Frontal-Plane Variability in Foot Orientation During Fatiguing Running Exercise in Individuals With Chronic Ankle Instability

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Context: Researchers have reported increased variability in frontal-plane movement at the ankle during jumping in individuals with chronic ankle instability (CAI), which may increase their risk of recurrent ankle sprain. It is not known if this behavior is present during running gait or how fatigue affects the amount of frontal-plane–movement variability in individuals with CAI.

Objective: To investigate the amount of roll-angle variability at the foot during a fatiguing exercise protocol in participants with CAI.

Design: Controlled laboratory study.

Setting: Motion-analysis research laboratory.

Patients or Other Participants: A total of 18 volunteers with CAI (10 men, 8 women; age = 29.8 \pm 9.2 years, height = 175.8 \pm 11.2 cm, mass = 75.4 \pm 10.7 kg) and 17 volunteers serving as controls (8 men, 9 women; age = 28.2 \pm 6.3 years, height = 172.3 \pm 10.6 cm, mass = 68.8 \pm 12.9 kg).

Intervention(s): Kinematic data for foot position were collected while participants performed a functional fatigue protocol based on shuttle runs.

Main Outcome Measure(s): Variability (ie, standard deviation) of the roll angle of the foot about the x-axis, corresponding to inversion-eversion, was measured at 2 discrete times: 50 milliseconds before foot strike and 65% of stance.

Results: No differences in roll-angle range or variability were observed between limbs in either group. At 65% of stance, we found a main effect for time, whereby both groups demonstrated decreased roll-angle ranges at the end of the fatigue protocol (P=.01). A between-groups effect in the roll-angle variability at 65% of stance was noted (P=.04), with the CAI group exhibiting higher levels of variability. No between-groups differences were observed at 50 milliseconds before foot strike.

Conclusions: Chronic ankle instability is a complex, multifactorial condition that can affect patients in diverse ways. Identifying excessive foot-position variability in particular situations could potentially inform targeted rehabilitation programs.

Key Words: ankle injuries, gait, kinematics

Key Points

- A between-groups difference was observed in the variability of frontal-plane ankle motion at 65% of stance during running, with the chronic ankle instability (CAI) group demonstrating increased variability of roll angle by the end of the fatigue protocol in contrast to reduced variability in the control group.
- Frontal-plane range of motion and variability at the ankle were not different between the injured and uninjured limbs of the CAI group, suggesting that both injured and uninjured limbs should be addressed in rehabilitation programs.
- Group differences at 65% of stance could be attributed to the high levels of variability observed in a subgroup of lower-functioning participants with CAI, indicating that this variability is detrimental and offers no defense to a predisposed sensorimotor system.
- Differences in the amount of roll-angle variability within the CAI group at 2 discrete time points (ie, 50 milliseconds before foot strike [non-weight bearing] and 65% of stance [weight bearing]) may provide important information about the integrity of specific motor-control mechanisms that govern these 2 phases of the gait cycle in individuals with CAI.
- Identifying excessive variability of foot positioning in particular situations could potentially inform targeted rehabilitation
 programs that support the successful return of athletes to competition.

hronic ankle instability (CAI), a condition that frequently persists after an initial ankle sprain, is characterized by self-reported disability, reduced activity levels, sensorimotor deficits, and recurrent ankle injury.¹ It has been linked to a variety of causes, including altered gait mechanics after initial sprain. Patients with CAI have been shown to have a more inverted foot position and decreased foot-floor clearance during walking^{2,3} and jogging,^{4,5} a more lateral foot positioning and loading pattern during barefoot running,⁶ and a more laterally located center of pressure during lateral shuffling.⁷ Inconsistent foot positioning as an output of the locomotor system in patients with CAI and the aforementioned aberrant gait patterns may put them at increased risk of further ankle injury. It takes only an instant in time for an unstable ankle joint to exceed its safe functional limits and be reinjured.

