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Kipp, Kristof and Palmieri-Smith, Rianna M., "Principal Component Based Analysis of Biomechanical Inter-Trial Variability in Individuals with Chronic Ankle Instability" (2012). *Exercise Science Faculty Research and Publications*. 48.

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Principal Component Based Analysis of Biomechanical Inter-Trial Variability in Individuals with Chronic Ankle Instability

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Abstract

Background

Biomechanical variability during movement may influence joint stability in individuals with chronic ankle instability (CAI). The purpose of this study was to compare the kinematic and the kinetic inter-trial variability between healthy and CAI individuals.

Methods

Eleven individuals with CAI and 11 matched controls performed five repetitions of a single-leg landing task. Biomechanical data were collected from 100 ms before to 200 ms after touchdown, and were used to calculate touchdown angles, peak angles and moments at the ankle joint in the frontal and sagittal planes. In addition, principal component analyses were used to quantify kinematic and kinetic patterns in the same planes across the 300 ms time window. Five trial averages and inter-trial variability were calculated for all variables for each subject. Independent t-tests were used to compare variables between groups.

Findings

The CAI group displayed greater inter-trial variability for principal component scores in the sagittal and frontal planes. The sagittal plane principal component captured a phase shift in plantar–flexion motion before touchdown, while the frontal plane principal component captured the general magnitude of motion during the entire movement. The CAI group therefore exhibited greater inter-trial variability in the sagittal plane before touchdown and in the frontal plane during the entire movement.

Interpretation

While average motions did not differ between groups, the CAI group displayed greater kinematic inter-trial variability when analyzed with the principal component analysis. More variable joint motions may indicate less dynamic stability in the CAI group, which may originate from greater ligamentous laxity or diminished neuromotor control.

Keywords

Ankle sprain, Principal component analysis, Landing biomechanics

1. Introduction

A lateral ankle sprain is a frequent musculoskeletal injury that results during a sudden inversion and plantar flexion movement of the ankle joint (Ferran and Maffulli, 2006, Hertel, 2005). Ankle sprains are among the most common injuries encountered during sports activities (Ferran and Maffulli, 2006). Despite contemporary treatments strategies, however, up to 80% of individuals will experience a subsequent sprain (Yeung et al., 1994). Perhaps most alarming is that slightly less than half of the people who suffer repeated ankle sprains will develop lasting instability known as chronic ankle instability (CAI) (Verhagen et al., 1995).

CAI is characterized by a subjective feeling of instability or tendency for the ankle to ‘give way’ during activity (Hertel, 2002). Individuals with CAI display different ankle motions compared to healthy individuals during a variety of tasks (Brown et al., 2008). In particular, individuals with AI demonstrate greater ankle motion variability during dynamic activity (Brown et al., 2009). Greater motion variability may in part reflect aberrant kinematic control and partially compromise joint stability, which in turn would predispose individuals to the recurring ankle sprains characteristic of CAI (Delahunt et al., 2006a, Delahunt et al., 2006b, Konradsen and Voigt, 2002). While several studies have identified differences in ankle motion variability (Brown et al., 2009, Drewes et al., 2009), none of these studies have reported on ankle joint kinetics. Knowledge of joint kinetics, however, provides more complete information about the neuromechanical control at the ankle joint during injury situations than joint kinematics alone (Kristianslund et al., 2011). For example, Kristianslund et al. (2011) recently reported a case study that linked excessive deviation from ‘normal’ ankle joint kinetics during sidestep cutting to the mechanism of injury of a lateral ankle sprain. Identifying differences in kinetic variability in CAI individuals may thus also help expand the clinical understanding of CAI.

Greater joint motion variability has been reported for discrete-dependent variables, such as peak kinematic variables (Brown et al., 2009, Brown et al., 2012). While these reports provide information about variability at either distinct time points or peak magnitudes, they do not account for the time-varying nature of movement patterns throughout the execution of dynamic tasks. Arguably, the analysis of entire waveforms instead of discrete variables may provide greater insight into movement patterns and their variability across the duration of a task (O'Connor and Bottum, 2009). One method that can be used to assess movement patterns across entire time-series data is principal component analysis (PCA) (Daffertshofer et al., 2004). This method allows for the analysis of time-varying movement patterns across the duration of entire movements and is therefore ideally suited for use in biomechanical analyses (Daffertshofer et al., 2004). In addition, variability measures based on PCA appear to be more sensitive to differences in research conditions than those based on peak magnitudes (O'Connor and Bottum, 2009).

