Ankle sprains are among the most common orthopedic injuries sustained within the general population. Over 600,000 ankle sprains are treated annually in United States emergency rooms alone. Approximately one in three individuals who sustain a single acute ankle sprain develop a health condition known as chronic ankle instability (CAI), which is characterized by bouts of recurrent ankle instability resulting in multiple future ankle sprains. In addition to the trauma associated with acute bouts of ankle instability and sprains, CAI has been linked to decreased physical activity, development of ankle osteoarthritis, and functional loss, indicating this condition is associated with long-term negative sequelae over the lifespan.

The development of CAI is thought to be a multifactorial phenomenon based on alterations in the mechanical structures surrounding the ankle complex and functional deficits in sensorimotor control that may occur throughout the lower extremity. The interaction between mechanical alterations in joint laxity, arthrokinematics, and degenerative structural changes with functional impairments in proprioception, neuromuscular control, and postural control are likely responsible for the repetitive ankle trauma associated with CAI. The negative consequences of this interaction may be most eminent during dynamic activities, such as gait, which require the coordination of several joints and segments during cyclic transitions from loaded to unloaded conditions while maintaining a base of support.

Single joint kinematic alterations have been identified during gait in those with chronic ankle instability (CAI). The purpose of this study was to compare sagittal plane hip, knee, and ankle kinematics during walking in participants with and without CAI. Twelve individuals with CAI and 12 healthy individuals walked on a treadmill at 1.5 m/s. Three-dimensional kinematics were analyzed using mean ensemble curves and independent t tests. Participants with CAI demonstrated less lower extremity flexion during the absorption phase of stance and the limb placement phase of swing, which may have implications for limb placement at initial contact.

### Key Points

- Few studies have examined kinematics of the hip and knee during gait in individuals with chronic ankle instability.
- During walking gait, participants with chronic ankle instability demonstrated substantially lower extremity flexion during the absorption phase of stance and this corresponded to an increased peak vertical ground reaction.
- In the swing phase of walking, those with CAI demonstrated substantially less flexion during the limb placement phase of swing.
- Examining the sagittal plane summary profile of the hip, knee, and ankle provides more robust information about the absorption capabilities of those with chronic ankle instability compared with examining any one individual joint.
increased shank external rotation during terminal swing phase, decreased ankle dorsiflexion in stance phase, and decreased foot clearance. The aforementioned kinematic alterations indicate that people with CAI demonstrate a more precarious positioning of the shank, ankle, and foot, particularly at the time of initial ground contact during walking, which could increase susceptibility to episodes of instability and recurrent ankle sprains. While the positioning of distal segments of the lower extremity is thought to be critical when examining the mechanisms of CAI, other aspects of lower extremity positioning should also be considered.

Examining the kinematics of the proximal lower extremity may provide insights into the central adaptations that have been identified in people with CAI. Previous studies have identified alterations in gait initiation and termination, proximal adaptations in muscle strength and activation, and proximal changes during functional tasks such as jump landing. Cumulatively, these studies point toward the possibility that central changes in sensorimotor function are responsibility for alterations in movement. A decrease in hip flexion, knee flexion, and dorsiflexion during landing or the stance phase of gait is associated with an inability to meet absorption demands. Exploring kinematic alterations of the hip, knee, and ankle during walking gait and their cumulative effect at producing motions related to absorption and propulsion of force could continue to elucidate how a combination of centrally-mediated changes in sensorimotor function and local changes in ankle mechanics contribute to functional deficiencies in individuals with CAI. Hip, knee, and ankle motions represent critical factors associated with the determinants of gait, but remain relatively unexamined in those with CAI. Therefore, the purpose of this study was to compare individual sagittal plane motion of the hip, knee, and ankle and their summary effect during walking gait in participants with and without CAI. We hypothesize that differences will be present in all three joints between groups.

**Methods**

**Participants**

This study employed a case-control design in which participants in the CAI and healthy control groups reported to the laboratory for a single data collection session. Participants were recruited from a large university through posted advertisements and were classified into the CAI group (7 males, 5 females; age: 25.9 ± 3.4 years; height: 176.5 ± 8.8 cm; weight: 80.3 ± 13.6 kg) or the healthy control group (7 males, 5 females; age: 26.7 ± 4.7 years; height: 171.8 ± 5.8 cm; weight: 72.5 ± 9.7 kg). Participants in both groups were matched by gender and limb. Independent t tests determined no group differences were present for age (p = .77), height (p = .28), or weight (p = .13). All participants provided written informed consent, which was approved by the university institutional review board.