Higher injury rates and more severe injuries have been observed toward the end of soccer games and practices,^{8,9}

researchers¹¹ have investigated the effect of fatigue on healthy ankle musculature, very few authors have examined the effect of fatigue on participants with CAI versus a control group. Gribble et al¹² found that dynamic postural control as measured by the Star Excursion Balance Test was disrupted in patients with CAI compared with control participants after a fatiguing lunge protocol and that this trend was amplified by fatigue. In contrast, Shills et al¹³ reported that an acute bout of intense exercise increased the time to stabilization when participants with or without ankle instability landed from a jump but reported no effect for ankle-stability status. Similarly, Steib et al¹⁴ observed no effect for ankle-stability status when investigating sensorimotor control after a fatiguing treadmill run in athletes with or without functional ankle instability. Thus, this area requires more investigation. Although other researchers have used a prefatigue-postfatigue study design, we adopted a more ecologically valid approach to investigating whether neuromuscular fatigue may affect individuals with CAI during athletic activities. Brown et al¹⁵ assessed movement variability in individuals with functional ankle instability during a stop-jump maneuver. These participants demonstrated greater variability in ankle frontal-plane movement than participants who had sprained their ankles only once.¹⁵ In other words, patients with functional ankle instability exhibited less consistent (more variable) positioning of the foot in the

suggesting an adverse effect of fatigue on the neuromus-

cular-control system. Woods et al¹⁰ reported that nearly half (48%) of all ankle sprains in soccer occurred during the last

third of each half of matches. Fatigue experienced during

sustained athletic activity is, therefore, considered an

important risk factor for ankle sprain. Whereas some

frontal plane during this dynamic task. The authors suggested that, if this variability is too great or unable to be controlled, individuals may exceed the limits of safe movement patterns, leading to further injury. In 2 other studies,^{5,16} researchers have identified differences in movement variability between people with CAI and healthy control participants. Yet how fatigue induced by dynamic activities common in athletics affects movement variability in individuals with CAI is unknown. Therefore, the purpose of our study was to investigate the magnitude of ankle frontal-plane variability at functionally important points in the gait cycle in participants with or without CAI during a functional fatigue protocol. Variability at the ankle joint can be measured in many ways, most recently using nonlinear analysis.¹⁷ Our study is based on a linear measure of variability similar to that in the study by Brown et al¹⁵ (ie, standard deviation [SD] of joint range of motion measured across repeated events, which in our case were strides). We hypothesized that participants with CAI would exhibit higher levels of variability than control participants and that this would be exacerbated by fatigue. In addition, given that the amount of movement variability present during walking has been linked to centrally mediated processes¹⁸ and that sensorimotor deficits associated with CAI have been observed in both injured and uninjured limbs,^{1,19} we examined the difference between injured and uninjured limbs in the CAI group. We hypothesized that we would observe no differences in frontal-plane variability at the foot between limbs, indicating that CAI is more than a peripheral musculoskeletal problem.

METHODS

Participants

We calculated an a priori sample size using published data¹⁵ in which the authors investigated differences in kinematic variability between individuals with functional or mechanical ankle instability during a stop jump. The variable chosen from this study was the SD of ankle inversion-eversion. Using a repeated-measures analysis of variance between-within-participants model to achieve a power of 0.8 with an α level of .05, we calculated that a sample size of 16 per group was needed. Accordingly, 18 individuals with CAI (10 men, 8 women; age = 29.8 ± 9.2 years, height = 175.8 ± 11.2 cm, mass = 75.4 ± 10.7 kg) and 17 healthy individuals serving as controls (8 men, 9 women; age = 28.2 ± 6.3 years, height = 172.3 ± 10.6 cm, mass = 68.8 ± 12.9 kg) participated.

Inclusion criteria followed those described by Drewes et al.⁵ Healthy participants were those who had never sustained an ankle sprain and had no history of lower extremity injury in the 12 months before the study. Participants with CAI had a history of more than 1 sprain of the same ankle but no sprains in the 8 weeks before the study. Neither group had peripheral neuropathies or a history of surgery to the lower limbs. The participants with CAI were identified based on validated questionnaires that assessed their injuries: the Cumberland Ankle Instability Tool (CAIT)²⁰ and the Foot and Ankle Ability Measure (FAAM).²¹ The CAIT examines each limb separately. Participants scoring 28 or more of 30 are unlikely to have CAI, whereas participants scoring 27 or less are likely to have CAI.²⁰ The FAAM includes 2 subscales: one for selfreported dysfunction during activities of daily living and the other for sporting activities. This questionnaire has been shown to be a valid tool for detecting self-reported functional deficits related to CAI.²² Activity levels were quantified using the short-form International Physical Activity Questionnaire. All participants provided written informed consent, and the study was approved by the Research Ethics Committee of University College Dublin.

