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Application of High-Speed Dual Fluoroscopy to Study In Vivo Tibiotalar and Subtalar Kinematics in Patients With Chronic Ankle Instability and Asymptomatic Control Subjects During Dynamic Activities

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Abstract

Background: Abnormal angular and translational (ie, kinematic) motion at the tibiotalar and subtalar joints is believed to cause osteoarthritis in patients with chronic ankle instability (CAI).

Methods: In this preliminary study the investigators quantified and compared in vivo tibiotalar and subtalar kinematics in 4 patients with CAI (3 women) and 10 control subjects (5 men) using dual fluoroscopy during a balanced, single-leg heel-rise and treadmill walking at 0.5 and 1.0 m/s.

Results: During balanced heel-rise, 69%, 54%, and 66% of mean CAI tibiotalar internal rotation/external rotation (IR/ER), subtalar inversion/eversion, and subtalar IR/ER angles, respectively, were outside the 95% confidence intervals of control subjects. During 0.5-m/s gait, 50% and 60% of mean CAI tibiotalar dorsi/plantarflexion and subtalar IR/ER angles, respectively, were outside the 95% confidence intervals of control subjects. During 1.0-m/s gait, 62%, 65%, and 73% of mean CAI subtalar dorsi/plantarflexion, inversion/eversion, and IR/ER, respectively, were outside the 95% confidence intervals of control subjects. Patients with CAI exhibited less tibiotalar and subtalar translational motion during gait; no clear differences in translations were noted during balanced heel-rise.

Conclusion: Overall, the balanced heel-rise activity exposed more tibiotalar and subtalar kinematic variation between patients with CAI and control subjects. Therefore, weight-bearing activities involving large range of motion, balance, and stability may be best for studying kinematic adaptations in patients with CAI.

Clinical Relevance: These preliminary results suggest that patients with CAI require more tibiotalar external rotation, subtalar eversion, and subtalar external rotation during weight-bearing stability exercises, all with less overall joint translation.

Keywords: chronic ankle instability, tibiotalar and subtalar kinematics, dual fluoroscopy, treadmill gait, heel-rise

Ankle sprains affect an estimated 32 000 Americans each day and are among the most common injuries during athletic and recreational activities.[8,17,21,36] Up to 40% of all acute ankle sprains progress to chronic ankle instability (CAI),[11,24] which involves persistent feelings of instability, ankle pain, and subsequent ankle sprains as well as difficulty walking on inclined or uneven surfaces.[7] CAI is clinically hypothesized to initiate ankle osteoarthritis (OA) by causing abnormal kinematics (ie, angles and translations) at the tibiotalar and subtalar joints, leading to premature wear of articular cartilage.[14,15,28,30,31] However, measurements of in vivo motion of the tibiotalar and subtalar joints are not available in patients with CAI. These data could clarify the mechanical characteristics of this condition and provide detailed arthrokinematics (ie, motion relative to the patient's underlying bony anatomy) to refine current treatment strategies.

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Traditional techniques used to quantify joint kinematics track the position of reflective markers adhered to the skin at bony landmarks. Despite widespread use, skin-marker motion capture is limited by errors associated with joint center estimations,[10] marker placement,[13] and soft tissue artifact[2,9] and cannot distinguish the independent roles of the tibiotalar and subtalar joints, as there are no reliable palpable landmarks for the placement of a skin marker about the talus. As a result, studies using traditional skin marker motion capture represent the ankle as a single joint and measure articulation of the shank relative to the heel.

Dual fluoroscopy (DF) is an imaging modality that allows 3-dimensional measurement of bone motion, thus providing calculations of angular and translational motion of multiple joints independent of one another. Using DF, prior studies have provided insight as to the functional roles of the tibiotalar and subtalar joints.[20,23] These studies have focused on tibiotalar and subtalar kinematics in healthy adults during overground gait, specifically the portion of the stance phase between heelstrike and heel-off. To our knowledge, the use of DF to study the kinematics of patients with CAI has been further limited to measuring the alignment of the tibiotalar joint at predefined positions in a quasi-static manner.[4,6,33] The combination of tibiotalar and subtalar joint kinematics has not been established during any type of dynamic activity in patients with CAI. Thus, in this study, we evaluated the feasibility of using DF to quantify ankle kinematics during dynamic loading in patients with CAI and asymptomatic control subjects.

Materials and Methods

Study Participants

After institutional review board approval and informed consent were obtained, 10 healthy volunteers were screened for gross ankle abnormalities and any history of back or lower limb surgery or pain (5 men and 5 women; mean age, 30.9 ± 7.2 years; mean body mass index [BMI], 23.6 ± 3.4 kg/m^2). In all subjects, standardized radiographic assessments were performed, including weight-bearing anteroposterior and lateral views of the foot, mortise view of the ankle, and hindfoot alignment view.[27] All radiographs were reviewed by an experienced and fellowship-trained foot and ankle surgeon (A.B.). Degenerative changes of the tibiotalar and subtalar joint were defined using the Kellgren-Lawrence scale.[16,19] Control subjects were screened for gross abnormalities and significant hindfoot OA (Kellgren-Lawrence score > 1). On the basis of these criteria, no control subjects were excluded. Additionally, patients with ankle pain, feelings of instability, and symptoms that limited exercise and activities of daily living were enrolled from one coauthor's (C.L.S.) clinic. Standard radiographic assessments were performed for the affected ankle of each recruited patient.

Patient 1 (CAI-01), a 32-year-old man (BMI 25.9 kg/m^2), presented with painful left lateral ankle instability with a positive anterior drawer test.[32] Conventional weight-bearing radiography and magnetic resonance imaging (MRI) confirmed the diagnosis. Conventional radiography demonstrated neutral hindfoot alignment and mild tibiotalar OA with small osteophytes on the talar and tibial side. MRI demonstrated complete disruption of the anterior talofibular ligament (ATFL) and calcaneofibular ligament (CFL), splitting of the peroneus brevis, presence of an accessory type 1 navicular, an osteochondral lesion in the posterolateral talar dome, and a loose body in the lateral ankle gutter.

Patient 2 (CAI-02), a 27-year-old woman (BMI 23.9 kg/m^2), presented with painful right lateral ankle instability with a positive anterior drawer test. Conventional weight-bearing radiography demonstrated neutral hindfoot alignment and no hindfoot OA. This patient elected not to undergo surgery; therefore, we did not obtain advanced imaging on this patient.

Patient 3 (CAI-03), a 36-year-old woman (BMI 30.4 kg/m^2), presented with painful right ankle instability with a positive anterior drawer test and substantial tenderness over the ATFL and CFL. Conventional weight-bearing radiography demonstrated neutral hindfoot alignment and no hindfoot OA. MRI demonstrated complete disruption of the ATFL, thickened and elongated CFL, partial lesion of the deltoid ligaments, and a small osteochondral lesion of the lateral talar dome.