Inclusion criteria were consistent with the International Ankle Consortium’s position statement on CAI selection criteria. To be included in the CAI group, participants reported a history of ≥ 1 significant ankle sprain, ≥ 2 episodes of “giving way” within the past three months, function scores of ≤ 90% on the Foot and Ankle Ability Measure (FAAM) Activities of Daily Living Scale, and a score of ≤ 80% on the FAAM-Sport Scale. Instability was further examined by requiring participants to answer “yes” to questions 1 and 4 and at least three other questions on the Ankle Instability Instrument. Inclusion criteria for the healthy group included no history of ankle sprains or instability, answering “no” to all questions on the Ankle Instability Instrument, and no functional loss on the FAAM subscales. The limb of each healthy participant matched to a corresponding CAI participant was considered the “involved” limb. Exclusion criteria for both groups consisted of an acute ankle sprain within the previous six weeks, a history of lower extremity surgery or fracture, other lower extremity injuries within six months, or conditions that affect gait (e.g., diabetes, multiple sclerosis).

**Instrumentation**

Three-dimensional kinematics were recorded at 150 Hz using motion capture cameras in a dual-belt treadmill with embedded force plates (Model TM-09-P, Bertec Corporation; Columbus, OH, USA), which provided standardized gait speeds and ground reaction forces that identified gait phases based on instants of initial contact exceeding a 30 N threshold and foot-off from falling below a 30 N threshold. All equipment was calibrated before each data collection.

**Task**

All participants completed a 10-min walk at speeds that were gradually increased from 0.5 to 1.5 m/s to...
allow participants to adjust to the treadmill before data collection. Once the target speed of 1.5 m/s was maintained for 1 min, a 30-s trial of walking was recorded.

**Procedures**

To assist in accurately placing the retroreflective markers for three-dimensional motion capture, all participants were barefoot, wore close-fitting shorts, and females wore tank tops and males wore no tops. A custom anatomical marker set was used to capture hip, knee, and ankle motion during gait. Retroreflective spherical markers (10 mm) were placed bilaterally over the anterior and posterior superior iliac spine, greater trochanter, lateral and medial femoral condyle, medial and lateral malleoli, and head of the first metatarsal using adhesive tape. After being outfitted with retroreflective markers, a static trial was recorded in an anatomical standing position followed by walking on the treadmill.

Data were reduced using custom written code in Matlab 7.9.0 (Mathworks Inc, Natick, MA, USA). From the 30 s of data capture, approximately 20 strides of the involved limb were recorded. Each stride was resampled to 101 frames to represent each percent of stride (0% representing initial contact, 100% instant before initial contact on the same limb). For each participant, a reference angle for each kinematic variable of interest was determined from the recorded static trial and was subtracted from the angles recorded during walking. \( \text{Hip flexion} = 45.2 \pm 6.4^\circ; p = .007; \text{ES} = 1.16 \pm 0.87 \) and decreased hip flexion from 70–100% of the gait cycle (Healthy: 16.6 ± 3.0°, CAI: 13.4 ± 3.6°; \( p = .01; \text{ES} = 0.93 \pm 0.84 \)). Individuals with CAI also demonstrated decreased hip flexion from 0–43% of the gait cycle, however it was not statistically significant (Healthy: 7.7 ± 3.4°, CAI: 5.5 ± 4.0°; \( p = .16; \text{ES} = 0.57 \pm 0.82 \)). Finally, those with CAI demonstrated decreased ankle dorsiflexion from 15–32% (Healthy: 3.9 ± 2.6°, CAI: 1.7 ± 3.5°; \( p = .10; \text{ES} = 0.66 \pm 0.82 \)) and 90–97% (Healthy: 0.9 ± 2.3°, CAI: −1.1 ± 2.9°; \( p = .07; \text{ES} = 0.75 \pm 0.82 \)) of the gait cycle; however, it was also not statistically significant. The group mean ensemble curves are presented in Figures 1, 2, and 3.

**Results**

**Individual Joint Analysis**

Based on the average vertical ground reaction forces of all participants, the stance phase was 0–63% whereas swing phase was 64–100% of the gait cycle. Individuals in the CAI group demonstrated decreased knee flexion from 69–98% of the gait cycle (Healthy: 42.8 ± 5.9°, CAI: 35.2 ± 6.6°; \( p = .007; \text{ES} = 1.16 \pm 0.87 \)) and decreased hip flexion from 70–100% of the gait cycle (Healthy: 16.6 ± 3.0°, CAI: 13.4 ± 3.6°; \( p = .01; \text{ES} = 0.93 \pm 0.84 \)). Individuals with CAI also demonstrated decreased hip flexion from 0–43% of the gait cycle, however it was not statistically significant (Healthy: 7.7 ± 3.4°, CAI: 5.5 ± 4.0°; \( p = .16; \text{ES} = 0.57 \pm 0.82 \)). Finally, those with CAI demonstrated decreased ankle dorsiflexion from 15–52% (Healthy: 3.9 ± 2.6°, CAI: 1.7 ± 3.5°; \( p = .10; \text{ES} = 0.66 \pm 0.82 \)) and 90–97% (Healthy: 0.9 ± 2.3°, CAI: −1.1 ± 2.9°; \( p = .07; \text{ES} = 0.75 \pm 0.82 \)) of the gait cycle; however, it was also not statistically significant. The group mean ensemble curves are presented in Figures 1, 2, and 3.