Instruments

Kinematic data were collected in a motion-analysis laboratory using 3-dimensional scanners (model CODA CX-1/MPX30; Charnwood Dynamics Ltd, Leicestershire, United Kingdom) that tracked the location of light-emitting diode markers placed on specific landmarks. The scanners were set up at either side of the runway to capture a portion of straight-line running over a distance of approximately 6 m (Figure 1). The data were sampled at 200 Hz. The cameras were placed approximately 3 m from the runway. The lateral-position resolution of a static marker measured with this system²³ at a 3-m range is 0.05 mm. Previous work²⁴ conducted with this system in our laboratory has shown excellent reliability (intraclass correlation coefficient >0.97) in measures of frontal-plane angular displacement of the ankle during gait.

Procedures

Participants began the protocol with a 5- to 10-minute warm-up on the treadmill at a self-selected intensity. Next,



Figure 1. Experimental setup.

they performed 2 maximal vertical jumps. The higher of the 2 jumps was used to calculate the target jump height for the fatigue protocol (80% of maximal jump height). A 14-m space was marked in the laboratory (Figure 1). The participants started at line A and ran 14 m to line B. They stopped at line B and quickly performed a vertical jump, reaching to the preset target height. After landing from the jump, they turned in a self-selected direction, ran back to line A, touched the line, turned, ran to line B, performed the jump, turned, ran to line A, and so on. When participants were familiar with the protocol, they were instructed to perform 10 timed repetitions at maximal effort to determine the velocity at which they would run. We calculated an average time for 1 repetition and set a beep interval at 125% of this time. This procedure was implemented to normalize the speed at which each person ran. The aim of the protocol was to induce fatigue in a way that was similar to that induced by athletic activities, and therefore the protocol included jumping, landing, running, and changes of direction. This protocol has been validated with participants exhibiting reduced knee-extensor maximal voluntary isometric contraction after performing the protocol and reporting a mean score of perceived exertion $(RPE)^{25}$ greater than 17.²⁶

Participants wore their own running shoes. To construct a rigid body, active light-emitting diode markers were firmly attached with tape to the outside of both running shoes on the following landmarks: the lateral aspect of the fifth metatarsal head, the posterior inferolateral aspect of the heel, and the lateral malleolus. A static trial in the upright standing posture was recorded to provide an anatomic zero reference for later analysis. The functional fatigue protocol was started at least 10 minutes after participants performed the 10 repetitions at maximum effort. Data were collected for 20 seconds at 1 minute after the protocol commenced and at each 2-minute interval thereafter until the protocol was terminated (ie, minutes 1, 3, 5, 7, etc). Within each 20second period, participants ran through the recording space at least 4 times, with 3 to 4 steps recorded each time. Therefore, approximately 12 foot contacts (6 right, 6 left) were recorded per 20-second period. The cameras were arranged so that the straight-line running gait could be assessed outside the periods of acceleration and deceleration. Heart rate was monitored regularly using a heart-rate monitor (Polar, Kempele, Finland) to ensure that participants did not exceed their age-predicted maximum heart rate (220 - age)²⁷ Strong encouragement was given to participants toward the end of the protocol. They ran in time to the beep interval until they were no longer able to maintain the tempo for 3 consecutive beeps. At the end of the protocol, heart rate, RPE, and exercise time were recorded. The same researcher (D.M.) conducted each test, minimizing the possibility of intertester errors.

Data Processing

Data were acquired using Codamotion analysis software (Charnwood Dynamics Ltd). Foot-strike and toe-off times were extracted from the data. The toe-off time was determined with the method of Fellin et al,²⁸ who used local maximum knee extension as the point of toe-off. We determined foot strike by detecting a negatively directed zero crossing on the vertical jerk curve of the heel marker. This method for calculating foot strike during running was validated a priori against force-plate data for a group of 35 participants.

