

Characterization of Multiple Movement Strategies in Participants With Chronic Ankle Instability

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Context: Chronic ankle instability (CAI) is characterized by multiple sensorimotor deficits, affecting strength, postural control, motion, and movement. Identifying specific deficits is the key to developing appropriate interventions for this patient population; however, multiple movement strategies within this population may limit the ability to identify specific movement deficits.

Objective: To identify specific movement strategies in a large sample of participants with CAI and to characterize each strategy relative to a sample of uninjured control participants.

Design: Descriptive laboratory study.

Setting: Biomechanics laboratory.

Patients or Other Participants: A total of 200 individuals with CAI (104 men, 96 women; age = 22.3 ± 2.2 years, height = 174.2 ± 9.5 cm, mass = 72.0 ± 14.0 kg) were selected according to the inclusion criteria established by the International Ankle Consortium and were fit into clusters based on movement strategy. A total of 100 healthy individuals serving as controls (54 men, 46 women; age = 22.2 ± 3.0 years, height = 173.2 ± 9.2 cm, mass = 70.7 ± 13.4 kg) were compared with each cluster.

Main Outcome Measure(s): Lower extremity joint biomechanics and ground reaction forces were collected during a maximal vertical jump landing, followed immediately by a side cut. Data were reduced to functional output or curves, kinematic data from the frontal and sagittal planes were reduced to a single representative curve for each plane, and representative curves were clustered using a Bayesian clustering technique. Estimated functions for each dependent variable were compared with estimated functions from the control group to describe each cluster.

Results: Six distinct clusters were identified from the frontal-plane and sagittal-plane data. Differences in joint angles, joint moments, and ground reaction forces between clusters and the control group were also identified.

Conclusions: The participants with CAI demonstrated 6 distinct movement strategies, indicating that CAI could be characterized by multiple distinct movement alterations. Clinicians should carefully evaluate patients with CAI for sensorimotor deficits and quality of movement to determine the appropriate interventions for treatment.

Key Words: Bayesian clustering, functional data, ankle sprains

Key Points

- Participants with chronic ankle instability (CAI) demonstrated 6 distinct movement patterns during a jump-cut task.
- The 6 distinct movements placed participants with CAI in different vulnerable positions, emphasizing the idea that CAI may be perpetuated in various ways depending on the movement pattern.
- To develop appropriate treatment interventions, clinicians need to carefully evaluate participants with CAI for sensorimotor deficits and quality of movement, considering the patients and their movements individually.

Lateral ankle sprains are the most common joint injury among the physically active.^{1,2} Furthermore, these sprains often result in chronic residual symptoms, recurrent injury, and perceived instability, typically referred to as *chronic ankle instability* (CAI).³ Chronic ankle instability is a condition that affects quality of life in the short term (instability) and potentially results in an increased risk of long-term degenerative changes to the joint.⁴ The condition has been studied extensively over the past 20 years as clinicians and researchers looked for ways to identify key factors that contribute to the problem and clues for how to intervene effectively.

Specific mechanical and functional deficits have been identified among the population with CAI,^{5,6} including dorsiflexion range-of-motion (DF ROM) limitations,^{7,8} ankle-muscle and hip-muscle dysfunction,^{9–13} postural-

control insufficiencies,^{14,15} and movement alterations.^{16–19} Whereas each of these factors could, and likely does, play a role in perpetuating CAI, discrepancies exist in the reported results associated with them. Indeed, not all patients with CAI have all or even most of the reported deficits, and this variability is consistent with discrepancies across the literature.

The International Ankle Consortium³ proposed a list of selection criteria for studying the population with CAI to reduce the amount of variability that exists among studies.³ This step helped to narrow and define the patient population for more consistency among data sets. However, large amounts of variability still exist among patients with CAI, especially when the measure seeks to capture functional movement, which may be associated with the reinjury mechanism. The variability may not stem from how we

define the patient population symptomatically; rather, it may reflect the diversity of movement within the population.

Variation in functional movement, especially a demanding and complicated movement involved in sports, is likely normal and within the scope of the sensorimotor system.²⁰ Yet depending on the specific constraints or limitations after injury, movement variability after ankle injury may become more pronounced and specific. In other words, after ankle injury, people likely move differently given the environment, the tasks, and the alterations to damaged tissues.²⁰ The differences in movement stem from and lead to varied deficits, each of which is important to consider in the treatment of CAI. As we continue to study and try to treat this patient population, we need to consider the variable deficits that exist, understanding that all patients with CAI cannot be treated the same. Therefore, the primary purpose of our study was to identify specific groups or clusters of movement strategies during a demanding movement task in a large sample of participants with CAI. After distinct movement strategies were identified, our secondary purpose was to describe each strategy relative to a matched, uninjured control group.

METHODS

This study used a descriptive laboratory design to classify multiple specific movement clusters within a large sample of participants with CAI. Each movement strategy was also compared between the CAI group and a sample of participants who had never sustained an ankle injury (control group) to describe each cluster.

Participants

Participant descriptive information is presented in Table 1. A total of 300 individuals (158 men, 142 women) volunteered. Of these, 200 were identified as having unilateral CAI and selected in accordance with the inclusion criteria recommended by the International Ankle Consortium.³ Participants were classified using the Foot and Ankle Ability Measure (FAAM)²¹ and the Modified Ankle Instability Instrument (MAII).²² Inclusion criteria for the CAI group consisted of (1) at least 2 episodes of giving way in the 6 months before the study, (2) a FAAM–Activities of Daily Living (FAAM-ADL) score of <90%, (3) a FAAM-Sports score of <80%, (4) at least 2 *yes* answers on questions 4 through 8 of the MAII, (5) a history of at least 2 acute unilateral ankle sprains, (6) no acute lower extremity musculoskeletal injuries in the 3 months before the study, and (7) no history of lower extremity surgery or fracture. The inclusion criteria for the control group consisted of (1) a score of 100% on the FAAM-ADL and FAAM-Sports, (2) no *yes* answers on questions 4 through 8 of the MAII, (3) no history of ankle sprain, and (4) no history of lower extremity surgery or fracture. All participants were physically active, exercising at least 30 minutes per day, 3 days per week, in the 3 months before data collection. All participants provided written informed consent, and the study was approved by the Brigham Young University Institutional Review Board.