The purpose of this study was to compare the kinematic and kinetic inter-trial variability between individuals with CAI and a healthy control group. It was hypothesized that the trial to trial variability in frontal and sagittal plane ankle kinematics and kinetics would differ between a group of individuals with CAI and a healthy control group. Moreover, it was hypothesized that inter-trial variability measures based on PCA would be more sensitive than those based on discrete variables and would therefore be more effective in identifying group differences.

2. Methods

Twenty two recreationally active individuals (11 with CAI [5 males and 6 females] and 11 healthy controls [5 males and 6 females]) were recruited to participate in this study. Individuals were included into the CAI group based on an inclusion questionnaire that assessed the severity and history of ankle sprains and established the presence of chronic ankle instability (McVey et al., 2005). All individuals in the CAI group reported having sustained at least one ankle sprain and having repeated episodes of instability. Healthy controls were then recruited and matched to CAI individuals based on sex, age, height, and weight (CAI group: 22.4(3.2) years; 1.68(0.11) m; 69.0(19.1) kg; control group: 22.6(4.2) years; 1.74(0.11) m; 66.8(15.5) kg). All subjects also completed the Foot and Ankle Disability Index (CAI group: 90.3(9.4) %; control group: 100.0(0.0) %) along with the Foot and Ankle Disability Index-Sport (CAI group: 88.6(9.1) %; control group: 100.0(0.0) %) version to measure self-report of function (Hale and Hertel, 2005). In addition, basic activity levels were also measured (CAI group: 5.3(1.2) Tegner Score; control group: 5.3(1.0) Tegner Score). All individuals signed an institutionally approved consent form before the beginning of data collection.

Biomechanical data were collected during the execution of a single-leg jump landing task. The task required individuals to initiate a forward jump off of two legs, jump over a 15-cm box, and land on a single leg. The forward jump distance was normalized to the individuals' leg length, measured as the distance from their greater trochanter to their lateral malleolus. Individuals with CAI were asked to use their affected leg for the landing task. In the case that both ankles were affected by CAI, individuals were asked to use their worse leg. Each matched healthy control was then also asked to use the same leg for the landing task. Five successful landings were collected from each participant. A successful landing required that subjects landed with their entire foot on a force plate (AMTI, Watertown, MA, USA), within the field of view of a high speed motion analysis system (ViconMx, Lake Forest, CA, USA), and balanced on the landing leg for at least 2 seconds. During each landing, the positions of 11 reflective markers were collected. Markers were attached to the 2nd metatarsal, base of the 5th metatarsal, mid-foot, heel, lateral and medial malleoli, distal and proximal tibia, tibial tuberosity, as well as the medial and lateral epicondyles of the knee (McLean and Samorezov, 2009). Kinematic and kinetic data were acquired at 240 and 1200 Hz, respectively.

All data were low-pass filtered with a cubic-spline at 12 Hz (Woltring et al., 1985). The filtered position data were then used as inputs to a two segment (rear-foot and shank) kinematic model in Visual 3D (C-Motion,

Rockville, MD, USA) that calculated ankle rotations in the local coordinate system of the ankle (McLean and Samorezov, 2009). Angles were computed based on Cardan rotation sequences of the distal segment with respect to the proximal segment, and expressed relative to a neutral standing position (McLean and Samorezov, 2009). The processed kinematic data were then combined with anthropometric data and the filtered kinetic data in an inverse dynamics approach to solve for the net internal joint moments (McLean and Samorezov, 2009). The joint moments were normalized to each individual's body mass and height. Although the kinematic and kinetic data processing procedures generated output in each cardinal plane, only variables from the sagittal and frontal plane were used for analysis. The retained joint angle and moment time-series data were then trimmed from 100 ms before to 200 ms after touchdown, which was defined as the point when the vertical ground reaction force exceeds 10 N. Based on the kinematic sampling rate of 240 Hz the trimmed 300 ms windows reduced the kinematic and kinetic data down to 75 data points.