A rigid body was defined by 3 markers on each foot; the lateral heel and fifth-metatarsal head markers defined the xaxis, and the lateral heel and lateral malleolus defined the zaxis. Rigid body orientation with respect to the floor was calculated. Rotation about the x-axis, called the Euler roll angle, was the variable of interest, as this corresponds to inversion-eversion motion at the ankle. Each individual's roll-angle data were calculated relative to a neutral standing posture recorded before beginning the protocol. Roll angle was measured at 2 discrete points: 50 milliseconds before foot strike and 65% of stance. These points were deemed important in the context of loading and unloading of the foot.^{29,30} Data inspection indicated that the greatest active force occurred at approximately 65% of stance, when the ankle was plantar flexing. To separate experimental error from movement variability, we visually inspected all raw marker data for each trial and each participant. When marker visibility was compromised (as with 6 foot strikes from 1 participant), these data were omitted from the analysis.

The data were exported to MATLAB (The MathWorks, Natick, MA), and the mean roll angle at the foot and variability of roll angle were calculated for each participant over time. The SD across strides was used to measure the variability of foot position.¹⁵ Therefore, the mean roll angle captured the mean across the groups, and the associated SD of this variability reflected interparticipant variability. Importantly, the variability of the roll angle captured the intraparticipant variability across trials, which was then averaged across groups (ie, the average SD). Thus, *variability of roll angle* referred to the mean intra-

Table 1. Comparison of Injured and Uninjured Limbs in the Chronic Ankle Instability Group

Variable	Fatigue Protocol			
	Beginning		End	
	t Value	P Value	t Value	P Value
Roll angle at 50 ms before foot strike ^a	0.91	.37	0.95	.36
Variability of roll angle at 50 ms before foot strike ^b	0.44	.66	-0.02	.98
Roll angle at 65% of stance ^a	0.36	.70	0.51	.61
Variability of roll angle at 65% of stance ^b	0.69	.50	-0.74	.47

^a Roll angle indicates the mean roll angle across the group.

^b Variability of roll angle is derived by calculating the SD across trials for each participant and then calculating the mean of these SDs across groups, representing the amount of intraparticipant variability.

participant variability across groups. To examine the effect of fatigue on each variable, strides from minutes 1 and 3 of the fatigue protocol were combined and compared with the data collected in the last 2 data-collection periods of the fatigue protocol. before foot strike and 65% of stance. The α level was set at .05.

RESULTS

Statistical Analysis

We used independent t tests to compare between-groups differences in CAIT and FAAM scores and demographic characteristics. Dependent t tests were performed to investigate differences between the injured and uninjured limbs of the CAI group and both limbs of the control group at 50 milliseconds before foot strike and 65% of stance. When no differences between limbs were observed, the right and left limbs were averaged, and a 2×2 betweenwithin-participants analysis of variance was conducted to assess the effect of fatigue (beginning and end of protocol) and group (CAI and control) on the variability of the roll angle at 50 milliseconds before foot strike and 65% of stance. Similarly, 2 additional analyses of variance were performed to compare mean foot-roll angle between the groups at 50 milliseconds before foot strike and 65% of stance. The Mauchly Test of Sphericity was used to assess the assumption of sphericity. All statistical analyses were conducted with SPSS (version 18; SPSS Inc, Chicago, IL). Two limbs from the same person were not included as independent samples in these analyses. We also conducted a single-participant analysis, graphing and visually inspecting the data for each participant to identify individual characteristics that might have been masked in the group analyses. We defined high levels of variability as magnitudes of variability that exceeded 1 SD above the overall group roll-angle variability at 50 milliseconds

The control group yielded average scores of 29.5 \pm 0.9 for the left limb and 29.5 \pm 0.9 for the right limb on the CAIT, whereas the CAI group produced average scores of 15.0 ± 6.0 for the injured limb and 29.1 ± 1.3 for the uninjured limb. On the FAAM, control participants scored $99.6\% \pm 1.5\%$ on the activities of daily living subscale and $98.0\% \pm 2.4\%$ on the sports subscale. The CAI group scored $89.2\% \pm 13.5\%$ on the activities of daily living subscale and $72.5\% \pm 17.0\%$ on the sports subscale. Independent t tests showed differences between groups on both instruments (t range = 3.05-8.41, P < .05) but did not reveal differences in age, height, mass, or habitual activity level (t range = 0.04-1.50, P > .05). Exercise time was 12.0 \pm 2.9 minutes for the CAI group and 11.4 \pm 2.3 minutes for the control group. The final heart rate was 183.0 ± 7.3 beats per minute for the CAI group and 180.0 ± 8.7 beats per minute for the control group. The rate of perceived exertion at the end of the fatigue protocol was 17.3 ± 0.9 for the CAI group and 17.4 ± 0.8 for the control group. The beep speed was set at an average speed of 10.3 \pm 0.8 k/h for the CAI group and 10.1 ± 0.8 k/h for the control group.