Patient 4 (CAI-04), a 28-year-old woman (BMI 22.8 kg/m^2), presented with painful right ankle instability with a positive anterior drawer test and substantial tenderness over the lateral and anterolateral ankle. Conventional weight-bearing radiography demonstrated neutral hindfoot alignment and no hindfoot OA. MRI demonstrated chronic injury of the ATFL and CFL and anterolateral tibiotalar impingement due to the Bassett ligament.[1,29]

DF and Skin-Marker Motion Capture

A custom high-speed DF system validated to a mean rotational and translational bias of 0.25 ± 0.81° and 0.03 ± 0.35 mm, respectively, was used to measure tibiotalar and subtalar kinematics.[34] A 10-camera near-infrared motion analysis system (Vicon Motion Systems, Oxford, UK) was temporally and spatially synced with the DF system.[25,34] Reflective skin markers were applied to each subject prior to data capture per a modified Helen-Hayes configuration.[18] These reflective markers were used to track the position of the pelvis and bilateral thighs, shank, and foot segments in 3 dimensions.[18]

All subjects completed 3 activities: a single-leg balanced heel-rise, treadmill walking at 0.5 m/s, and treadmill walking at 1.0 m/s. Two trials were captured of each activity. All activities were performed barefoot. Subjects practiced each activity prior to data acquisition. The balanced heel-rise activity was selected because it likely requires coordination, balance, and stability. Additionally, similar heel-rise activities are used as clinical diagnosis tools.[22] During balanced heel-rise, subjects were instructed to perform the activity in a comfortable position at their desired speed to promote natural movement. DF images and tracking of skin-marker trajectories were acquired simultaneously throughout the entire heel-rise activity. Walking was chosen because it is a frequent activity of daily living. During treadmill walking, each subject was allowed to ambulate for at least 30 seconds prior to DF acquisition. Skin-marker trajectories were recorded starting several strides prior to and ending at least 1 stride after DF acquisition. For walking, subjects were not informed when data acquisition would begin.

The DF emitter beam energy settings were subject specific and determined prior to the dynamic imaging of each subject to optimize the quality of the fluoroscopic images. Beam energy settings ranged from 62 to 78 kVp and from 1.2 to 2.2 mA·s and depended on the size of the subject's bones and orientation of their foot within the DF field of view. DF images and skin marker motion data were acquired at 300 Hz as described previously.[25] The balanced heel-rise activity was captured in its entirety. The treadmill moved the foot out of the DF field of view prior to the completion of the gait cycle.[25] Thus, heelstrike and toe-off were imaged as separate trials and midstance was not captured in its entirety. The combination of the heelstrike and toe-off portions of the gait cycle that were imaged was referred to as "captured stance." The fluoroscopy time of each subject was limited to 60 seconds.

Computed Tomography and Model-Based Markerless Tracking

A computed tomographic (CT) scan of each control and CAI subject was acquired (SOMATOM Definition AS; Siemens Medical Solutions, Malvern, PA) from midtibia through toe tips at 1.0-mm slice thickness, 355 ± 59.2 mm^2 field of view, 512×512 acquisition matrix, 80 or 100 kVp, and 20 to 93 mA·s. The use of CT image segmentation and model-based markerless tracking required several steps (Figure 1). Briefly, the tibia, talus, and calcaneus of each subject were semiautomatically segmented from the respective CT images (Amira 5.5; Visage Imaging, San Diego, CA). Ray-traced projection through the CT volumes of these segmentations was used to generate digitally reconstructed radiographs of each bone. Model-based markerless tracking[3] was used to semiautomatically align the digitally reconstructed radiographs of each individual bone with the DF images from each time point. The combined DF and CT radiation exposure did not exceed 0.11 mSv, which was equivalent to 10 days of natural background radiation. This radiation exposure estimation was calculated on the basis of radiation doses from dosimeters implanted in phantoms[26]; the value of 0.11 mSv was anticipated to represent the maximum possible dose to the subject.

Data Analysis

Joint angles and translations during each activity were calculated as detailed previously.[25] Briefly, the CT segmentations of each bone were used to create 3-dimensional reconstructions of the tibia, talus, and calcaneus. Landmarks were identified on the 3-dimensional reconstructions of each bone and used to define subject-specific anatomic coordinate systems for the tibia, talus, and calcaneus. A weight-bearing neutral position was determined by using DF to align the tibia, talus, and calcaneus to their respective positions during midstance. The talus and calcaneus coordinate systems were then aligned with the tibia coordinate system but maintained their respective joint center locations.

Skin-marker data were used to determine gait events such as heelstrike and toe-off. Specifically, heelstrike was defined as the frame corresponding to the minimum height of the heel marker following a downward trajectory. Toe-off was defined as the frame corresponding to the minimum height of the toe marker prior to an upward trajectory. The duration of stance phase was determined as the time between heelstrike and toe-off and used to normalize each trial. All gait trials were aligned at either heelstrike (0% of normalized stance) or toe-off (100% of normalized stance). The balanced heel-rise activity was normalized and aligned across subjects using inflection points from the dorsi/plantarflexion (D/P) angles calculated between the calcaneus in relation to the tibia.[25]

The anatomic coordinate system of each bone was applied to the bone orientations and locations determined via markerless tracking and used to calculate dynamic tibiotalar and subtalar joint angles.[34] A fourth-order bidirectional low-pass Butterworth filter was applied to the dynamic joint angles and translations. A cutoff frequency of 10 Hz was selected using the residual analysis method of Winter.[35] Joint angles were reported as D/P, inversion/eversion (In/Ev), and internal rotation/external rotation (IR/ER). Dorsiflexion, eversion, and external rotation were considered positive. Joint translations were reported in the medial-lateral, anterior-posterior, and superior-inferior directions.[25]

The means and 95% confidence intervals (CIs) of joint angles and translations for the 2 trials of each activity were calculated across the 10 control subjects.[25] The 2 trials of each patient with CAI were averaged for each activity. For each activity, the mean trial of each patient with CAI was plotted against the means and 95% CIs of the control subjects for qualitative comparison. To facilitate comparison with the control subjects, the portion of each mean CAI trial that fell outside the 95% CIs was calculated and expressed