Table 1. Participants' Descriptive Information

Characteristic	Group	
	Chronic Ankle Instability	Control
Sex		
Male	104	54
Female	96	46
	Mean ± SD	
Age, y	22.3 ± 2.2	22.2 ± 3.0
Height, cm	174.2 ± 9.5	173.2 ± 9.2
Mass, kg	72.0 ± 14.0	70.7 ± 13.4
Body mass index ^a	22.3 ± 4.0	20.4 ± 3.2
Foot and Ankle Ability Measure, %		
Activities of Daily Living subscale	84.1 ± 7.3	100
Sports subscale	64.7 ± 10.7	100
Modified Ankle Instability Instrument, No. of <i>yes</i> responses to questions 4–8	3.5 ± 1.1	0
No. of ankle sprains	4.1 ± 2.4	0

^a Calculated as kg/m².

Procedures

A total of 59 reflective markers were placed over anatomic landmarks as described elsewhere.²³ Twelve high-speed video cameras (VICON, Oxford, UK) recording at 250 Hz were used to collect 2 dynamic video trials so that we could calculate the right and left functional hip-joint centers.²⁴ After performing up to 10 practice trials of a landing-cutting task onto a force plate (AMTI, Watertown, MA) collecting data at 2500 Hz,¹⁹ participants performed 10 trials of the task in which the first 5 successful trials were used to determine the maximal vertical jump height and the second 5 successful trials were used for data analysis. For a trial to be considered *successful*, the vertical jump height had to be within 5% of the maximal vertical jump height, and the participant had to hit the target locations. Vertical jump height was monitored by tracking the vertical position of the sacral marker.

The landing-cutting task consisted of a maximal, 2-footed vertical jump from a distance that was 50% of the participant's height from the center of the force plate, a landing on the involved limb, and an immediate 90° side-cut to the contralateral side at a distance that was 65% of the participant's height (Figure 1). Three target locations (starting, landing on the force plate, and side-cutting jump-landing locations) were marked to ensure consistency during the tasks. Participants were instructed to “jump as high as you can,” “land on the force plate with the test leg only,” and “side-cut at 90° to the contralateral side as quickly as possible” using maximal effort while facing forward during the movement. This jump task was chosen for several reasons: (1) it mimics the intensity of sport movement with a maximal jump, sudden deceleration and acceleration, and a change in direction; (2) it requires the participant to perform a demanding neuromuscular task while stabilizing the ankle; and (3) we could control the height of the jump, the starting point, and the landing point, allowing for some limits on the movement.

Dependent variables were analyzed during the ground-contact phase of the task.¹⁹ *Ground contact* was defined as

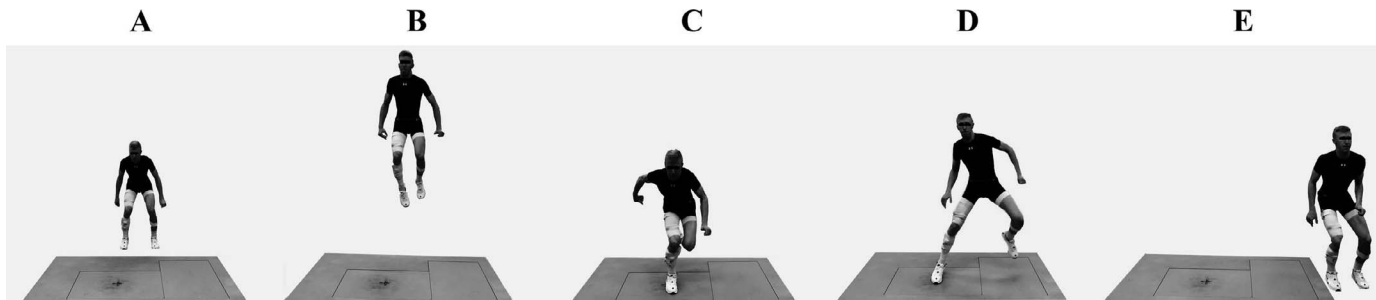


Figure 1. Jump-landing-cutting task. **A**, Starting position: a distance 50% of the participant's height away from the center of the landing target. **B**, Maximal vertical jump. **C**, Landing on the involved limb. **D**, Immediate transition to a side jump. **E**, Landing with the uninvolvement limb on a point 65% of the participant's height. Reprinted with permission from Kim et al.¹⁸

the time from foot contact on foot departure from the plate. Furthermore, for clarification in the discussion, the ground-contact phase was divided into 2 phases: (1) *landing*, which was from initial contact to peak dorsiflexion (approximately 50% of ground contact), knee flexion (approximately 50% of ground contact), and hip flexion (approximately 32% of ground contact); and (2) *cutting*, which was from peak sagittal-plane ankle, knee, and hip angles to toe-off.