**Lower Extremity Summary Kinematic Analysis**

From the summary analysis, a distinct pattern of flexion and extension across the lower extremity emerged and was consistent across both groups, however there were substantial differences between groups (Figure 4). In the stance phase, individuals in the CAI group displayed significantly less flexion from initial contact to 45% of the gait cycle (Healthy: 24.1 ± 6.8°, CAI:
17.6 ± 6.5°; p = .02; ES = 0.94 ± 0.84), which corresponded to the time windows for the heel and ankle rockers, representing the absorption phase of stance. There were no significant differences between groups from 45% to 71% of the gait cycle, however there were substantial differences again from 72% of the swing phase to initial contact (Healthy: 53.5 ± 6.4°, CAI: 44.8 ± 5.8°; p = .002; ES = 1.38 ± 0.89).
Discussion

The primary findings were that participants with CAI demonstrated less knee and hip flexion during the swing phase. While statistically significant differences were only identified in hip and knee kinematics during swing phase, strong ESs were associated with differences in sagittal plane kinematics of the hip during stance phase and the ankle during the stance and swing phases, suggesting clinically meaningful differences may be present. Overall, the positioning of the lower extremity in the sagittal plane appears to be reduced in individuals with CAI, particularly in the phases of walking gait leading up to initial contact.

Figure 3  Hip flexion/extension kinematics during the gait cycle for healthy (n = 12) and chronic ankle instability ([CAI] n = 12) participants. The percent of gait cycle is from initial contact (0%) to the instant before the subsequent initial contact on the same limb (100%). The solid line represents the group mean while the dashed lines represent the mean ± SE.

Figure 4  Sagittal plane summary kinematics during the gait cycle for healthy (n = 12) and chronic ankle instability ([CAI] n = 12) participants. The percent of gait cycle is from initial contact (0%) to the instant before the subsequent initial contact on the same limb (100%). The solid line represents the group mean while the dashed lines represent the mean ± SE.
The altered hip and knee kinematics in those with CAI have substantial implications, but this is the first study to determine these alterations. Previous reports which have examined hip and knee gait kinematics of those with CAI did not identify significant differences, however these studies primarily examined kinematics immediately before and during stance phase. In the current study, many of the alterations in hip and knee kinematics were identified during the mid- and terminal aspects of swing, which were not examined in previous studies. Another key difference in these past studies is that they examined overground walking, while the current study used a treadmill with a standardized speed. Overall, the more extended hip and knee kinematics during swing phase and the overall summary decrease in flexion range of motion in the latter part of swing suggests a decreased ability to control motions related to limb placement in preparation for the transition from an unloaded to loaded limb in those with CAI. The more extended hip and ankle during the stance phase and the overall summary decrease in the early part of stance suggests individuals with CAI may have a decreased ability to effectively absorb forces arising from initial contact which may influence the ability to attenuate forces and maintain a stable base of support during stance.

In a secondary analysis of the vertical ground reaction force profile of these groups, we found that in the early part of stance the CAI group demonstrated significantly higher normalized vertical peak ground reaction force compared with the healthy group (Healthy: 0.8 ± 0.1 N/kg, CAI: 0.9 ± 0.1 N/kg; \( p = .03; \) ES = 0.97 ± 0.85). These findings, while not part of the initial design of the study, help to substantiate the hypothesis that the summary sagittal kinematic profiles between the groups provide insight into the ability to attenuate the forces arising from ground contact. In addition, these results support previous research which identified difficulty with foot clearance during swing, which, when combined with the inability to control limb placement and reduce ground reaction force, may promote episodes of giving way due to tripping or stumbling in more unpredictable environments. When combined with the self-reported functional deficits of the CAI group as reported via the FAAM-ADL and the FAAM-Sport, it is quite possible that these kinematic alterations provide insight into the underlying factors related to functional deficits experienced by those with CAI.