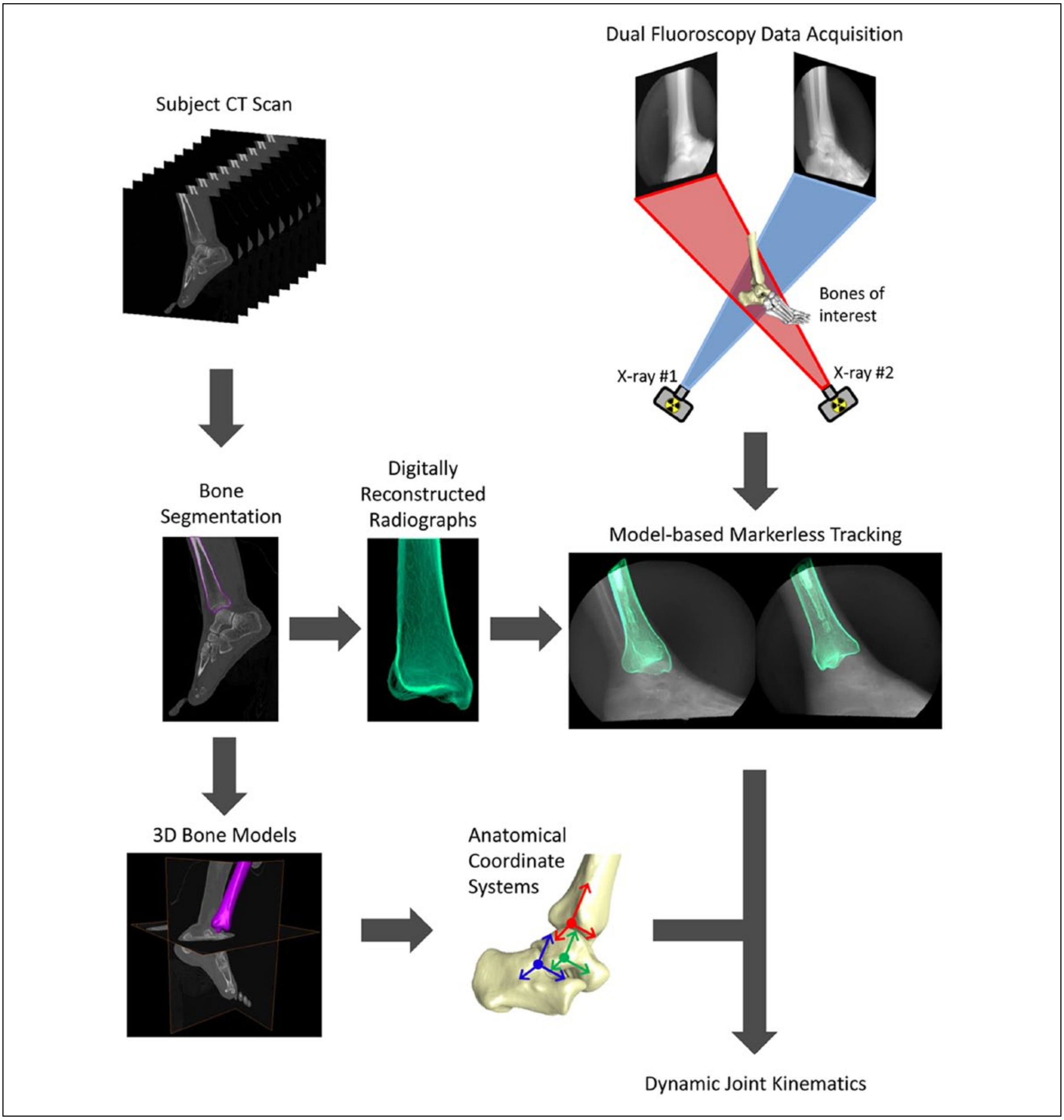

Figure 1. Flowchart of the methodologic approach. A computed tomographic (CT) scan was obtained of the subject's ankle and foot and segmented to create 3-dimensional (3D) reconstructions of the tibia, talus, and calcaneus bones. A digitally reconstructed radiograph was created from each segmented bone. Anatomical coordinate systems were defined for the tibia, talus, and calcaneus on the basis of landmarks visible on the 3D surfaces. Separately, dual fluoroscopic images were acquired. The dual fluoroscopic images and digitally reconstructed radiographs were used by model-based markerless tracking software to quantify the position and orientation of each bone. Bone positions and orientations were used to calculate angles and translations for the tibiotalar and subtalar joints.

as a percentage of the entire trial. For treadmill walking at 0.5 and 1.0 m/s, we evaluated the percentage of CAI joint angles that fell outside the 95% CIs of the control subjects during captured stance. We then calculated this analysis for the individual heelstrike and toe-off portions of gait. In doing so, we were able to investigate whether differences between patients with CAI and control subjects were more evident during ankle loading or unloading. We considered

CAI joint angles to be different compared with control subjects and reported these differences in the text, if a majority (≥50%) of CAI joint angles during balanced heel-rise, captured stance, or the heelstrike or toe-off portions of gait fell outside the 95% CIs of the control subjects. Finally, using a paired *t* test, we compared the percentage of CAI joint angles that fell outside the 95% CIs of the control subjects during captured stance to determine if there were statistically significant differences by joint, gait speed, or portion of gait (heelstrike or toe-off).

Tibiotalar and subtalar range of motion (ROM) was calculated for control subjects and patients with CAI for balanced heel-rise and 0.5 and 1.0 m/s captured stance as described previously.[25] For each joint and activity, the rotational and translational ROM of each patient with CAI was plotted relative to the mean and 95% CIs of the control subjects. The ROM for a patient with CAI was considered different if outside the 95% CIs of the control subjects.

Results

Balanced Heel-Rise

The mean ± SD time to complete the balanced heel-rise activity was 0.87 ± 0.20 seconds and 1.16 ± 0.19 seconds for control subjects and patients with CAI, respectively. During balanced heel-rise, the tibiotalar (Figure 2) and subtalar (Figure 3) joint angles of the patients with CAI were different than the control subjects and frequently exhibited opposing trends. Tibiotalar and subtalar IR/ER angles and subtalar In/Ev angles of the patients with CAI differed from the control subjects. Here, the mean percentages of CAI joint angles that fell outside the 95% CIs of the control subjects during balanced heel-rise were 69%, 54%, and 66%, for tibiotalar IR/ER, subtalar In/Ev, and subtalar IR/ER, respectively (Table 1). There were no statistically significant differences between the tibiotalar and subtalar joint angle percentages outside the 95% CIs of the control subjects during heel-rise.

Treadmill Walking

Although CAI tibiotalar joint angles often exhibited trends that were similar to the control subjects during captured stance CAI joint angles were not always within the 95% CIs of the control subjects (Figure 4). During captured stance, a majority of CAI tibiotalar D/P joint angles fell outside the 95% CIs of the control subjects at the 0.5-m/s walking speed (50%). Differences between the patients with CAI and control subjects were more notable when the heelstrike and toe-off portions of gait were compared separately. For the heelstrike portion of 1.0-m/s gait, a majority of CAI tibiotalar joint angles were outside the 95% CIs for In/Ev and IR/ER (63% and 58%, respectively) (Table 2). For the toe-off portion of 0.5 and 1.0 m/s gait, a majority of CAI