We identified the 3-dimensional trajectories for each reflective marker using VICON Nexus and then exported these trajectories and ground reaction forces (GRFs) to Visual 3D software (C-Motion, Germantown, MD) for further analysis. Trajectory and GRF data were filtered using a fourth-order, low-pass Butterworth filter with a 10-Hz cutoff frequency. As described previously,¹⁹ a rigid link model (foot, shank, thigh, and pelvis segments) was created, and ankle-, knee-, and hip-joint angles were calculated using a Cardan rotation sequence. Frontal-plane and sagittal-plane net internal joint (ankle, knee, and hip) moments were calculated from the synchronized joint kinematics, anthropometric data, and GRF data using a standard inverse-dynamics approach.²⁵ The joint moments were normalized to the participant's body mass.

Statistical Analysis

Data were analyzed as functions or curves, which represented the entire ground-contact portion of the landing-cutting task. The observed curves were treated as realizations of functional output, so functional data techniques were used to model the data.²⁶ Before model fitting, we registered (ie, aligned) the participants' functional output using landmark-based registration.^{27,28} Next, for both the frontal and sagittal planes, the functional output from the ankle, knee, and hip was reduced to 1 representative curve through functional principal components.²⁶ Finally, using landmark-based registration,²⁸ the representative curves were independently aligned across participants for each plane. The resulting representative curves were used as a bivariate response in statistical modeling; therefore, both influenced curve clustering simultaneously.

We used a hierarchical model to represent the bivariate representative curve response so that participant-specific curves were assumed to originate from cluster-specific mean curves. The hierarchical Bayes model comprises 3 levels. At the first level, the observed participant-specific representative movement curves for each plane are flexibly modeled using penalized B-splines with errors that are

normally distributed.^{29,30} At the second level, for each plane, the spline coefficients are modeled with a normal distribution centered at the cluster-specific curve to which the individual was randomly allocated. In other words, the individual representative curves for each plane are modeled with a mixture model that has components centered on the cluster-specific curves. At the third level, a product partition model³¹ is used to model the clustering of curves for both planes. It assigns each participant a set of probabilities that indicate to which cluster he or she will be assigned. The cluster probabilities are based on the similarity³² of individual curves for each plane relative to cluster-specific curves. The product partition model results in probabilistic clustering based on the sagittal-plane and frontal-plane representative curves simultaneously. After fitting the hierarchical model, the partition (ie, cluster configuration of the 200 participants with CAI) was estimated using the Dahl least-squares method.³³ The resulting clusters are provided in Figure 2.

After each cluster was defined, data (ankle-joint, knee-joint, and hip-joint angles and moments and GRFs) composing each cluster were compared with the control-group data using a functional data-analysis approach (R version 2.15.1; The R Project for Statistical Computing, Vienna, Austria) in which entire functions (curves) were compared between each cluster and the control group. When the difference between the functions and the corresponding 95% confidence interval (CI) did not cross zero, group findings were considered different. This functional approach allowed comprehensive evaluation of statistical between-groups differences along with 95% CIs to provide an estimate of effect size across the entire ground-contact phase of the jump-landing-cutting task.

RESULTS

Representative curves for each participant with CAI ($n = 200$) in the frontal and sagittal planes are shown in Figure 2A. The 6 clusters from the representative curves are represented in Figure 2B. When we used frontal-plane and sagittal-plane representative curves simultaneously, participants naturally fit 6 distinct movement patterns (clusters). Descriptive data for the participants with CAI in each cluster are presented in Table 2.

With participants fit into clusters, each cluster was used in group assignment for comparisons of each dependent variable. These comparisons are represented in Supplementary Figures 1 through 5 (available online at <http://dx.doi.org/10.4085/1062-6050-480-17.S1>), and those data are