Several discrete variables were extracted from the 300 ms window for analysis. First, the maximum/minimum angles and peak moments during the 200 ms after touchdown were extracted for analysis. In addition, discrete joint angles at the point of touchdown were also extracted for analysis. The trimmed time-series data were then used as inputs to PCA (Daffertshofer et al., 2004, O'Connor and Bottum, 2009). Briefly, four separate 110×75 (5 trials/subject \times 75 time-series data point) input matrices were generated for the kinematic and kinetic time-series data in the frontal and sagittal plane. Principal components were then extracted from the co-variance matrices of each of these input matrices. Principal components were retained if they explained at least 3% in the waveform variance. Principal component (PC) scores were calculated for each trial by projecting each subject's time-series data back onto each retained principal component and summing the projections.

Within-subject averages for touchdown angles, maximum/minimum angles, peak moments, and PC scores were generated from the five trials of each subject (O'Connor and Bottum, 2009). In addition, the inter-trial variability for each subject was calculated as the standard deviation of the five trial average for each kinematic, kinetic, and PCA-derived variable (O'Connor and Bottum, 2009). Two-tailed *t*-tests were used to compare the five trial average and inter-trial variability between groups. Data are presented as mean (SD). Statistical significance was set at $\alpha = 0.05$. Effect sizes (Cohen's *d*) were calculated for significant comparisons. All statistical analyses were performed in SPSS (IBM Corporation, Armonk, NY, USA).

3. Results

No significant differences between the CAI and healthy control group were found for the five trial averages or inter-trial variability of touchdown, maximum, or minimum angles (Table 1). Similarly, no significant differences were found for the five trial averages or inter-trial variability in the peak moments (Table 2). In addition, the five trial averages for all extracted principal components did not differ between groups. Group differences were, however, detected between the inter-trial variability for the third principal component (PC3) for sagittal plane motion ($P = 0.001$; $d = 1.73$) and of the first principal component (PC1) for frontal plane motion ($P = 0.02$; $d = 1.16$). PC3 captured a phase shift in sagittal-plane motion before touchdown (Fig. 1a). Specifically, the PC3-related shift affected the magnitude of ankle plantar-flexion motion before touchdown. Inspection of the inter-individual variability about the ensemble average shows that the greater PC3 scores in the CAI group translated into more variable trial-to-trial sagittal plane motion during the 100 ms before touchdown. PC1 captured the magnitude of frontal-plane motion throughout the entire 300 ms time period (Fig. 1b). Inspection of the inter-individual variability about the ensemble average shows that the greater PC1 scores in the CAI group translated into more variable trial-to-trial frontal plane motion throughout the entire 300 ms time period.

Table 1. Mean(SD) for the five-trial average and inter-trial variability in touchdown angles (°), maximum/minimum angles (°), and kinematic PC scores for the chronic ankle instability (CAI) and healthy control group (CON).

Empty Cell	Group			
	CAI		CON	
	Average	Variability	Average	Variability
Touchdown angle				
Sagittal plane	- 31.2(6.2)	2.4(1.1)	- 32.7(7.6)	1.9(0.9)
Frontal plane	7.9(3.1)	1.5(0.7)	10.7(6.3)	1.2(0.9)
Maximum angle				
Sagittal plane	8.1(3.2)	1.4(0.7)	11.0(6.3)	1.1(0.5)
Frontal plane	10.1(5.4)	2.6(1.3)	9.5(6.2)	1.9(1.2)
Minimum angle				
Sagittal plane	- 31.2(6.2)	2.3(1.1)	- 32.1(7.9)	3.2(4.0)
Frontal plane	6.5(3.6)	1.7(0.7)	4.8(5.5)	1.5(0.5)
Kinematic PC scores				
Sagittal PC1	- 98.6(37.0)	17.4(6.8)	- 108.3(38.2)	12.2(7.5)
Sagittal PC2	80.9(28.3)	13.2(6.9)	84.4(32.1)	11.7(7.5)
Sagittal PC3	60.7(12.7)	7.9(2.7)*	59.8(19.0)	4.0(1.8)*
Sagittal PC4	1.7(9.6)	5.2(2.1)	1.0(6.5)	3.8(1.9)
Frontal PC1	1.9(25.5)	9.3(3.1)*	19.1(41.2)	6.2(2.3)*
Frontal PC2	36.8(16.2)	7.5(4.6)	42.7(19.3)	9.8(3.3)
Frontal PC3	9.8(7.2)	4.6(1.2)	6.7(8.8)	4.9(1.7)
Frontal PC4	- 8.4(3.4)	3.9(2.1)	- 11.0(7.4)	4.3(1.7)

Note: Positive and negative angles in the sagittal plane indicate dorsiflexion and plantarflexion, respectively. Positive and negative signs in the frontal plane indicate inversion and eversion, respectively.