The assumption of sphericity was violated for all variables, and consequently, only the corrected multivariate statistics were considered. No differences were observed between limbs in either group for any variable (Table 1). At 65% of stance, an effect for fatigue was present in the mean roll angle ($F_{1,33} = 6.94$, P = .01), indicating that as the individuals in both groups fatigued, they reduced the amount of the roll angle (Table 2). No between-groups

Table 2	Variables for Each Grou	n at the Beginning	and End of the Fati	que Protocol (Mean + SD)
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Variable, °	Fatigue Protocol			
	Beginning		End	
	Chronic Ankle Instability Group	Control Group	Chronic Ankle Instability Group	Control Group
Roll angle at 50 ms before foot strike ^a	15.5 ± 3.9	16.8 ± 4.9	15.6 ± 3.5	16.3 ± 4.5
Variability of roll angle at 50 ms before foot strike ^b	4.0 ± 1.4	3.7 ± 1.1	4.0 ± 1.3	3.5 ± 0.7
Roll angle at 65% of stance ^a	4.1 ± 5.9	$4.6~\pm~6.1$	$3.5~\pm~5.8^{\circ}$	$3.4~\pm~5.8^{\circ}$
Variability of roll angle at 65% of stance ^b	2.4 ± 0.6	2.1 ± 0.7	$2.1~\pm~0.8^{d}$	1.9 ± 0.6^{d}

^a Roll angle indicates the mean roll angle across the group.

^b Variability of roll angle is derived by calculating the SD across trials for each participant and then calculating the mean of these SDs across groups, representing the amount of intraparticipant variability.

^c Within-group effect (P = .01).

^d Between-groups difference (P = .04).



Figure 2. Maximum amount of variability recorded from each participant at A, 50 milliseconds before foot strike, and B, 65% of stance. ^a Threshold of 1 standard deviation above the mean. Levels of variability above this threshold were classified as high.

differences were noted in mean roll angle ($F_{1,33} < 0.001$, P = .93); however, differences were evident in the variability of the roll angle at 65% of stance ($F_{1,33} = 4.44$, P = .04), with increased variability of the roll angle by the end of the protocol in the CAI group and reduced variability in the control group (Table 2). No between-groups effects were seen in either variability ($F_{1,33} = 1.72$, P = .20) or the mean roll angle ($F_{1,33} = 0.46$, P = .50) at 50 milliseconds before foot strike.

The individual analyses helped us to identify participants who demonstrated high levels of roll-angle variability (Figure 2). As noted, we defined high levels of variability as magnitudes of variability that exceeded 1 SD above the overall group roll-angle variability at 50 milliseconds before foot strike and at 65% of stance. Accordingly, high variability at 50 milliseconds before foot strike was classified as values greater than 5.4° . High variability at 65% of stance was classified as values greater than 3° .

DISCUSSION

We investigated the magnitude of frontal-plane intraparticipant movement variability in people with CAI and a healthy control group during a fatiguing athletic activity. Frontal-plane roll-angle variability at 2 discrete points in the gait cycle during a sustained exercise task was examined. Fatigue was induced through a functional fatigue protocol that included acceleration, deceleration, change of direction, and jumping to a target to emulate the demands of a real-life athletic situation. The rate of perceived exertion and heart-rate values indicated that the protocol was challenging enough to induce fatigue in both groups. Our hypotheses were partially supported; no differences were observed between the injured and uninjured limbs, indicating that CAI is more than a peripheral musculoskeletal problem. At 65% of stance but not at 50 milliseconds before foot strike, both groups reduced the mean roll angle in response to fatigue, and the CAI group demonstrated greater roll-angle variability than the control group. However, no interaction effect (ie, fatigue by group) was observed. This finding supports the research of Steib et al,¹⁴ who also found no interaction effects in their study on fatiguing treadmill running.