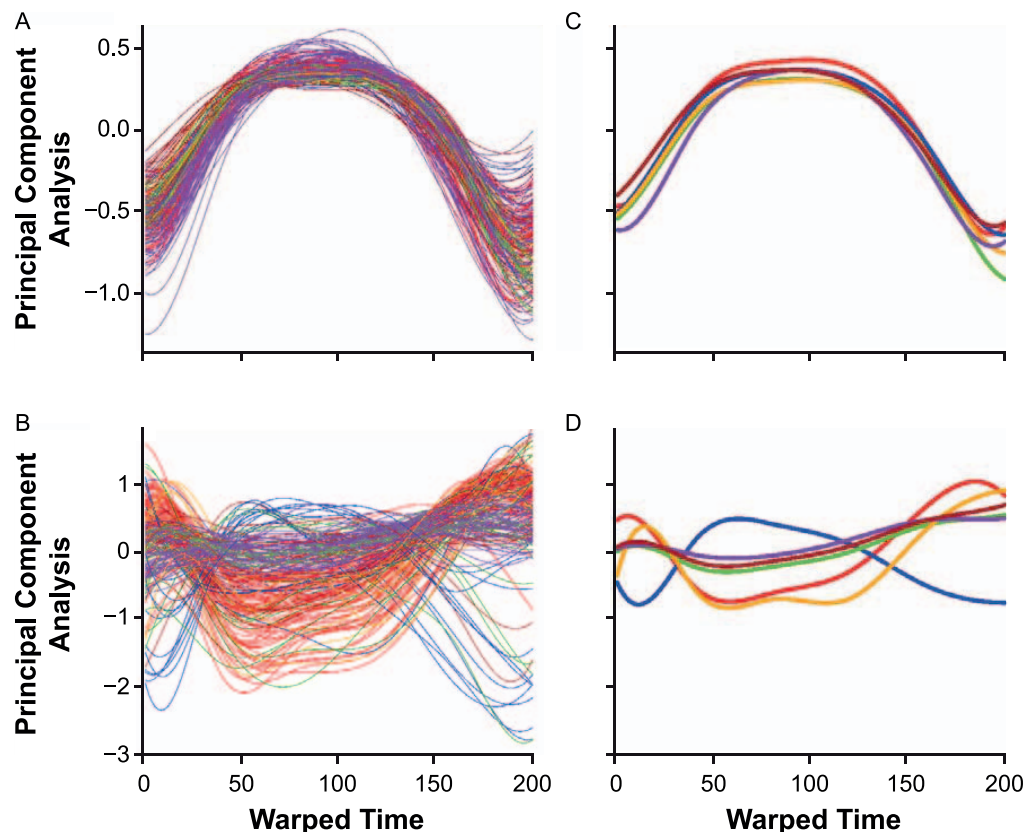


Figure 2. Functions (curves) from each ground-contact phase and from each joint (ankle, knee, and hip) were reduced to a single curve using principal component analysis in the, **A**, sagittal and, **B**, frontal planes. Representative curves from both, **C**, sagittal and, **D**, frontal planes were modeled simultaneously using a Bayesian technique to cluster functions according to the characteristics of each function (amplitudes, changes in direction, duration of changes, etc).

summarized in this section. The differences reported include the 95% CI bands.

Cluster 1 Versus Control Group

The findings for this cluster are illustrated in Column A of Supplementary Figures 1 through 5. Vertical GRF

(vGRF) was up to 40% of body weight (BW) less in cluster 1 than in the control group from 0% to 12% and 20% to 65% of ground contact. Posterior GRF (pGRF) was up to 28% of BW less from 0% to 14%. Medial GRF (mGRF) was up to 35% of BW more from 0% to 8% and less from 9% to 100%. Cluster 1 also demonstrated up to 4° more plantar-flexion (PF) range of motion (ROM) from 0% to

Table 2. Cluster Descriptive Data

Characteristic	Chronic Ankle Instability Cluster						Control Group
	1 (n = 71)	2 (n = 58)	3 (n = 28)	4 (n = 21)	5 (n = 14)	6 (n = 8)	
Sex							
Male	40	41	7	10	5	1	54
Female	31	17	21	11	9	7	46
	Mean ± SD						
Age, y	21.9 ± 2.4	22.1 ± 1.9	22.4 ± 2.9	21.7 ± 2.1	22.0 ± 2.0	21.3 ± 1.5	22.2 ± 3.0
Height, cm	176.2 ± 10.3	176.6 ± 10.2	170.0 ± 8.8	173.8 ± 11.4	171.2 ± 9.0	169.4 ± 5.9	173.2 ± 9.0
Mass, kg	75 ± 13	76 ± 15	64 ± 9	75 ± 13	67 ± 14	66 ± 9	70.7 ± 13.4
Body mass index ^a	23.9 ± 3.7	22.2 ± 4.2	20.4 ± 3.3	21.8 ± 3.3	20.9 ± 4.4	20.4 ± 2.7	20.4 ± 3.2
Maximum jump, cm	36.2 ± 10.9	40.9 ± 11.0	27.4 ± 12.2	30.3 ± 11.9	28.4 ± 10.9	28.0 ± 4.4	35.2 ± 12.0
Foot and Ankle Disability Measure, %							
Activities of Daily Living subscale	85.8 ± 4.7	85.0 ± 6.8	82.3 ± 10.9	81.3 ± 9.6	78.1 ± 8.4	85.7 ± 3.7	100
Sports subscale	66.9 ± 11.0	66.1 ± 10.3	63.8 ± 11.4	60.0 ± 13.8	59.0 ± 12.9	69.3 ± 7.4	100
Modified Ankle Instability Instrument,							
no. of yes responses to questions 4–8	3.5 ± 1.0	3.5 ± 1.2	3.6 ± 1.2	3.7 ± 1.3	3.8 ± 1.1	3.4 ± 1.3	0
No. of ankle sprains	3.9 ± 2.2	3.9 ± 2.0	3.9 ± 2.6	4.7 ± 2.8	5.1 ± 3.4	3.6 ± 2.8	0

^a Calculated as kg/m².

10%, 2° less dorsiflexion (DF) angle from 27% to 65%, 2° less knee flexion from 30% to 57%, and 4° more hip flexion from 0% to 9% and 17% to 87% of ground contact. In the frontal plane, cluster 1 showed up to 2° more eversion from 0% to 6%; up to 11° more inversion from 7% to 73%; up to 3° less inversion from 79% to 96%; up to 6° more knee abduction from 6% to 88%; and up to 6° more hip abduction from 0% to 24%, 31% to 43%, and 58% to 100% of ground contact. Cluster 1 also demonstrated up to 0.2 Nm/kg BW less PF moment from 0% to 69%, up to 0.35 Nm/kg BW more PF moment from 76% to 94%, up to 0.6 Nm/kg BW less knee-extension moment from 0% to 70%, up to 0.4 Nm/kg BW more hip-flexion moment from 5% to 15%, up to 0.1 Nm/kg BW less hip-extension moment from 26% to 33%, and up to 0.25 Nm/kg BW more hip-extension moment from 38% to 82% of ground contact. In the frontal plane, cluster 1 participants demonstrated up to 1.0 Nm/kg BW greater inversion and up to 0.4 Nm/kg BW less knee-abduction moments across the entire ground-contact phase, as well as up to 0.2 Nm/kg BW less hip-abduction moment from 0% to 44% and 80% to 100% of ground contact.