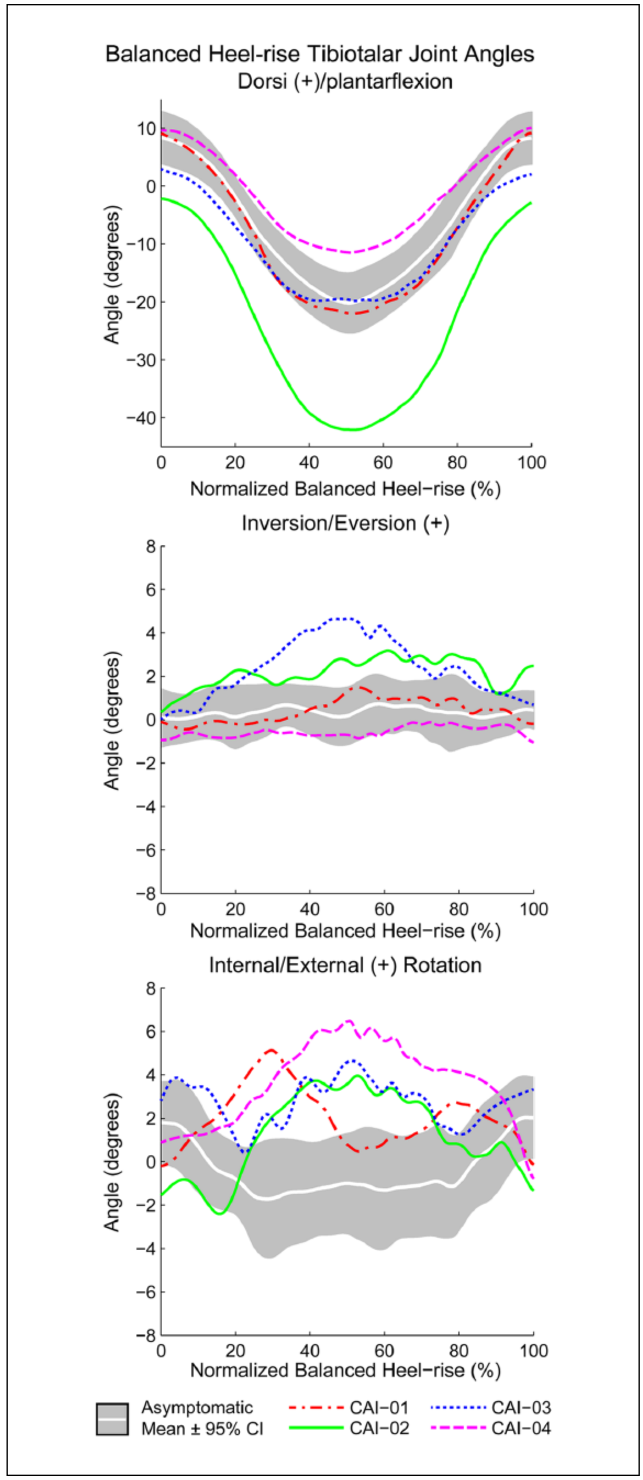

Figure 2. Tibiotalar dorsi (+)/plantarflexion (top), inversion/eversion (+) (middle), and internal rotation/external rotation (+) (bottom) mean joint angles of patients with chronic ankle instability (CAI) compared with asymptomatic control subjects during a single-leg balanced heel-rise activity. Data are plotted per normalized balanced heel-rise. The joint angles of the asymptomatic control subjects are presented as the mean (white line) ± 95% confidence interval (CI) (gray). Each line represents the mean joint angles of a different patient with CAI.

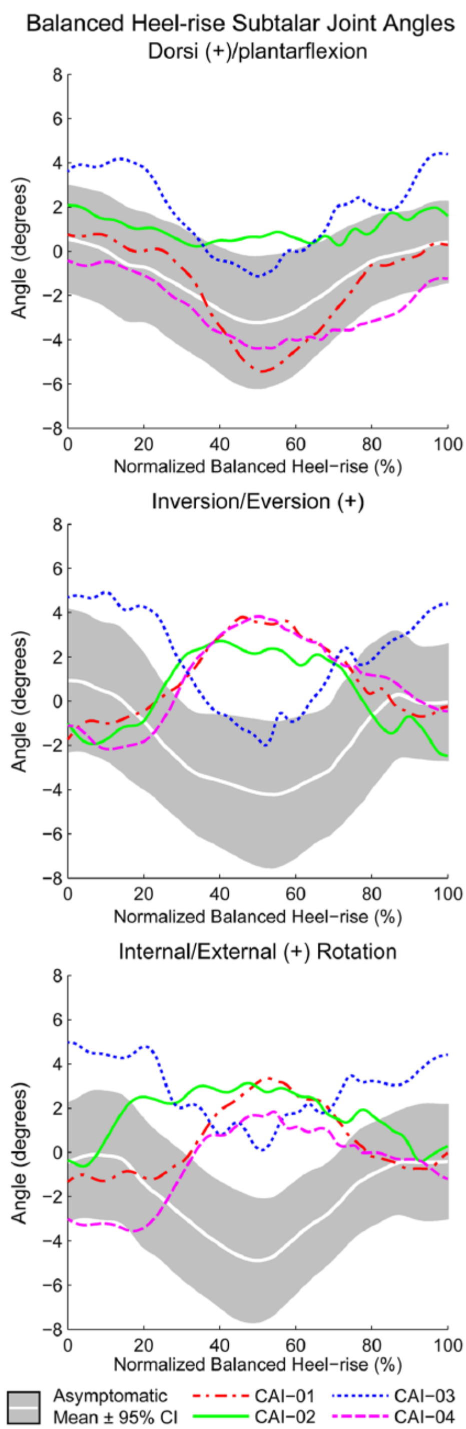

Figure 3. Subtalar dorsi (+)/plantarflexion (top), inversion/eversion (+) (middle), and internal rotation/external rotation (+) (bottom) mean joint angles of patients with chronic ankle instability (CAI) compared with asymptomatic control subjects during a single-leg balanced heel-rise activity. Data are plotted per normalized balanced heel-rise. The joint angles of the asymptomatic control subjects are presented as the mean (white line) ± 95% confidence interval (CI) (gray). Each line represents the mean joint angles of a different patient with CAI.

tibiotalar joint angles were outside the 95% CIs for D/P (73% and 50%, respectively) (Table 2).

Subtalar joint angles of the patients with CAI were often different compared with control subjects during captured stance (Figure 5). The most notable differences were observed in subtalar IR/ER during 0.5- and 1.0-m/s captured stance. During captured stance, a majority of CAI subtalar joint angles fell outside the 95% CIs of the control subjects for IR/ER at the 0.5-m/s walking speed (60%) and for D/P, In/Ev, and IR/ER at the 1.0-m/s speed (62%, 65%, and 73%, respectively). Differences in subtalar joint angles between patients with CAI and control subjects were most evident when the heelstrike and toe-off portions of gait were independently compared, particularly during toe-off. For the heelstrike portion of gait, a majority of CAI subtalar joint angles fell outside the 95% CIs of the control subjects for D/P, In/Ev, and IR/ER (77%, 81%, and 97%, respectively) at the 1.0-m/s speed (Table 3). During the toe-off portion of gait, a majority of CAI subtalar joint angles fell outside the 95% CIs of the control subjects for In/Ev and IR/ER at the 0.5-m/s speed (65% and 64%, respectively) and for D/P, In/Ev, and IR/ER at the 1.0-m/s speed (62%, 82%, and 91%, respectively) (Table 3).

There were no statistically significant differences between heelstrike and toe-off for the 2 gait speeds for the portion of tibiotalar (Table 2) or subtalar (Table 3) joint angles outside the 95% CIs of the control subjects.

ROM

The patients with CAI exhibited angular ROM similar to that of the control subjects during the captured stance of gait and balanced heel-rise, but there were some exceptions (Figure 6). Notably, patients with CAI often exhibited less In/Ev ROM than the control subjects during captured stance and balanced heel-rise, although the individual ROM values were not always outside the 95% CIs of the control subjects. Two patients during 0.5-m/s gait and 3 patients during 1.0-m/s gait exhibited subtalar In/Ev ROM below the lower 95% CI of control subjects. Also of note, CAI-01 and CAI-03 exhibited subtalar angular ROM that was consistently less than the mean and often less than the lower 95% CI of the control subjects during captured stance. In addition, CAI-03 exhibited tibiotalar D/P ROM that was less than the lower 95% CI of the control subjects throughout all activities.

