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Clinical Predictors of Movement Patterns in Patients with Chronic Ankle Instability

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ABSTRACT

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BACKGROUND: Chronic ankle instability (CAI) patients have varying levels of mechanical and sensorimotor impairments that may lead to disparate functional movement patterns. Current literature on landing biomechanics in a CAI population, however, considers all patients as a homogeneous group. In our prior work, we identified 6 subgroups of movement patterns using lower extremity kinematics during a landing/cutting task and that showed promise in furthering understanding of movement patterns in a laboratory-based environment. To increase the utility of this methodology in clinical settings, there is a need to find easily administered clinical tests that can help identify multiple subgroups of movement patterns in a CAI population. The purpose of the present study was to identify clinical tests that would help identify frontal and sagittal kinematic movement pattern subgroups during a landing/cutting task. We hypothesized that clinical tests would help predict group assignment; which CAI patient is assigned to frontal and sagittal kinematic movement pattern subgroups, respectively. METHODS: We recruited 100 CAI patients from a university population. We used three-dimensional instrumented motion analysis to capture ankle, knee and hip kinematics as subjects performed a single-leg maximal jump landing/cutting task. We used sagittal and frontal joint angle waveforms to group CAI patients. We then used 12 demographic and clinical measures to predict these subgroups of CAI. These consisted of gender, Star Excursion Balance Test-Anterior (SEBT-ANT), Biodex static balance, figure 8 hop, triple crossover hop, dorsiflexion range of motion (DFROM), number of failed trials, body mass index, a score of Foot and Ankle Ability Measure-Activities of Daily Living (FAAM-ADL), a score of FAAM-Sports, number of "yes" responses on Modified Ankle Instability Index, and number of previous ankle sprains. First, we used functional principal component analysis to create representative curves for each CAI patient and plane from the 3 lower extremity joint angles. We then used these curves as inputs to a predictor-dependent product partition model to cluster each CAI patient to unique subgroups. Finally, we used a multinomial prediction model to examine the accuracy of predicting group membership from demographic and clinical metrics. RESULTS: The predictor-dependent product partition model identified 4 frontal and 5 sagittal movement pattern subgroups. Six predictors (e.g., gender, SEBT-ANT, figure 8 hop, triple crossover hop, DFROM, and FAAM-ADL) predicted group membership with 55.7% accuracy for frontal subgroups. Ten predictors (minus Biodex static balance and number of previous ankle sprains) predicted group membership with 59% accuracy for sagittal subgroups. CONCLUSION: Novel statistical analyses allowed us to predict group membership for multiple frontal and sagittal kinematic movement patterns during landing/cutting using a series of clinical predictors. However, due to relatively lower accuracy (56–59% accuracy), the clinical utility of the current prediction model may be limited. Future work should consider including other clinical predictors to maximize prediction accuracy for identifying multiple kinematic movement patterns during a landing/cutting task.
Keywords: Ankle sprains, prediction, functional test, Bayesian model, landing

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INTRODUCTION

The ankle is the second most-injured joint in the body, and ankle sprains account for approximately 15% of all sport injuries.[1,2] More than 25,000 ankle sprains occur daily in the U.S. which is equivalent to 1 in every 10,000 people,[3] costing the U.S. an estimated $2 billion annually for treatment.[4] One in every 3 individuals who sustains an ankle sprain suffers from repeated ankle sprains.[5] Despite a high recurrence rate, approximately 55% of ankle sprains are not treated by healthcare professionals.[6] Up to 74% of patients 2 years postinjury still reported at least one residual symptom (e.g., pain, swelling, weakness, instability, etc.).[5] Researchers suggest that 70–85% of patients suffering ankle sprain injuries go on to develop chronic joint degenerative diseases such as posttraumatic ankle osteoarthritis.[7-11] Even though surgical and nonsurgical management of posttraumatic ankle injury and arthritis have been administered, and the interventions may be effective in managing the symptoms of the injury,[12,13] no effective interventions have been identified to prevent the progression of ankle osteoarthritis.[14,15]