Cluster 2 Versus Control Group

The observations for this cluster are supplied in column B of Supplementary Figures 1 through 5. Compared with the control group, cluster 2 demonstrated up to 20% BW less vGRF from 0% to 13% followed by up to 11% BW more vGRF from 16% to 87% of ground contact, up to 8% BW less pGRF from 0% to 14% followed by up to 12% BW more pGRF from 16% to 100% of ground contact, and less than 3% BW less mGRF from 35% to 100% of ground contact. Cluster 2 also demonstrated up to 6° more PF ROM from 0% to 23%, up to 3.5° less knee flexion from 0% to 92%, and up to 3.5° less hip flexion from 0% to 90% of ground contact. In the frontal plane, cluster 2 demonstrated up to 2.5° greater inverted foot position from 6% to 62% of ground contact, less than 1° decrease in knee abduction from 66% to 100% of ground contact, and 4° to 5° more hip abduction over the entire ground-contact phase. For joint moments, cluster 2 had up to 0.1 Nm/kg BW more PF moment from 71% to 96% of ground contact; up to 0.25 Nm/kg BW less knee-extension moment from 0% to 70% of ground contact; up to 0.15 Nm/kg BW more hip-extension moment at 0% to 6%, 21% to 35%, and 42% to 84% of ground contact; and up to 0.15 Nm/kg BW more hip-flexion moment from 88% to 100% of ground contact. In the frontal plane, cluster 2 demonstrated up to 0.4 Nm/kg BW more inversion moment from 0% to 95% of ground contact, up to 0.1 Nm/kg BW less knee-abduction moment from 2% to 18% and 83% to 100% of ground contact, and up to 0.25 Nm/kg BW less hip-abduction moment across the entire ground-contact phase.

Cluster 3 Versus Control Group

The results for this cluster are shown in Column C of Supplementary Figures 1 through 5. Compared with the control group, cluster 3 showed a small increase (18% BW) in vGRF from 5% to 12%, up to 40% BW less vGRF from 15% to 74%, a small increase (up to 10% BW) in vGRF from 78% to 100%, a small decrease in pGRF (up to 5% BW) from 23% to 40%, up to 12% BW more pGRF from

57% to 100%, and up to 20% BW less mGRF from 12% to 86% of ground contact. Cluster 3 demonstrated up to 2° less DF ROM from 19% to 72%, up to 2.5° more knee flexion from 10% to 87%, and up to 4° more hip flexion from 0% to 91% of ground contact. This cluster also had up to 2° more inversion from 9% to 56%, up to 1.5° more knee abduction from 10% to 89%, and up to 4° less hip abduction from 7% to 79% of ground contact. Cluster 3 displayed up to 0.5 Nm/kg BW less PF moment from 8% to 78%, up to 0.45 Nm/kg BW less knee-extension moment from 22% to 67%, and up to 0.2 Nm/kg BW more hip-extension moment from 9% to 19% and 31% to 88% of ground contact. In the frontal plane, cluster 3 demonstrated up to 0.2 Nm/kg BW greater inversion moment from 9% to 98%, slightly greater (up to 0.05 Nm/kg BW) knee-abduction moment from 81% to 97% of ground contact, and up to 0.15 Nm/kg BW more hip-abduction moments from 3% to 17% and 67% to 96% of ground contact.

Cluster 4 Versus Control Group

The findings for this cluster are given in Column D of Supplementary Figures 1 through 5. Cluster 4 demonstrated up to 25% BW less vGRF from 15% to 82%, less pGRF from 0% to 9% and 24% to 48%, up to 5% BW more pGRF from 81% to 100%, and up to 12% BW less mGRF from 13% to 100% of ground contact. This cluster also had up to 6° less PF ROM from 0% to 17% and up to 3° more PF from 67% to 97% of ground contact, up to 8° more knee flexion over the entire ground-contact phase, and up to 6° more hip flexion from 0% to 67% and 92% to 100% of ground contact. In the frontal plane, cluster 4 displayed up to 2° less foot inversion from 84% to 100% and up to 3.5° less hip abduction from 9% to 72% of ground contact. Compared with the control group, cluster 4 also had slightly more (up to 0.15 Nm/kg BW) knee-extension moment from 9% to 19%, less than 0.1 Nm/kg BW less knee-extension moment from 27% to 69%, up to 0.15 Nm/kg BW more hip-flexion moment from 2% to 8%, up to 0.15 Nm/kg BW more hip-extension moment from 11% to 18%, and up to 0.2 Nm/kg BW less hip-extension moment from 22% to 29% of ground contact. In the frontal plane, cluster 4 demonstrated less than 0.1 Nm/kg BW less eversion moment from 45% to 95%, up to 0.1 Nm/kg BW less knee-abduction moment from 26% to 96%, and up to 0.1 Nm/kg BW less hip-abduction moment from 28% to 97% of ground contact.

Cluster 5 Versus Control Group

The observations for this cluster appear in Column E of Supplementary Figures 1 through 5. Cluster 5 demonstrated up to 30% of BW less vGRF from 13% to 75%, up to 12% more vGRF from 82% to 99%, up to 20% of BW less pGRF from 0% to 13% and 21% to 40% of ground contact, up to 8% of BW more pGRF from 60% to 100%, and up to 25% more mGRF from 11% to 100% of ground contact compared with the control group. This cluster had a small increase of up to 1.5° in DFROM from 7% to 20%, up to 1.5° more knee flexion from 5% to 24% and 74% to 94%, and up to 3° more hip flexion from 0% to 56% and 72% to 96% of ground contact. In the frontal plane, cluster 5 showed up to 8° greater inversion ROM over the entire ground-contact phase, up to 5° greater knee abduction from

7% to 97% of ground contact, and up to 5° greater hip adduction from 9% to 90% of ground contact. Cluster 5 demonstrated up to 0.1 Nm/kg BW less PF moment from 0% to 71%, up to 0.3 Nm/kg BW less knee-extension moment from 18% to 69%, and up to 0.1 Nm/kg BW less hip-extension moment from 46% to 67% of ground contact. In the frontal plane, cluster 5 had up to 0.4 Nm/kg BW more inversion moment from 3% to 97% and up to 0.15 Nm/kg BW less knee-abduction moment from 12% to 87% of ground contact.

