle while keeping the tips straight."

3 = Intrinsic (+) easily assumed and maintained

2 = Intrinsic (+) assumed with difficulty

1 = Demonstrates intrinsic (-) or extrinsic dominant pattern



Intrinsic Foot Muscle Test

Satisfactory:
Neutral navicular height without over-activity of the extrinsics **consistent** throughout the 30-sec trial

Fair:
Unsteadiness of the neutral navicular height and/or over-activity of the extrinsics are **inconsistently** observed during the 30-sec

Poor:
Unsteadiness of the neutral navicular height and/or over-activity of the extrinsics are **consistently** observed during the 30-sec

Star Excursion Balance Test

Anterior (cm)	1	
	2	
	3	
Posteromedial (cm)	1	
	2	
	3	
Posterolateral (cm)	1	
	2	
	3	

Goniometry (deg)

Ankle (On Shank)	DF	
	PF	
1st MTP	EXT	
	FLEX	
Calcaneal (On Shank)	INV	
	EV	

Inclinometry (deg)

		1	2	3
Forefoot (On Rearfoot)	INV			
	EV			

Linear Excursion (mm)

		1	2	3
1ST MT	DF			
	PF			

Handheld Dynamometry

	1	2	3
DF			
PF			
INV			
EV			
Lesser toe Flexion			
Great toe Flexion			

Dynamic Leap and Balance Test (DLBT)

_________ Errors

_________ sec Completion Time

Global Rating of Change

Please rate the overall condition of your injured body part or region
FROM THE TIME THAT YOU BEGAN TREATMENT UNTIL NOW
(Check only one)

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

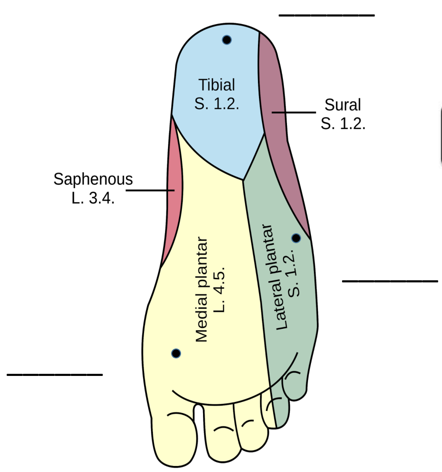
VAS

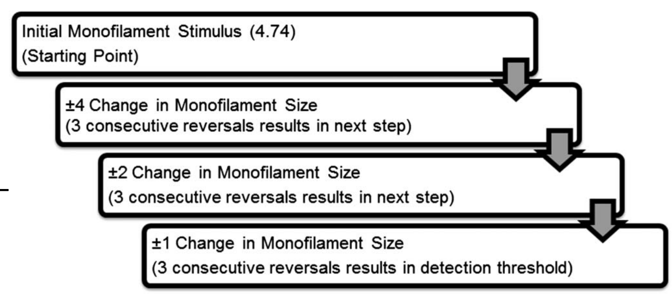
How severe is your pain in the worst of the two ankles and/or feet at present?

Place a vertical mark on the line below to indicate how bad you feel your pain is at present.

No Pain ______________________________ Very Severe Pain

Semmes-Weinstein Monofilament





Subject ID _____________ Tester ID ______ Date ___________ Limb Assessed **RT** _____ **LT**______

<u>VAS</u>

How severe is your pain in the worst of the two ankles and/or feet at present?

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No Pain ____ Very Severe Pain

How severe has your pain been in the worst of the two ankles and/or feet during the past week?

Place a vertical mark on the line below to indicate how bad you feel your pain has been during the past week.

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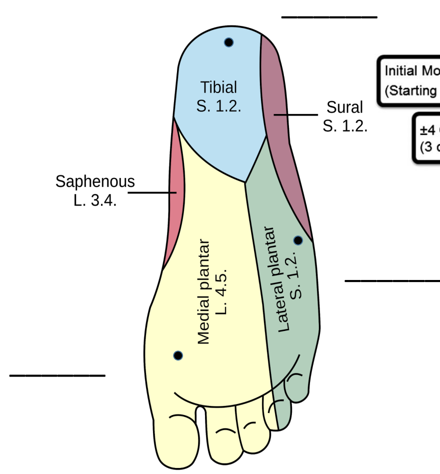
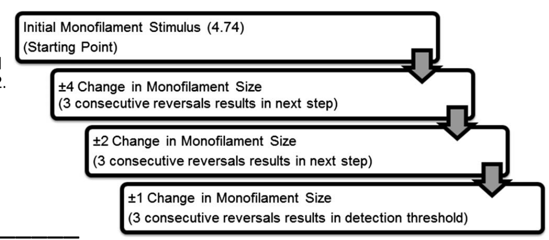
<u>Palpation</u>

	Yes	**No**
Pain to palpation of syndesmosis?		
If yes, how far proximal of the malleolar line does the pain extend (cm)?	cm	
Pain to palpation of the Deltoid ligament?		
Pain to palpation of ATFL?		
Pain to palpation of CFL?		
Pain to palpation of PTFL?		
Pain to palpation of Bifurcate ligament?		

<u>Semmes-Weinstein Monofilaments</u>





<u>Global Rating of Change</u>

Please rate the overall condition of your injured body part or region
FROM THE TIME THAT YOU BEGAN TREATMENT UNTIL NOW
(Check only one)

(+7) A very great deal better
(+6) A great deal better
(+5) Quite a bit better
(+4) Moderately better
(+3) Somewhat better
(+2) A little bit better
(+1) A tiny bit better

About the same
(0)

A very great deal worse (-7)
A great deal worse (-6)
Quite a bit worse (-5)
Moderately worse (-4)
Somewhat worse (-3)
A little bit worse (-2)
A tiny bit worse (-1)

Foot Morphology Measures

	Unloaded	Loaded
Total Foot length (cm)		
Truncated Foot length (cm)		
Foot Width (mm)		
Dorsal Arch Height (50% total foot length, cm)		

Weight Bearing DF (cm) ______

Intrinsic (+) Test

"While keeping the big toe straight, bend your lesser toes from the knuckle while keeping the tips straight."

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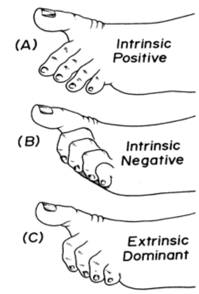

Intrinsic Foot Muscle Test

	<u>**Satisfactory**</u>: **Neutral navicular** height without over-activity of the extrinsics **consistent** throughout the 30-sec trial
	<u>**Fair**</u>: **Unsteadiness** of the neutral navicular height and/or over-activity of the extrinsics are **inconsistently** observed during the 30-sec
	<u>**Poor**</u>: **Unsteadiness** of the neutral navicular height and/or over-activity of the extrinsics are **consistently** observed during the 30-sec

Star Excursion Balance Test

Anterior (cm)	1	
	2	
	3	
Posteromedial (cm)	1	
	2	
	3	
Posterolateral (cm)	1	
	2	
	3	

Goniometry (deg)

Ankle (On Shank)	DF	
	PF	
1^{st} MTP	EXT	
	FLEX	
Calcaneal (On Shank)	INV	
	EV	

Inclinometry (deg)

		1	2	3
Forefoot (On Rearfoot)	INV			
	EV			

Linear Excursion (mm)

		1	2	3
1^{ST} MT	DF			
	PF			

Handheld Dynamometry

	1	2	3
DF			
PF			
INV			
EV			
Lesser toe Flexion			
Great toe Flexion			

<u>**Dynamic Leap and Balance Test (DLBT)**</u>

________ Errors

________ sec Completion Time