No differences were observed between limbs for mean roll angle or variability of roll angle at either 50 milliseconds before foot strike or 65% of stance. The existence of bilateral deficits due to a unilateral ankle injury suggests a centrally mediated motor-control adaptation. Evidence of bilateral postural-control impairments,³¹ alterations in proximal muscle control,^{29,32,33} and altered feedforward motor programs in individuals with CAI³⁴ supports the theory that spinal and supraspinal motor-control mechanisms are involved in CAI.¹⁹ Whereas a body of evidence has identified sensorimotor deficits only on the injured side,¹ the fact that we observed no differences in mean roll angle or roll-angle variability between the injured and uninjured limbs supports the theory that alterations in centrally mediated control mechanisms are involved in CAI. This has important implications for the design of rehabilitation programs: both injured and uninjured limbs should be included in rehabilitation tasks. The magnitude of variability in gait variables has been associated with changes in blood flow to cortical structures.¹⁸ Movement variability, therefore, may be a useful model for investigating centrally mediated deficits in musculoskeletal disorders.

We investigated foot rotation about the x-axis at 2 discrete points: 50 milliseconds before foot strike and 65% of stance. These points were deemed important in the context of the mechanism of lateral ankle injuries. With cadavers³⁰ and computer modeling,³⁵ investigators³⁶ have shown that the foot position at touchdown can affect the occurrence of ankle sprains. If the foot is held in an excessively inverted position when it reaches the ground, an external inversion load is placed on the joint, increasing the likelihood of injury. Ankle destabilization occurs during loading and unloading of the stance limb.³⁷ Many researchers^{2,3,5} examining changes in joint kinematics during gait in participants with CAI have focused on the

critical loading phase (ie, just before foot strike). Few investigators have explored the kinematic behavior of the foot leading up to the unloading phase in these patients. The passive forces associated with heel strike have a shorter duration than the longer active forces exerted in the latter portion of the stance phase.³⁸ Renstrom and Konradsen³⁷ stated that the most common mechanism of lateral ligament injuries was combined plantar flexion and inversion of the ankle. Therefore, we wanted to examine how the chronically unstable ankle joint behaves when large forces are actively exerted in late stance through a loaded, plantarflexing foot. Inspection of our data confirmed that at 65% of stance, the power-generation phase is ongoing and the foot is moving into plantar flexion. The reduced base of support, the vulnerable position of the ankle mortise, and the magnitude of ground reaction force being exerted together with more inconsistent foot positioning could create a precarious situation for the ankle.

At 50 milliseconds before foot strike, no differences between groups were observed. This finding is in contrast to the results of several other studies^{2,3,5} in which researchers reported differences in frontal-plane motion between CAI and control groups immediately before foot strike during walking and jogging. However, Chinn et al⁴ observed these differences not during jogging before foot strike but during other parts of the stride. They suggested that this discrepancy might have been because their participants wore shoes as opposed to previous studies in which participants were barefoot. Similar to Chinn et al,⁴ we required participants to wear their own running shoes. Future work, therefore, is required to ascertain the effect of shoes on the biomechanical aspects of running in participants with CAI.

At 65% of stance, roll-angle variability was different between the CAI and control groups, with the CAI group demonstrating increased variability of foot positioning in the frontal plane (inversion-eversion) during running. Both groups reduced the mean roll angle because of fatigue. Reducing the amount of movement in this plane while fatigued may have been an adaptive strategy that these participants adopted to combat impaired muscle-activation patterns observed in fatigue.¹⁴ Crucially, the CAI group executed this movement strategy less consistently. This result mirrors the work of Kipp and Palmieri-Smith,³⁹ who reported that average motion did not differ between CAI and control groups but magnitudes of intertrial variability did. Higher levels of intraperson variability in the CAI group could have 2 implications: (1) this poorly controlled, erratic movement strategy puts the individual at greater risk of going over on the ankle (ie, if the foot is improperly positioned and if the center of pressure moves laterally within the base of support, thereby creating a laterally directed ground reaction force vector, an injurious external inverting moment could result), or (2) the increased variability represents a sensitive corrective mechanism that reacts to larger roll angles in the inversion direction. However, even if the latter case is correct and participants with CAI adopt a sensitive corrective strategy during running, this rather complex intervention may overload a sensorimotor system that is already constrained by the injury itself, as previously suggested.⁴⁰