Cluster 6 Versus Control Group

The results for this cluster are provided in Column F of Supplementary Figures 1 through 5. Compared with the control group, cluster 6 demonstrated up to 35% BW less vGRF from 14% to 73%, up to 10% BW more vGRF from 80% to 100%, up to 8% BW more pGRF from 12% to 23% and 70% to 100%, and up to 12% BW less mGRF from 10% to 84% of ground contact. Cluster 6 also displayed a small increase of up to 1.5° in DF ROM from 7% to 18%, up to 4° greater knee flexion from 4% to 92%, and up to 6° greater hip flexion from 0% to 98% of ground contact. In the frontal plane, cluster 6 showed up to 2.5° more inversion over the entire ground-contact phase, less than 1° more knee adduction from 4% to 14% of ground contact, and up to 5° more hip adduction from 12% to 83% of ground contact. Cluster 6 also demonstrated up to 0.15 Nm/kg BW less knee-extension moment from 26% to 92%, up to 0.11 Nm/kg BW less eversion moment from 6% to 93%, slightly less (<0.05 Nm/kg BW) knee-abduction moment from 46% to 70%, and up to 0.1 Nm/kg BW more hip-abduction moment from 55% to 78% and 87% to 100% of ground contact.

DISCUSSION

Our primary finding was that 200 participants with CAI, as defined by the International Ankle Consortium,³ clustered into 6 distinct movement strategies during a complex jump-landing-cutting task. Whereas the population with CAI has often been studied as a homogeneous group, our data demonstrated that movement within this population was variable but with distinct tendencies. This could account for much of the variability seen in research related to this patient population, despite efforts to create more consistency regarding the inclusion criteria.³ It should come as no surprise that variability in movement exists,²⁰ especially considering the complexity of the movement used in this study. The distinct strategies that this patient population demonstrated can provide clues concerning the ranges of deficiencies or movement alterations, or both, that lead to reinjury and perpetuate instability. In other words, it is unlikely that 1 set of factors perpetuates ankle instability, and multiple sets of factors need to be considered when evaluating and treating patients with CAI. Therefore, these patients will present with a wide range of clinical findings and neuromechanical deficits.

Clinically, our observations of distinct movement patterns presented many interesting ideas. As clinicians, we want a clear set of primary and secondary problems for any specific pathologic condition or syndrome to focus our treatment. However, these data suggested that no consistent set of problems was present among patients with CAI, so a

treatment course may vary substantially based on the deficits associated with any 1 cluster. For example, DF ROM deficits have been consistently reported in this patient population, and these deficits pose several problems that could perpetuate instability.^{7,8} Yet whereas clusters 1 and 3 demonstrated the expected limitations in DF ROM through the loading portion of stance, other clusters demonstrated no apparent DF ROM limitations. This finding accounted for approximately 50% of the participants with CAI in our study. This result was also noted for other mechanical measures. The population with CAI was diverse in its movements, which likely stemmed from a range of sensorimotor and tissue alterations. Clinicians should assess movement along with tissues to identify these alterations and develop specific treatment strategies based on the deficits. More data are needed to help identify clinical tests that are sensitive to the specific deficits associated with movement clusters within the population with CAI.

To identify movement alterations associated with each movement strategy, each cluster was compared with an uninjured control group. This approach had some inherent limitations. First, as stated, the control group also varied in its movement patterns. Analyzing the control group in the same way that we analyzed the CAI group yielded many more clusters ($n = 11$) with half as many participants ($n = 100$), demonstrating the diversity of movement in an uninjured population. Comparing the 6 CAI clusters with the 11 control clusters would be a confusing process, so we used a mean of the control group ($n = 100$) as a reference comparison for each CAI cluster. We consider the mean used for the control group only a reference because *normal movement* would be difficult to define. Second, whereas we tried to match the control group with the CAI group, the clustering process diminished those efforts. Therefore, the participants included in the comparison of each cluster with the control group were not matched. The participant characteristics for each cluster are presented in Table 2. Some notable observations for each cluster are discussed in this section. Given these limitations, caution should be exercised when drawing conclusions from the comparison of each cluster with the control-group mean.

Cluster 1

Cluster 1 was the largest cluster ($n = 71$) and was characterized by several factors, including landing-impact attenuation (a visually apparent decreased vGRF load rate), deficient control of the center of mass (COM), limited DF ROM, and large inversion moments. This cluster tended to attenuate landing impact (decreased landing GRFs) with corresponding increased joint angles in both the sagittal and frontal planes. Cluster 1 landed with more PF and inversion at the ankle and more flexion and abduction at the hip. These observations, along with decreases in PF and knee-extensor moments, increased inversion moment, increased hip-flexion moment, and decreased hip-abduction moment, indicated a potential combination of voluntary avoidance and involuntary motor dysfunction. Participants with CAI have commonly demonstrated eversion and hip-abductor dysfunction.⁹⁻¹³ In addition, individuals with a history of ankle injury and giving way might avoid positions and loads that they perceive as potentially risky. The combination of voluntary and involuntary alterations likely results

in repetitive reinforcement of altered movement that, depending on the movement, could place participants in positions that are vulnerable to loads that cause injury. This idea is consistent with our data. The extent to which this altered movement could lead to injury is unknown. More data are needed to link the altered movement with the reinjury risk.