Many patients with CAI exhibited decreased translational ROM relative to control subjects, especially during the captured stance of gait (Figure 7). During 1.0-m/s gait, most patients with CAI demonstrated tibiotalar translational ROM in each direction that was less than the mean values of the control subjects. In fact, a majority of the patients with CAI exhibited tibiotalar translational ROM in each direction that was less than the lower 95% CI of the control subjects during 1.0-m/s captured stance. Furthermore, between 1 and 3 patients with CAI displayed tibiotalar translational ROM in

Table 1. Individual and Mean Percentages of the Balanced Heel-Rise Activity for Which the Joint Angles of the Patients With CAI Fell Outside the 95% Confidence Intervals of the Control Subjects.[a]

	Tibiotalar Joint			Subtalar Joint		
	D/P	In/Ev	IR/ER	D/P	In/Ev	IR/ER
CAI-01	0.00	0.00	0.55	0.00	0.48	0.43
CAI-02	1.00	0.92	0.67	0.33	0.48	0.65
CAI-03	0.37	0.70	0.74	0.73	0.71	1.00
CAI-04	0.59	0.18	0.78	0.21	0.47	0.56
Mean	0.49	0.45	0.69	0.32	0.54	0.66
SD	0.42	0.43	0.10	0.31	0.12	0.24

Abbreviations: CAI, chronic ankle instability; D/P, dorsi/plantarflexion; In/Ev, inversion/eversion; IR/ER, internal rotation/external rotation.
[a]Two trials for each patient with CAI were averaged. Percentages are expressed as ratios.

the anterior-posterior and superior-inferior directions that was less than the lower 95% CI of the control subjects during each gait speed. During 0.5- and 1.0-m/s gait, all patients with CAI exhibited subtalar translational ROM in the anterior-posterior direction that was less than the mean of the control subjects, with 1 and 3 patients with CAI, respectively, falling below the lower 95% CI of the control subjects.

Discussion

To our knowledge, this is the first study to investigate differences in tibiotalar and subtalar kinematics between patients with CAI and control subjects during dynamic activities. Overall, we found larger differences in kinematics between patients with CAI and control subjects during the balanced heel-rise activity. The CAI heel-rise trials showed a distinctly different trend than the control subjects for tibiotalar IR/ER and subtalar In/Ev and IR/ER. During captured stance, CAI joint angles typically exhibited trends similar to the control subjects but were often shifted higher or lower than the 95% CIs of the control subjects, which became more evident when the toe-off portion of stance was analyzed separately. Collectively, our results imply that weight-bearing activities involving larger ROM, balance, and stability may be most effective for evaluating kinematic differences in patients with CAI.

During balanced heel-rise and 0.5-m/s captured stance, CAI-02 demonstrated values for tibiotalar plantarflexion that could have been considered outliers. CAI-02 was the only patient who did not undergo surgery, and thus, instability in CAI-02 may have been less severe than the other patients. This may have enabled CAI-02 to achieve greater peak plantarflexion and D/P ROM. During balanced heel-rise, CAI-02 exhibited tibiotalar angular ROM that was similar to or greater than that of the control subjects and subtalar angular ROM that was less than the lower 95% CI of the control subjects. This may indicate that the tibiotalar joint provided additional motion to compensate for the limited ROM at the subtalar joint.

CAI-03 demonstrated kinematics that differed from those of the other CAI patients, notably with subtalar In/Ev and IR/ER trends and ROM values during balanced heel-rise that were more akin to the control subjects than the other patients with CAI. These trends exhibited by CAI-03 during balanced heel-rise were accompanied by translational ROM values that were on the lower end of the control values. CAI-03 was the only patient with torn deltoid ligaments, possibly causing medial ankle instability in addition to the lateral instability demonstrated by the other patients with CAI. This may explain why the subtalar joint of CAI-03 became more inverted and internally rotated during balanced heel-rise, a motion similar to the control subjects, yet with greater In/Ev and IR/ER values. The increased tibiotalar In/Ev ROM of CAI-03 may indicate possible changes to the articular surface, because the articular surface is primarily responsible for In/Ev stability when the ankle is loaded.[29] Furthermore, the deltoid is the main contributor to internal rotation restraint, especially when loaded and plantarflexed, as the foot would be during a balanced heel-rise.[29] With a damaged deltoid ligament, it is possible that CAI-03 had less control over internal rotation during loaded plantarflexion, thus causing increased internal rotation throughout balanced heel-rise.

CAI-01 and CAI-04 demonstrated relatively similar joint kinematics throughout the balanced heel-rise and captured stance, potentially as a result to their injury patterns to the ATFL and CFL. During balanced heel-rise, CAI-01 and CAI-04, along with CAI-02, exhibited tibiotalar IR/ER, subtalar In/Ev, and subtalar IR/ER that differed from those of the control subjects. During captured stance, CAI-01 and CAI-04 often exhibited joint angles that were within the 95% CIs of the control subjects. However, both CAI-01 and CAI-04 demonstrated tibiotalar D/P during toe-off and subtalar IR/ER angles during captured stance that were greater than the upper 95% CI limit of the control subjects. These differences may provide insight into the effects of CAI due to ATFL and CFL injuries on tibiotalar and subtalar kinematics during weight-bearing activities requiring plantarflexion.

The joint angles of patients with CAI differed most from the control subjects during motions requiring plantarflexion, such as toe-off and heel-rise. The largest differences were found for subtalar In/Ev and IR/ER. These results may suggest that substantial differences between CAI patients and control subjects are present only in specific kinematic metrics and/or are activity dependent. The plantarflexion motion involved during toe-off and heel-rise is a position that is more susceptible to rolling of the ankle.[5,12] Given that patients with CAI are more prone to rolling of the ankle (and subsequent sprains), kinematic differences may be most evident during activities that demand substantial weight-bearing plantarflexion.