* $P < 0.05$ for CAI vs. CON.

Table 2. Mean(SD) for the five-trial average and inter-trial variability in peak moments (N m/kg m) and kinetic PC scores for the chronic ankle instability (CAI) and healthy control group (CON).

Empty Cell	Group			
	CAI		CON	
	Average	Variability	Average	Variability
Peak moment				
Sagittal plane	1.32(0.09)	0.04(0.12)	1.37(0.28)	0.04(0.14)
Frontal plane	0.16(0.06)	0.03(0.02)	0.15(0.05)	0.03(0.02)
Kinetic PC scores				
Sagittal PC1	- 6.72(0.66)	0.84(0.84)	- 6.53(1.35)	1.04(0.53)
Sagittal PC2	- 1.43(0.72)	0.42(0.19)	- 1.71(0.77)	0.59(0.24)
Sagittal PC3	- 1.01(0.30)	0.28(0.20)	- 0.88(0.30)	0.36(0.35)
Sagittal PC4	- 0.13(0.27)	0.28(0.15)	0.02(0.23)	0.23(0.13)
Frontal PC1	- 0.62(0.32)	0.18(0.07)	- 0.53(0.45)	0.26(0.14)
Frontal PC2	0.05(0.14)	0.10(0.05)	- 0.03(0.18)	0.12(0.04)
Frontal PC3	- 0.02(0.10)	0.05(0.02)	0.01(0.08)	0.06(0.02)
Frontal PC4	0.07(0.09)	0.05(0.02)	0.02(0.06)	0.05(0.02)

Note: The peak frontal plane moment is an eversion moment and the peak sagittal plane moment is a plantarflexion moment. The dorsiflexion and inversion moments are not shown because their magnitudes were essentially zero.

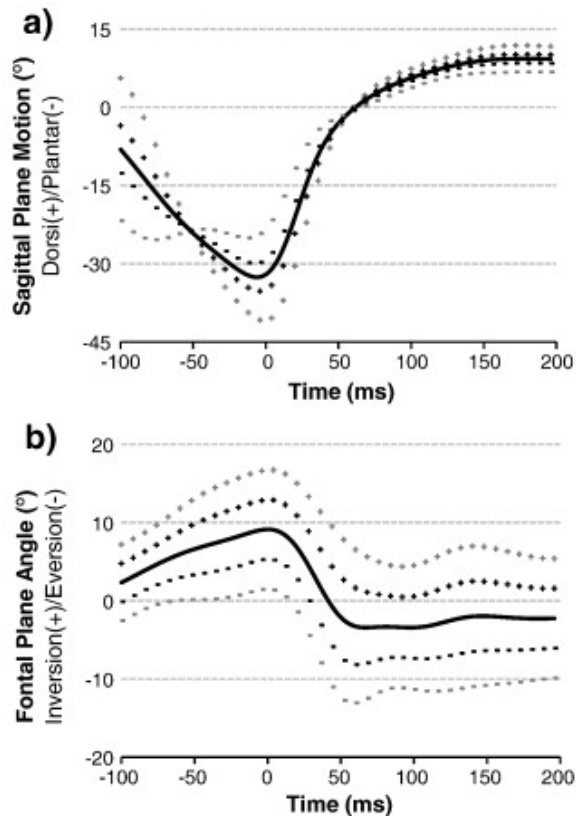


Fig. 1. Ensemble average of (a) sagittal plane and (b) frontal plane motion from all individuals (solid line) and effects of inter-trial variability in kinematic PC scores in the chronic ankle instability (gray symbols) and the control group (black symbols). Note: The effects of inter-trial variability in kinematic PC scores are depicted as the positive and negative 'standard deviations' about the ensemble group average and are hence displayed as '+' and '-' symbols, respectively.