The GRF data, along with hip-angle and -moment data for cluster 1 compared with the control group, are consistent with the concept that these participants had difficulty controlling their COM during landing relative to the movement task. The relatively large differences in both mGRF and pGRF demonstrated that participants had difficulty controlling the deceleration of landing coupled with the acceleration and change of direction of the lateral jump. The decreased mGRF might be due to a shift in the COM relative to the stance limb, such that the COM remained medial to the stance limb and the participants did not completely transition their mass to the contralateral limb at the end of the side jump. This effectively reduced the distance the COM had to travel and, therefore, reduced the need to produce as much mGRF for the side cut. This finding was consistent with the observed decrease in vGRF early in ground contact, when participants might have been trying to consciously unload during the landing impact. This strategy also allowed them to produce less force during the lateral jump, which was consistent with the decreased knee-extensor moment during early takeoff. The observed increases in braking GRF during midstance and takeoff (33% to 100% of ground contact) might also have reflected an inability to control the COM during the landing phase, as the body continued to try to slow a forward-moving COM, well into the takeoff phase. Supporting this idea, sagittal-plane hip moments demonstrated the hip and trunk overcorrecting with several changes in both directions (flexion and extension moments) during the landing phase. Whereas researchers have proposed that the hip plays a role in CAI,^{10,13,34} Dastmanesh et al³⁵ suggested that the trunk or core plays this role. More data are needed to further understand the role of the trunk and core in CAI.

Cluster 1 landed initially in a more plantar-flexed position than the control group and was in less DF through midstance when peak DF would have been attained. Researchers^{7,8,19} have consistently reported limited DF ROM in the population with CAI, and whereas only clusters 1 and 3 exhibited less DF through midstance, 93 of the 200 participants with CAI (clusters 1 and 3) demonstrated this important clinical finding. Increased PF at initial contact and limited DF ROM through midstance have important ramifications. Increased PF and increased inversion place the foot in an unstable position at impact.³⁶ Limited DF at midstance prevents the foot from reaching its closed-packed position when it is completely loaded, so it is vulnerable to loads that could cause injury. Limited DF also limits the amount of positive, ankle-joint mechanical work that can subsequently be performed, limiting cutting ability and athletic performance.

Most clusters (1–3, 5, and 6) demonstrated increased inversion at the foot through all or some ground contact. However, cluster 1 demonstrated a large difference compared with the control group (up to 8°) from 10% to 75% of ground contact (Figure 5). Furthermore, whereas the control group had a general eversion moment

throughout ground contact, cluster 1 demonstrated a large inversion moment throughout ground contact (also evident in clusters 2 and 5). The proximal joint movements could have some effect on the large inversion moment, but we suspect that an imbalance between evertor and invertor function also influenced these observations. Indeed, evertor dysfunction, coupled with invertor excitation, has been reported,¹¹ and this motor pattern may have played a large role not only in our findings but also in the perceived instability of this patient population. The timing of the inversion angle and inversion moment are also potential concerns. In an ankle-inversion–injury case, Kristianslund et al³⁷ documented a concurrent increase in inversion angle and inversion torque during ankle injury, in that inversion angle and torque peaked simultaneously during the injury mechanism. Our cluster 1 data were consistent with this observation, with peak inversion (8° more than the control group) occurring approximately 100 milliseconds after foot contact at the same time as a large inversion torque (162% greater than the control group) was observed. This combination of factors might create a tenuous time in movement, when the invertors and the GRF both force the foot into inversion. More data are needed to better understand the mechanisms that create this series of events. Regardless, clinicians should examine foot position in this patient population and intervene to balance evertor-invertor function. Clinically, evaluating foot position during loading (ie, forward foot maintains metatarsal heads evenly on the ground during a forward lunge) may provide some information about balanced invertor-evertor function. If the patient cannot keep the first metatarsal head on the ground during loading, then the invertors are often dominating the coupled contraction. A therapeutic exercise strategy to force evertor firing could help to recover some balance, but data are needed to confirm this approach for restoring invertor-evertor coupling during loading.

Cluster 2

Cluster 2 was the second largest cluster (n = 58) and was characterized by a rigid sagittal-plane landing, increased hip abduction throughout ground contact, increased ankle-inversion and -invertor moments, and poor COM control in the sagittal plane. This cluster was similar to cluster 1 as participants demonstrated similar problems with foot position and invertor-evertor moments through ground contact. Another similarity was an inability to control braking GRF far into the takeoff phase to effectively transition to the side jump. Whereas participants in cluster 2, unlike those in cluster 1, initially landed with decreased vGRF, they demonstrated increased vGRF at the peak and through most of the landing and takeoff. Consistent with the increased vGRF, cluster 2 displayed increased hip extension and abduction and increased knee extension. This cluster was the only cluster to exhibit increased vGRF and extended positions of the knee and hip. These findings, along with a more plantar-flexed and inverted position at impact, might suggest that the ankle and foot were absorbing the initial contact through ankle motion, followed by high impacts through the lower extremity marked by higher peak vGRF at approximately 20% of ground contact. We suspect that these factors place the ankle in a vulnerable position early in the landing phase and

result in high-impact forces through all lower extremity joints during early ground contact, potentially increasing the injury risk at the ankle and, to a lesser degree, the knee and hip. These alterations in loading could also affect the health of the ankle articular cartilage over time.⁴ Segal et al³⁸ reported that increased contact stress at the knee was associated with an increased risk for developing osteoarthritis. Moreover, load distribution may be even more important to maintaining articular-cartilage health, especially after injury.³⁹ Contact stress and load distribution may have been at play in this cluster, with increased vGRF and decreased joint angles. More data are needed to better understand the relationship between these mechanical factors and the development of ankle osteoarthritis in the population with CAI.