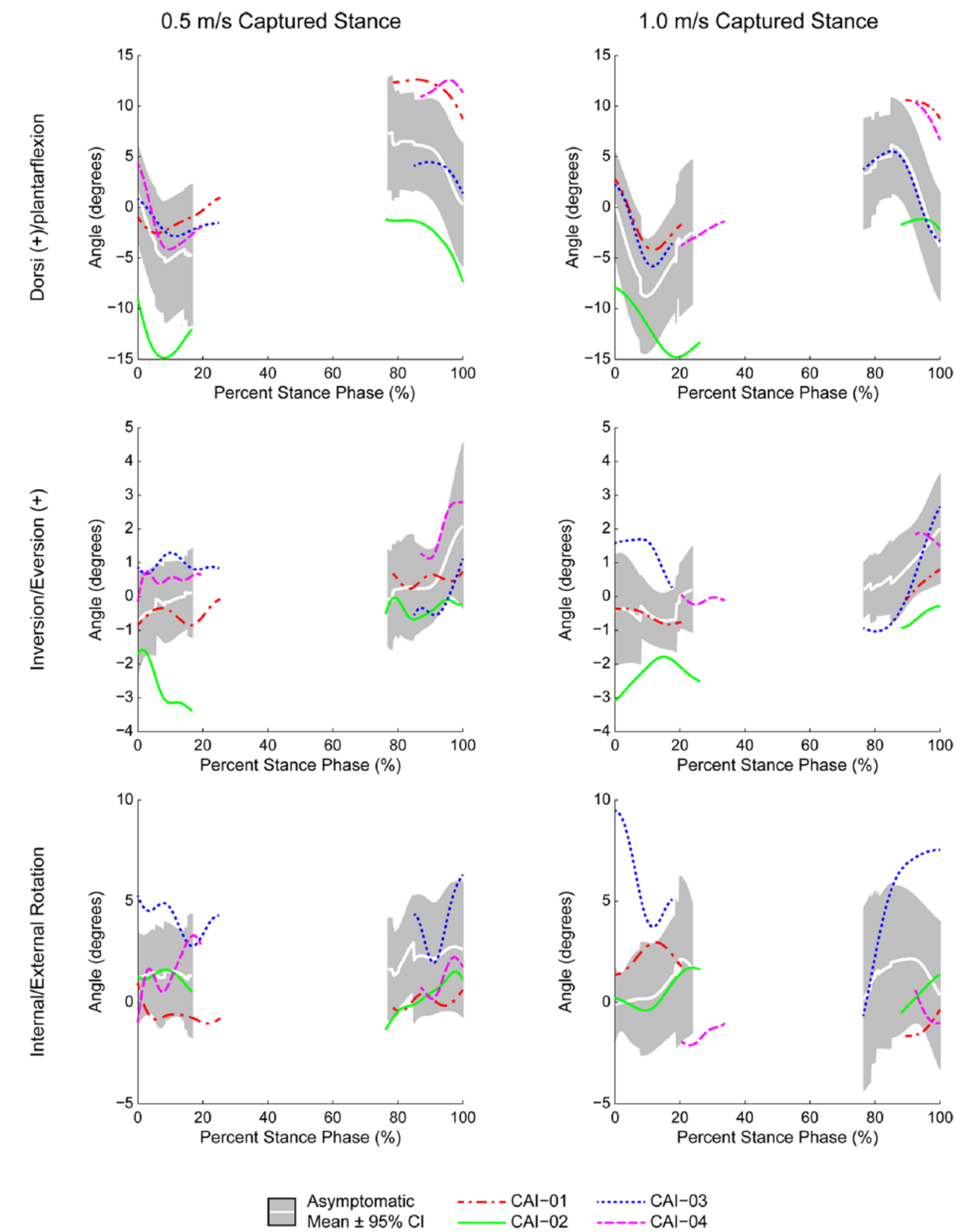

Figure 4. Tibiotalar dorsi (+)/plantarflexion (top), inversion/eversion (+) (middle), and internal rotation/external rotation (+) (bottom) mean joint angles of patients with chronic ankle instability (CAI) compared with asymptomatic control subjects during 0.5-m/s (left) and 1.0-m/s (right) gait. Data are plotted per normalized stance, with all subjects aligned at heelstrike (0%) and toe-off (100%). The heelstrike and toe-off portions of stance were collected as separate trials, because the movement of the treadmill caused the foot to move out of the combined field of view of the fluoroscopes prior to the completion of the stance phase of gait. The joint angles of the asymptomatic control subjects are presented as the mean (white line) ± 95% confidence interval (CI) (gray). Each line represents the mean joint angles of a different patient with CAI.

Table 2. Individual and Mean Percentages of the Heelstrike and Toe-Off Portions of Captured Stance (at 0.5 and 1.0 m/s) for Which the Tibiotalar Joint Angles of the Patients With CAI Fell Outside the 95% Confidence Intervals of the Control Subjects.[a]

	Dorsi/Plantarflexion				Inversion/Eversion				Internal Rotation/External Rotation			
	0.5 m/s		1.0 m/s		0.5 m/s		1.0 m/s		0.5 m/s		1.0 m/s	
	HS	TO	HS	TO	HS	TO	HS	TO	HS	TO	HS	TO
CAI-01	0.00	1.00	0.24	1.00	0.00	0.00	0.00	0.31	0.50	0.00	0.59	0.31
CAI-02	1.00	0.91	0.85	0.00	0.81	0.47	0.89	1.00	0.00	0.05	0.00	0.00
CAI-03	0.00	0.00	0.00	0.00	0.56	0.15	0.95	0.60	0.71	0.38	1.00	0.69
CAI-04	0.00	1.00	0.61	1.00	0.09	0.00	0.66	0.00	0.02	0.07	0.74	0.00
Mean	0.25	0.73	0.43	0.50	0.37	0.16	0.63	0.48	0.31	0.13	0.58	0.25
SD	0.50	0.49	0.38	0.58	0.39	0.22	0.44	0.43	0.35	0.17	0.42	0.33

Abbreviations: CAI, chronic ankle instability; HS, heelstrike; TO, toe-off.
[a]Two trials for each patient with CAI were averaged. Percentages are expressed as ratios.

Perhaps surprisingly, translational ROM was often decreased for the patients with CAI in our study. Previous studies found that patients with CAI had significantly greater translation of the talus in the anterior direction compared with their uninjured ankle.[4,6,33] However, these studies evaluated motion of the talus during static weight-bearing poses,[4,6,33] not overall ROM throughout an activity in which active muscle control is highly engaged and may not be directly comparable.

Although direct comparisons of results in our study and data in the literature cannot be made, some generalizations can be deduced. Prior studies determined tibiotalar kinematics in patients with CAI quasi-statically at 25%, 50%, 75%, and 100% of body weight but did not evaluate dynamic gait.[4,6,33] Caputo et al[6] reported no significant differences in tibiotalar D/P or In/Ev between patients with unilateral ATFL or combined ATFL and CFL injuries and intact ankles, a finding that is supported by our balanced heel-rise and captured stance results. Both Caputo et al[6] and Wainright et al[33] found that the talus in an ankle with instability (injury to the ATFL or ATFL and CFL) had significantly more internal rotation than an uninjured ankle when loaded at specific percentages of body weight. Data from Bischof et al[4] indirectly supported these findings, in which it was determined that patients with lateral ankle instability (injury to the ATFL or ATFL and CFL) had significantly higher peak cartilage contact strains on the medial side of the tibiotalar joint. Conversely, our study demonstrated more tibiotalar external rotation in patients with CAI than control subjects during balanced heel-rise. One explanation for this discrepancy may be that the patients with CAI had more relaxed neutral positions with more internal rotation than the control subjects, causing the patients with CAI to exhibit more external rotation. Additionally, 3 patients with CAI in the present study had injured CFLs, which provides external rotation restraint[29] and may have contributed to external rotation values that were higher than control subjects.

There were limitations to this study that warrant discussion. First, gait was performed at relatively slow speeds, which may have been unnatural for some subjects, especially control subjects. These speeds were chosen to ensure that all subjects could perform the same gait speed. Per our institutional review board approval, each subject was limited to 60 seconds of fluoroscopy time, which prevented us from capturing additional activities, such as a self-selected walking speed and/or additional trials. We could have sought approval to increase the allowable radiation exposure. However, model-based tracking is a time-consuming endeavor. In addition, we wanted to minimize radiation exposure. For these reasons, we chose not to analyze multiple trials. Although treadmill walking allowed us to have a more consistent step cadence and stride length across subjects, it caused the foot to exit the combined field of view of the fluoroscopes prior to the completion of stance and required us to capture heelstrike and toe-off as separate trials. For this reason, we analyzed heelstrike and toe-off separately. Although our imaging technique prevented us from analyzing a majority of stance, we successfully investigated kinematic trends during peak loading (heelstrike to foot-flat) and unloading (late midstance to toe-off) of the ankle during stance. An additional limitation was our small sample size. With only 4 patients with CAI, our results should be interpreted as case studies. Nevertheless, we believe these preliminary results provide conceptual proof that our DF approach can assess kinematics in a complex ankle patient population, which was the objective herein. A final limitation is that joint angles were considered different if 50% or more of a trial fell outside the 95% CIs of the control subjects; this criterion was not based on a clinically meaningful difference, and thus, we advocate for caution when interpreting these results.