4. Discussion

The purpose of this study was to compare the kinematic and kinetic inter-trial variability between individuals with CAI and a healthy control group. It was hypothesized that a group of individuals with CAI would exhibit different inter-trial variability compared to a healthy control group in a number of biomechanical variables. An additional hypothesis was that inter-trial variability measures derived from PCA would be more effective in identifying group differences than those based on discrete variables. The results of this study confirmed both hypotheses in that the CAI group displayed greater inter-trial variability for two principal components, but none of the discrete variables.

The CAI group displayed greater inter-trial variability in the third principal component extracted from the sagittal plane ankle motion. This principal component captured a phase shift in sagittal-plane motion during the pre-landing phase. More specifically, this phase shift affected the sagittal positioning of the ankle during the period before touchdown. The greater inter-trial variability in this principal component thus indicated that the CAI group displayed greater differences in the degree of plantarflexion in preparation for landing. Using the effect size from the group comparison, it was estimated that the difference in inter-trial variability of this principal component influenced the sagittal plane ankle angle by up to 6° during the time phase before touchdown. This result is of clinical importance, because ankle positioning in preparation for ground contact is thought to play a significant role in perpetuating CAI in several ways. First, ankle positioning affects foot ground clearance, which may increase risk for unplanned contact and thus episodes of instability (Brown, 2011, Delahunt et al., 2006a).

Second, computer simulations indicate that greater plantar flexion at touchdown increases the moment arm of the ground reaction forces about the subtalar joint, which may be a mechanism that directly influences the susceptibility of subsequent sprains in a person with a history of ankle instability (Wright et al., 2000). It should be pointed out that the discrete peak averages and inter-trial variability for the ankle in the sagittal plane at the point of touchdown did not differ between groups. The lack of difference in discrete variables in the sagittal plane is in line with another report (Brown et al., 2009). The group difference for this principal component therefore captures a unique aspect in the 'patterning' of the ankle motion before landing, which was not evident from the analysis of traditional discrete variables. Since the neuromechanical strategies used to prepare for touchdown during pre-landing periods stem from pre-planned motor programs (Jones and Watt, 1971), the motion pattern displayed by the CAI group likely reflects altered central motor control (Hass et al., 2010). The greater inter-trial variability in sagittal plane motions prior to touchdown in individuals with CAI may therefore reflect altered motor control strategies and reveal a reduced ability to effectively use a consistent pattern, which may allow for a greater chance of movement error. Retraining or rehabilitating centrally mediated motor control strategies would thus seem important in the management of CAI. However, since the effect of rehabilitation interventions on motor control strategies remain largely unknown, future research should focus on intervention studies where motor control strategies are assessed under dynamic conditions. In addition, establishing the predictive capabilities of these measures within prospective cohort studies may provide additional clinical applications to improve injury prevention protocols.

In addition to the difference in inter-trial variability in sagittal plane ankle motion, the CAI group also displayed greater inter-trial variability in frontal plane ankle motion. Group differences were found for a principal component that captured the general magnitude of ankle motion in the frontal plane throughout the entire 300 ms time period (i.e., from 100 ms before touchdown to 200 ms after touchdown). The greater inter-trial variability in this principal component therefore indicated that the CAI group displayed greater trial to trial differences in the overall amount frontal plane movement before and after touchdown. Again, using the effect size from the group comparison, it was estimated that the difference in inter-trial variability of this principal component influenced the frontal plane ankle angle by up to 8° throughout the movement. Since the overall motion pattern captured by this principal component was the same for both groups, the greater motion variability likely points to a lack of consistency in the patterning in frontal plane motion in those with CAI. This suggests that the ability to produce relatively the same results across five trials during a relatively simple task is compromised in individuals with CAI. It could be argued that the inability to successfully coordinate movement patterns presents a contributing factor as to why these individuals do not have the ability to maintain ankle stability in more complex tasks. Similar to the present results, Brown et al. (2009) reported that individuals with functional ankle instability display greater average standard deviations in ankle inversion/eversion motions during the stance phase of a stop-jump maneuver. The present results, however, expand on those reported by Brown et al. (2009) in that they also identify differences in inter-trial frontal plane variability before touchdown. Practically, the greater variability in frontal plane motion is significant because it would increase the risk of excessive inversion, which may precipitate the risk of an inversion ankle sprain by bringing the ankle closer to a position where the foot loses bony restrictions and move into enough rotation leading to an ankle sprain (Fong et al., 2009, Mok et al., 2011). While the greater variability in frontal plane motion in preparation for landing may indicate compromised central control for reasons discussed above, the greater variability during the landing phase may also partially reflect greater ligamentous laxity, because hypermobility may result in abnormal joint mechanics during weight-bearing activities (Hubbard and Hertel, 2006). However, individuals with mechanical ankle instability reportedly exhibit greater inter-trial variability in anterior–posterior ground reaction forces and not ankle kinematics (Brown et al., 2009). Since the current investigation did not differentiate between individuals with mechanical or functional ankle instability, the exact reason for greater inter-trial variability in the frontal plane kinematics is not clear.