While significant differences were detected in hip and knee kinematics, no statistically significant differences were detected in ankle dorsiflexion. Although significant differences in dorsiflexion were not identified between groups, the CAI group demonstrated strong trends toward decreased dorsiflexion during stance and swing phases compared with healthy individuals. This finding supports previous research in which those with CAI exhibited approximately 3° less dorsiflexion from 42–51% of the walking gait cycle. While this study examined walking gait on a treadmill, it differed from the methods of the current study by using a shod condition. Although the mean differences in this study were only 2.2°, the moderate-to-strong ESs indicate these trends may have clinical implications. Specifically, these trends may reflect functional deficits in force absorption, the transition to propulsion, and the transition to a loaded condition for people with CAI. When considering the summary findings, it appears that the cumulative effect of ankle dorsiflexion combined with knee and hip flexion profiles elucidate the functional deficit in those with CAI to a greater extent that any single joint alteration alone. There is also evidence to suggest that the amount of dorsiflexion available influences knee flexion angle during landing as well as the magnitude of the vertical ground reaction force during the absorption phase. As well, those with CAI demonstrate reduced weight bearing dorsiflexion as well as a talar positional fault due to posterior capsular restrictions in the talocrural joint. Therefore, future studies that examine gait in individuals with CAI should also consider assessing alterations in dorsiflexion range of motion not only to simply increase motion at this individual joint, but to free up the entire lower extremity absorption capabilities.

The retrospective design of this study does not permit a causal link to be established between CAI and these alterations in gait. Another limitation is that all participants walked barefoot on a treadmill. While using a treadmill allowed for controlled speed and efficient capture of multiple trials, barefoot walking on a treadmill may not be directly generalized to the common injury mechanisms associated with recurrent ankle sprains. We used a set walking speed (1.5 m/s) for all participants which may not have represented the preferred walking speed for each individual and potentially created an artificial environment to some extent. While the methods used in this study enabled more precise marker placement and control over certain walking parameters, examining shod or overground gait may have elicited different results in
regard to lower extremity kinematics. However, when combined with the functional deficits in the CAI group self-reported through the increased episodes of giving way and lower FAAM scores, it appears that the results from this investigation lend insight into the nature of CAI development. Further investigation into the consistency of gait alterations under different constraints is warranted.

**Clinical Implications**

The findings of this study further support the presence of central adaptations in sensorimotor function and local mechanical impairments in the ankle as contributing factors to functional alterations in people with CAI. The combination of these factors suggests that the treatment for acute sprains is not effective in restoring normal movement patterns for fundamental tasks such as walking gait. This is evidenced by a recent study, which identified changes in hip, knee, and ankle positioning during gait in individuals with a first-time acute ankle sprain. Because gait deviations may manifest as early as the initial ankle sprain, interventions that address alterations in gait are an important rehabilitation consideration. Currently, few studies have examined gait as an outcome following intervention for patients with CAI. A four-week dynamic balance training program did not significantly alter gait kinematics. This study only investigated ankle and shank kinematics and did not examine hip or knee kinematics. Therefore, it is unclear if this program, which was designed to address deficits in sensorimotor function, may have altered movement patterns throughout the lower extremity. However, the application of an ankle brace has increased ankle dorsiflexion and altered neuromuscular activity throughout the lower extremity in people with CAI. This intervention may address local mechanical ankle function as indicated by improvements in dorsiflexion, however knee kinematics remained unchanged despite alterations in neuromuscular activity throughout the extremity. It may be that freeing up ankle dorsiflexion has a net effect on the absorption behavior of the entire lower extremity during the transition from an unloaded to a loaded limb. Cumulatively, these studies suggest an intervention that addresses the central adaptations and local mechanical alterations, and specifically focuses on CAI-related gait alterations, is likely required to make a significant impact on this aspect of function.

**Future Research Directions**

This study examined the individual and summary kinematics of the hip, knee, and ankle in the sagittal plane. We have gained insight into how these joints work together to produce motion and stability within the gait cycle to meet the demands of absorption and propulsion. From this information, new insights can be shed onto the underlying potential mechanisms for the development of CAI. In addition, interventions that can address both central adaptations and local mechanical alterations associated with CAI are necessary to restore gait patterns in these patients. Exploring gait intensive intervention strategies that have been successful for patients with other lower extremity conditions should be considered.

**References**

13. Spaulding SJ, Livingston LA, Hartsell HD. The influence of external orthotic support on the adaptive gait characteristics of individuals


Matthew C. Hoch is with the School of Physical Therapy and Athletic Training, Old Dominion University, Norfolk, VA.

David R. Mullineaux is with the School of Sport and Exercise Science, University of Lincoln, UK.

Kyoungkyu Jeon is with the Sport Science Institute, Incheon National University, Incheon, Korea.

Patrick O. McKeon is with the Department of Exercise and Sport Sciences, Ithaca College, Ithaca, NY.

Lindsey E. Eberman, PhD, ATC, LAT, is with Indiana State University, is the report editor for this article.