In conclusion, the results of this exploratory study demonstrate that DF is a viable modality to study

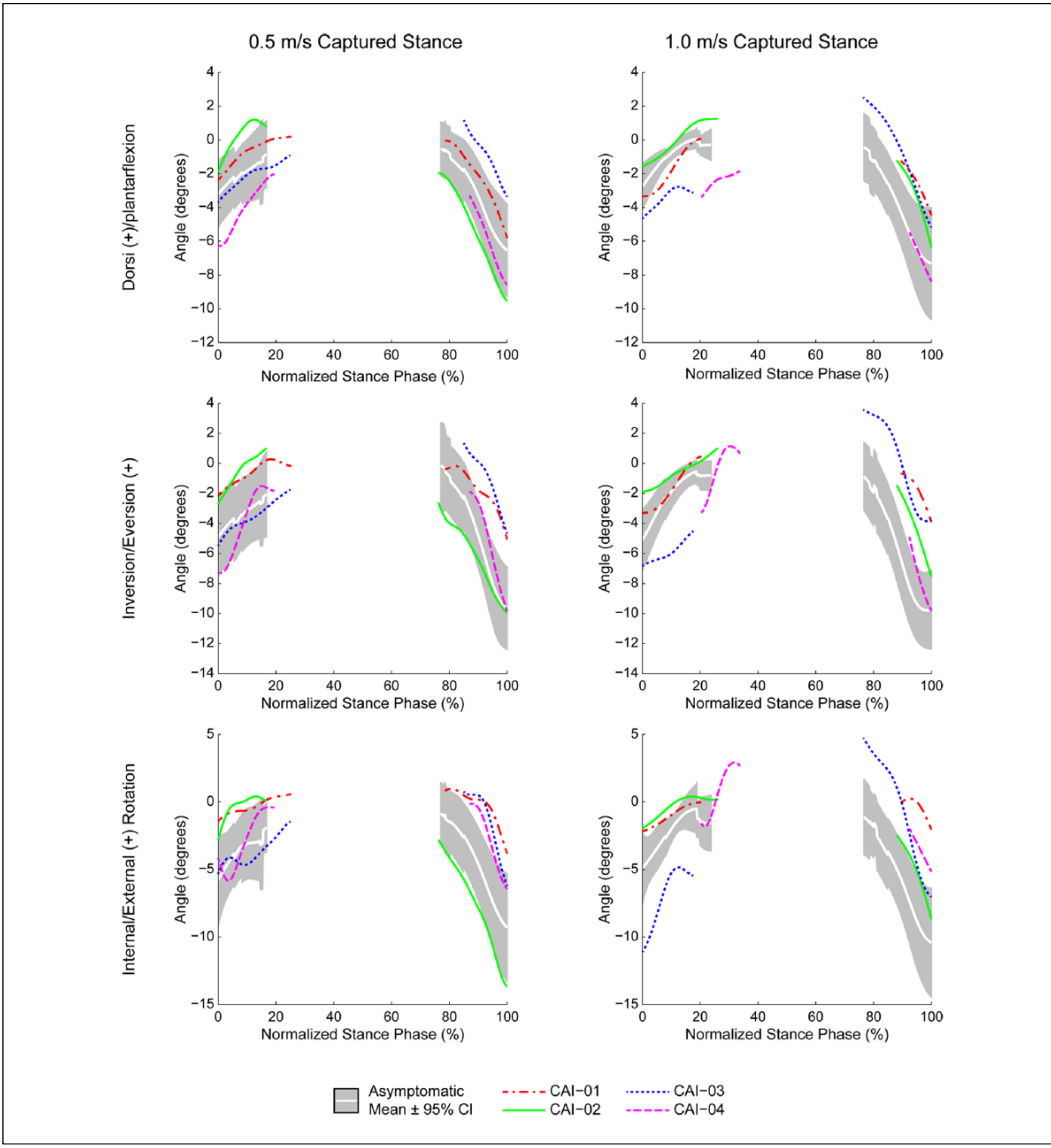

Figure 5. Subtalar dorsi (+)/plantarflexion (top), inversion/eversion (+) (middle), and internal rotation/external rotation (+) (bottom) mean joint angles of patients with chronic ankle instability (CAI) compared with asymptomatic control subjects during 0.5-m/s (left) and 1.0-m/s (right) gait. Data are plotted per normalized stance, with all subjects aligned at heelstrike (0%) and toe-off (100%). The heelstrike and toe-off portions of stance were collected as separate trials, because the movement of the treadmill caused the foot to move out of the combined field of view of the fluoroscopes prior to the completion of the stance phase of gait. The joint angles of the asymptomatic control subjects are presented as the mean (white line) ± 95% confidence interval (CI) (gray). Each line represents mean joint angles of a different patient with CAI.

Table 3. Individual and Mean Percentages of the Heelstrike and Toe-Off Portions of Captured Stance (at 0.5 and 1.0 m/s) for Which the Subtalar Joint Angles of the Patients With CAI Fell Outside the 95% Confidence Intervals of the Control Subjects.[a]

	Dorsi/Plantarflexion				Inversion/Eversion				Internal Rotation/External Rotation			
	0.5 m/s		1.0 m/s		0.5 m/s		1.0 m/s		0.5 m/s		1.0 m/s	
	HS	TO	HS	TO	HS	TO	HS	TO	HS	TO	HS	TO
CAI-01	0.19	0.70	0.32	0.90	0.96	1.00	0.49	1.00	1.00	1.00	1.00	1.00
CAI-02	0.87	0.06	0.76	0.69	0.85	0.00	1.00	0.94	0.96	0.06	0.96	0.74
CAI-03	0.00	0.91	1.00	0.87	0.00	1.00	0.90	1.00	0.00	0.72	1.00	0.89
CAI-04	0.46	0.00	1.00	0.00	0.08	0.60	0.86	0.35	0.00	0.79	0.90	1.00
Mean	0.38	0.42	0.77	0.62	0.47	0.65	0.81	0.82	0.49	0.64	0.97	0.91
SD	0.38	0.46	0.32	0.42	0.50	0.47	0.22	0.32	0.57	0.41	0.05	0.12

Abbreviations: CAI, chronic ankle instability; HS, heelstrike; TO, toe-off.
[a]Two trials for each patient with CAI were averaged. Percentages are expressed as ratios.