Classifying variability as either good or bad is challenging. The idea that all variability has detrimental effects or is

advantageous is too simplified. Classifying variability in either category depending on its context may be more reasonable. A closer examination of each participant was required to answer this question, particularly in view of the large SDs for the CAIT and FAAM questionnaires in the CAI group. We identified participants who exhibited high variability at 65% of stance, a level of variability 1 SD above the overall mean, which resulted in a subgroup of 13 individuals: 8 from the CAI group and 5 from the control group (Figure 2B). The 5 participants from the control group were classified as having high levels of habitual activity by the International Physical Activity Questionnaire. Specifically, this subgroup consisted of competitive athletes: 1 mountain runner, 1 ballet dancer, 2 volleyball players, and 1 squash player. These athletic activities particularly challenge dynamic neuromuscular control via rapid changes in direction, landing from jumps, or running over uneven ground, which could suggest that the variability observed in their performance would be a beneficial strategy. Variability in foot orientation during late stance in these types of movements may afford the adaptability necessary to safeguard the ankle joint during demanding dynamic activities that are common to their respective sports. Conversely, the 8 participants with high variability from the CAI group composed a subset who scored an average of 62% on the sports subscale of the FAAM and 12.3 on the CAIT. These values were considerably less than the CAI group averages of 72.5% and 15.0, respectively. The group differences at 65% of stance could perhaps be attributed to the high level of variability observed in this subgroup of lower-functioning CAI participants, suggesting that this variability is detrimental and offers no defense to a predisposed sensorimotor system.

At 50 milliseconds before foot strike, 4 participants from the control group and 7 participants from the CAI group demonstrated high levels of variability (Figure 2A). Four competitive athletes from the control group who exhibited high levels of variability at 65% of stance were in this subgroup. This corroborates the suggestion that participating in sports characterized by demanding dynamic activities that challenge the neuromuscular-control system may have engendered highly variable foot positioning in these uninjured participants as a functional adaptation. However, only 1 participant from the CAI subgroup who displayed a high level of variability at 65% of stance was in the subgroup that also displayed a high level of variability at 50 milliseconds before foot strike. This finding raises an interesting question: why do some participants with CAI exhibit high levels of variability at 50 milliseconds before foot strike but not at 65% of stance, whereas others exhibit high levels of variability at 65% of stance but not at 50 milliseconds before foot strike? The answer may lie in the motor-control mechanisms involved. Optimal positioning of the foot in weight bearing (65% of stance) is predominantly mediated by proprioceptive information emanating from the muscle, joint, and cutaneous mechanoreceptors of the foot and ankle.⁴¹ At this point, increased variability in participants with CAI may suggest some amount of feedback impairment that results in unreliable foot positioning. Yet optimal positioning of the foot before foot contact is thought to be governed predominantly by preparatory activity.^{42,43} The fact that subgroups of

participants with CAI in this study demonstrated taskspecific, mutually exclusive variability behaviors may have important implications for treatment interventions and warrants further research.

Moreover, this study raises the important factor of heterogeneity among individuals with CAI that may preclude the emergence of differences when group analyses are performed. Thoroughly examining standard group analysis, particularly in relation to the effect of fatigue, could be a useful adjunct in CAI studies. After all, clinicians treat individual patients and not the "average" patient. Recently, the effect of CAI has been described in terms of patient-, clinician-, and laboratory-oriented alterations.⁴⁴ Implicit in this model is the understanding that not all patients with CAI present with all of the known deficits associated with CAI. Rather, ankle sprains increase the organismic constraints in diverse ways, depending on, for example, the individual's state of health, the mechanisms of injury, acute-phase interventions, or an individual's underlying beliefs about being injured. The varied organismic constraints that emerge require patients to adopt strategies that best enable them to achieve their personal movement goals in whatever environments they choose to place themselves.⁴⁴ Therefore, in reporting research findings, investigators should to try to reveal the nuanced patterns within this diversity.