Another important alteration seen in cluster 2 was a large decrease in the hip-abduction moment. This decrease was also observed to a lesser extent in clusters 1 and 4. It could be explained, in part, by a possible trunk lean (large hip-abduction angle), but it might also be due to hip-abductor weakness,¹⁰ gluteus medius onset deficits,⁴⁰ or altered supraspinal control.⁴¹ Regardless of the origin, an inability to control the hip in the frontal plane could result in increased loads on the outside of the foot, increasing the risk of lateral ankle sprains or resprains and episodes of giving way.

Cluster 3

Twenty-eight participants clustered into the third largest group. Cluster 3 demonstrated an initially increased vGRF, followed by a decrease over midstance and an increase again at the end of takeoff. These participants also had less DF, more knee flexion, and more hip flexion through midstance. Similar to clusters 4 through 6, this cluster showed increased hip adduction with a corresponding increase in hip-abduction moment. Cluster 3 appeared to attenuate impact forces during the middle of the movement task by increasing joint angles and dropping the contralateral hip. This cluster may also have used a hip strategy to perform the mechanical work necessary for takeoff, as hip-extension and hip-abduction moments increased and ankle and knee moments decreased. Kim et al¹⁸ supported this idea: their participants with ankle instability used a hip-dominant strategy to absorb and produce power during a jump task. This redistribution of work from the ankle to the hip could be an effective way for participants with ankle instability to function, but it may also place the ankle in problematic positions during movement, as evidenced by the increased inversion and inversion moments in this cluster.

Cluster 4

With 21 participants, cluster 4 was the fourth largest cluster. Participants in this cluster showed increased DF early in the landing phase and increased knee and hip flexion. Cluster 4 had the least total sagittal-plane ankle displacement compared with the control group and all other clusters. Begalle et al⁴² found that less DF displacement was associated with greater knee and hip flexion and greater hip internal-rotation and knee-adduction angles. Less displacement may also suggest more impact to the ankle tissues, which might have short- and long-term implications

for ankle-joint health. Cluster 4 also demonstrated a hip-adduction position that could be associated with a contralateral hip drop. Similar to cluster 3, this cluster might have been trying to attenuate the landing impact by using increased frontal-plane and sagittal-plane hip motion, which would be consistent with the GRF data in this cluster. However, cluster 4 was the only cluster to show no differences in frontal-plane motion or moment until late takeoff, and at the end of ground contact, this cluster demonstrated less inversion rather than more. Furthermore, no DF ROM limitations were present in this cluster. Movement (angles and moments) associated with this cluster was very different from many of the movement deficits that have often been attributed to CAI (no inversion increases, no DF ROM deficits). Cluster 4, along with cluster 5, also reported the highest number of ankle sprains and had the lowest scores on the FAAM (Table 2).

Clusters 5 and 6

Clusters 5 and 6 comprised 14 and 8 participants, respectively. Whereas these clusters had no DF limitations, large increases were present in the inversion position of the foot throughout ground contact along with increased inversion moment. Clusters 5 and 6 also displayed large hip-adduction positions relative to the control group. One distinction between clusters 5 and 6 was evident in the frontal plane of knee motion. Cluster 5 had a different knee frontal-plane curve, with increased abduction relative to the control group. This finding, in combination with other joint-position alterations, may signify an effort to reduce impact by increasing joint motion in both planes. In this case, the knee and hip seemed to collapse through ground contact (increased knee abduction and hip adduction). This strategy, which appeared to be prevalent through many of the clusters, did seem to successfully reduce GRF; however, it also contributed to extremely variable movement through the segments of the lower extremity, potentially exposing the lower extremity joints to acute and chronic joint-injury loads. The knee frontal-plane data also looked exaggerated (clusters 1 and 5), as the range between peak adduction and abduction was approximately 12°. This may result from contributions of the sagittal and transverse planes in the calculation of frontal-plane movement (ie, kinematic crosstalk) due to small differences in knee-joint marker placement. However, whereas these frontal-plane knee angles may have been artificially exaggerated, the shape and trends of the curve throughout ground contact were realistic, especially when ankle and hip motion were considered.

The Clustering Process

Clustering movement was a multistep process. First, data were considered as functions, which are curves of the entire period of interest. In this study, that period was the ground-contact phase: initial foot contact to final takeoff. Functions from each joint (ankle, knee, and hip) were reduced to a single curve using separate principal component analyses in the frontal and sagittal planes. By representing curves in each plane, the average proportion of variability explained by the first principal component was excellent (96% for sagittal angles and 91% for frontal angles). Representative curves from both frontal and sagittal planes were modeled

simultaneously using a Bayesian technique to cluster functions according to the characteristics of each function (amplitudes, changes in direction, duration of changes, etc). When examining the representative curves in Figure 2B, we found that redundancy appeared to be present in some of the curves. However, when the coupled curve from the other plane was considered, distinctions among clusters were more easily observed. Whereas we did not consider transverse-plane motion or other mechanics, this combination of frontal-plane and sagittal-plane motion data appears to represent movement more comprehensively during the jump-landing-cutting task.

CONCLUSIONS

Two hundred participants with CAI, classified according to the inclusion criteria recommended by the International Ankle Consortium,³ were clustered into 6 distinct movement strategies during a jump-landing-cutting task. Although some common CAI movement alterations were demonstrated across many clusters, movement alterations varied among clusters. Our findings are potentially important for both researchers and clinicians. For researchers, these findings appeared to indicate that the inclusion criteria established for participants with CAI did not provide a homogeneous sample from which consistent neuromechanical alterations can be identified. For clinicians, patients with ankle instability will present with a wide range of clinical findings and neuromechanical deficits. Participants with CAI should be carefully evaluated for sensorimotor deficits and quality of movement so that appropriate treatment interventions can be provided.

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