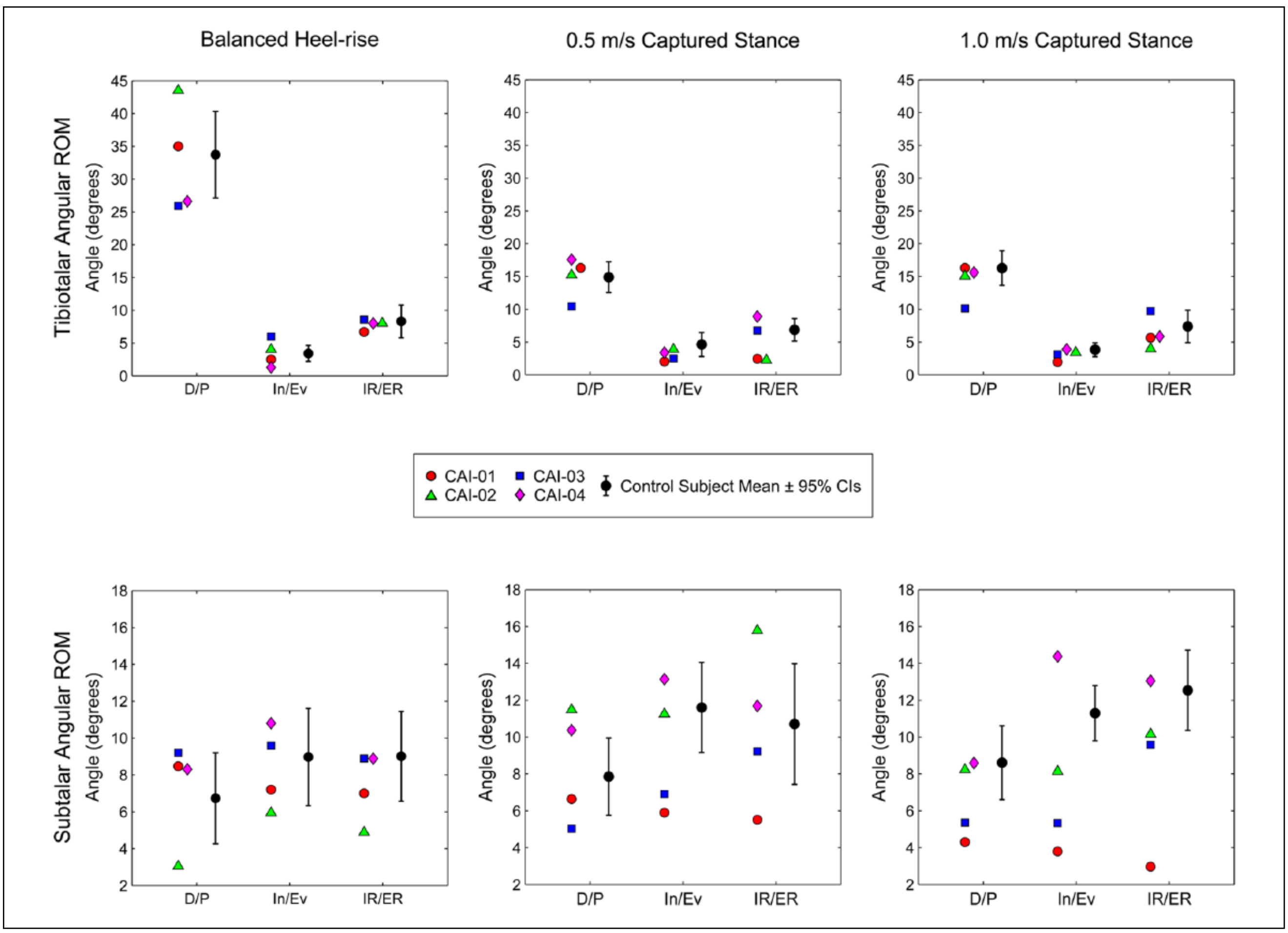

Figure 6. Joint angle range of motion (ROM) values for patients with chronic ankle instability (CAI) (symbols) plotted against the mean (black dots) ROM and 95% confidence interval (CI) (black bars) of asymptomatic control subjects for the tibiotalar (top) and subtalar (bottom) joints during balanced heel-rise (left), 0.5-m/s captured stance (middle), and 1.0-m/s captured stance (right). D/P = dorsi/plantarflexion; In/Ev = inversion/eversion; IR/ER = internal rotation/external rotation.

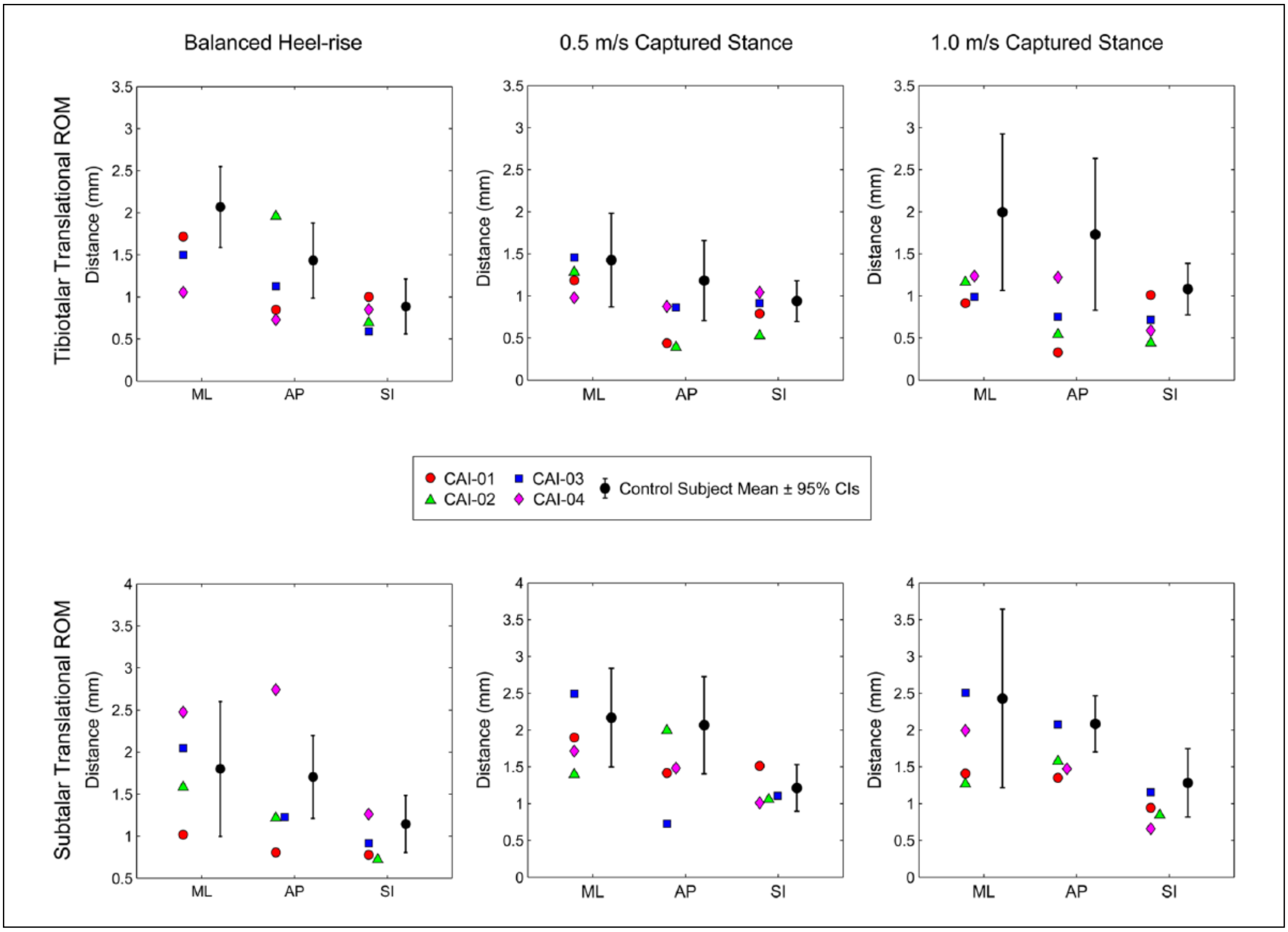

Figure 7. Joint translation range of motion (ROM) values for patients with chronic ankle instability (CAI) (symbols) plotted against the mean (black dots) ROM and 95% confidence interval (CI) (black bars) of asymptomatic control subjects for the tibiotalar (top) and subtalar (bottom) joints during balanced heel-rise (left), 0.5-m/s captured stance (middle), and 1.0-m/s captured stance (right). AP = anterior-posterior; ML = medial-lateral; SI = superior-inferior.

the subject-specific kinematics of CAI during dynamic activities. However, coupling DF with a treadmill may not be ideal for evaluating gait, as it does not image all of stance. Thus, we recommend imaging overground gait. The balanced heel-rise helped expose kinematic differences between patients with CAI and control subjects, but differences were more subtle during walking. Therefore, demanding activities, such as stair-climbing, or high-impact activities such as jumping and landing, should be examined in future kinematic studies of patients with CAI.

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