Whereas the between-groups comparison of roll-angle variability at the end of the fatigue protocol was different, the magnitude of this difference was less than 1°. This raises the question of whether this difference is clinically meaningful. Konradsen⁴⁵ examined a similar question in the context of unprovoked collisions between the foot and the ground in patients with previous ankle injuries. He calculated that inversion-angle replication errors of approximately 0.9° in acutely injured or chronically unstable ankles could statistically lead to an unprovoked collision with the ground once in every 1000 steps, compared with once in every 100 000 steps for individuals with stable ankles. This suggests that the small group difference in rollangle variability we found could have considerable clinical effects. Interestingly, closer investigation of the CAI group revealed that increased roll-angle variability was a much more pertinent factor for some individuals than for others, with some participants with CAI exhibiting levels of variability that substantially exceeded the between-groups difference.

Our study had some limitations. The participants performed the protocol wearing their own athletic shoes for comfort and to enable us to generalize our results to shod-athlete conditions. Given that the motion of the ankle, subtalar, and transverse tarsal joints cannot be accurately detected in athletic shoes, movement at the ankle was measured and reported as a rigid body. Whereas this is an oversimplified model, it is a commonly used method in running research.³⁸ Furthermore, sweating combined with velocity-related movement artifact was a considerable challenge when participants executed this protocol. Markers adhered to shoes conferred the greatest reliability.

Another limitation was the challenge of controlling the fatigue levels experienced by participants. It is necessary to establish functional fatigue models that represent the type of physical activity that occurs in athletic training and competition (ie, accelerating and decelerating the body, changing direction, jumping, landing, and metabolic stress). Although this approach cannot match the high reliability associated with laboratory-based ergometers, the high ecological validity of sport-specific functional fatiguing protocols makes them a more meaningful research tool. In addition, as with all fatigue-related research, the points at which each participant terminated the fatigue protocol may have represented disparate levels of fatigue. All participants reported high RPE scores after the fatiguing protocol, but it is widely accepted that perception of effort depends on motivation and previous experience with pushing oneself beyond the limits of exercise-induced discomfort. However, all participants were strongly encouraged in the same manner and were highly motivated to complete the protocol to the best of their ability. All participants had engaged in sport or exercise at some level and were accustomed to exercise-induced discomfort.

Using SD as a linear measure of variability in our study suggests that each step is independent of any other. Whereas this method is commonly applied in variability research,⁴⁶ many researchers^{47,48} have shown this assumption to be untrue. To create a complete picture of human movement variability, nonlinear measures that examine how fluctuations in gait evolve over time should be used in addition to the standard linear measures of the magnitude of these fluctuations, as presented here. Future researchers can adopt this approach to investigate how the underlying dynamics of the sensorimotor system are affected in CAI. Advances in technology can facilitate this goal, where continuous running data can be collected using on-body wearable sensors in an outdoor, ecologically valid environment.

CONCLUSIONS

We observed a reduced roll angle of the foot during running due to a functional fatigue protocol in both a CAI group and a control group. More inconsistent frontal-plane foot positioning was observed in the CAI group than in the control group. This difference was evident around the active push-off phase in running at 65% of stance but not at 50 milliseconds before foot strike. No differences were observed between the injured and uninjured limbs. Ecological validity was emphasized in the experimental design to enable us to generalize our findings to athletic activities. When examining the individual data, we observed some interesting, more subtle characteristics within the CAI group. We propose that the increased variability observed could be a maladaptive movement strategy associated with CAI that may increase the risk of repeated ankle sprains during training or competition. Differences in the amount of roll-angle variability in participants with CAI under 2 conditions, at 50 milliseconds before foot strike (non-weight bearing) and 65% of stance (weight bearing), may reveal important information that relates to the integrity of specific motor-control mechanisms that govern these 2 phases of the gait cycle in patients with CAI. Chronic ankle instability is a complex, multifactorial condition that can affect patients in diverse ways. Identifying excessive variability of foot position in particular situations could potentially inform targeted rehabilitation programs that support the successful return of athletes to competition.

ACKNOWLEDGMENTS

This study was funded by a University College Dublin Ad Astra scholarship (Dr McGrath).

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