It is interesting to consider that neither the averages nor standard deviations of the ankle moments differed between groups. Based on findings that linked excessive ankle joint kinetics during sidestep cutting to the mechanism of injury of a lateral ankle sprain (Kristianslund et al., 2011) it was hypothesized that kinetic inter-trial variability would differ in a group with CAI. Contrary to our initial hypothesis, however, we found no group differences for any kinetic variables. Further, the lack of kinetic differences was consistent for discrete and PCA based variables, which was not the case for joint kinematics. One should bear in mind that the joint moments calculated in the current study represent only the 'net' internal moments, and therefore reflect only the 'net' force output of all active and passive structures that cross the ankle joint. Subsequently a similar 'net' moment between groups could be achieved through different levels of muscle co-activation, even though the activation of individual muscles varies considerably. Although different activation patterns have been identified in the peroneus longus muscle of CAI individuals during different activities (Delahunt et al., 2006a, Delahunt et al., 2006b), no studies have investigated the effects of altered muscle co-activation ratios among ankle muscles. Since it could be surmised that altered peroneus longus activity would also affect co-activation ratios to control instability during landing, examining such variables would present another avenue for future research.

The results and conclusions drawn from the results of this study should be interpreted in light of several limitations. Participants in the CAI group were included based on self-reports of instability and no distinction between individuals with mechanical or functional ankle instability were made. Since the neuromechanical adaptations may differ between these populations (Brown et al., 2009) it may be necessary to replicate a similar study to further elucidate the mechanisms that contribute to CAI. Indeed, delineating between the effects of inter-trial variability between the different populations within CAI would provide important information about the mechanisms associated with this condition. In addition, the single-leg landing task chosen in this study represented a very controlled laboratory task. The ecological validity of such tasks with regards to sports-relevant situations, where decisions and movements have to be made and executed under time-critical conditions, has recently been questioned for similar sports medicine research paradigms (McLean, 2008). Including experimental conditions that replicate sports-relevant situations may help identify and reveal group differences not apparent during controlled laboratory tasks. Two further issues that bear consideration are the number of data trials needed to calculate inter-trial variability and the variance associated with some of the dependent variables. In part, these issues are related as a low number of trials may artificially inflate the variance of dependent variables, which may not produce representative means and inter-trial variability. The current study used only five trials to calculate inter-trial variability. While this number is lower than what has been used by others, the analysis still found significant differences for some of the PCA derived variables. Interestingly, these variables also had relatively high standard deviations, which may speak to the fact that PCA derived variables are more sensitive indicators of biomechanical differences between experimental conditions than traditional discrete variables. Future investigations should try to establish the numbers of trials necessary to study inter-trial variability using PCA, to provide the best insight into biomechanical impairments in clinical populations, such as CAI individuals.

5. Conclusion

Individuals with CAI exhibited greater kinematic inter-trial variability compared to a group of healthy matched controls. Greater kinematic inter-trial variability in these individuals is clinically relevant as it may originate from diminished neuromotor control the ankle musculature. Since the effect of clinical interventions on neuromotor control strategies in individuals with CAI remain largely unknown, focus on intervention studies where such strategies are assessed under dynamic conditions may be warranted. To this end, prospective cohort studies that examine the predictive capabilities of variability-based measures may provide additional clinical applications to improve injury prevention protocols. Furthermore, examining changes in kinematic inter-trial

variability in groups with varying extents of ankle instability, or after targeted interventions may prove helpful in delineating between the mechanisms associated with CAI.

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