Chronic ankle instability (CAI) is a condition characterized by chronic residual symptoms including pain, swelling, loss of function, joint instability, a feeling of “giving way,” and/or recurrent ankle sprains.[16,17] Delahunt et al[18] characterized CAI as “an encompassing term used to classify a subject with both mechanical and functional instability.” Mechanical ankle instability is related to mechanical impairments including pathological laxity,[19,20] arthrokinematic restrictions (e.g., a positional fault of the talus[21,22] or fibula[23,24]), osteokinematic restrictions (e.g., restricted dorsiflexion[25-27]), degenerative articular changes[28,29] and/or synovial changes.[30,31] Functional ankle instability is associated with sensorimotor impairments including diminished proprioception,[32-34] slower reflex reactions,[35-37] arthrogenic muscle inhibition,[38] diminished strength[39,40] and/or impaired postural control[41,42] through spinal and/or supraspinal pathways.[43,44] It is believed that any single or any combination of the aforementioned mechanical and/or sensorimotor impairments would result in altered movement patterns during walking,[35,36,45,46] running,[26,27,46] landing[47-51] or cutting.[47,52,53] when compared to healthy controls and/or ankle sprain copers.[54]

It is believed that initial ligament damage and impaired sensory pathways to the central nervous system result in structural changes and spinal reflex inhibition, which further leads to altered joint loads and altered movement patterns during various functional tasks (e.g., walking, running, landing, cutting, etc.).[55,56] Altered movement patterns have been reported across various phases of ankle sprain injury. Specifically, patients with a first-time acute ankle sprain at 2 weeks postinjury revealed altered landing patterns (e.g., 10% reduction in peak vertical impact and 6° increased hip flexion angle).[57] Patients with a first-time ankle sprain at 6 months postinjury exhibited 5° more ankle inversion and 5° more hip flexion angle during single-leg drop landing.[58] Patients with CAI appeared to: (i) walk with a more laterally deviated center of pressure trajectory during stance[36]; 2.5–3° more inversion angle during stance[45,59] and 2.9° less dorsiflexion angle during stance[27]; (ii) land with 2.5–3° less dorsiflexion angle during stance[47,48]; and (iii) run with a 4.8° less dorsiflexion angle during stance[26] and 3.9–4.8° less eversion angle during stance.[27] These altered movement patterns are thought to predispose CAI patients to recurrent ankle sprains due to a more injury-prone and loose-packed position of the foot. Further, altered joint loads, due to altered movement patterns as a postinjury compensatory adaptation, over the long-term may initiate the onset of ankle articular cartilage degeneration.[7,8]

In CAI research, subjects with CAI are selected in accordance with the consensus statement of selection criteria defined in the International Ankle Consortium.[60] For example, studies have identified CAI subjects using valid and reliable self-reported questionnaires.[61,62]

Because of this self-reported subject inclusion method, a CAI population is considered homogeneous. However, the current method does not consider potential individual variability of mechanical and sensorimotor impairments, which could potentially lead to conflicting results between studies, as demonstrated by varied findings in a single outcome measure showing greater inversion kinematics,[49,63,64] less inversion kinematics,[47] or no difference in frontal ankle kinematics[48,50,53] during the same or similar landing tasks. According to the Dynamic Systems Theory,[65] each CAI patient would have a different severity level of mechanical and/or sensorimotor impairments following ankle sprain injury based on the interaction of organismic, task and environmental constraints.[56] This speculation led us to consider multiple movement patterns during landing in CAI patients who were selected using subjective self-reported questionnaires. Our prior unpublished work (n = 300 patients with CAI) identified 6 kinematic movement patterns during landing/cutting. However, we conducted our recent study in a research laboratory-based setting using high-speed video cameras and force plates, which limited the clinical practicality in clinical settings in identifying multiple movement patterns during landing. Therefore, there is a need to find clinical (or functional performance) tests that would help identify multiple movement patterns in a CAI population to increase its clinical utility. In this study, we selected 12 clinical predictors. Five predictors were clinical tests that are used in clinical settings such as a Star Excursion Balance Test-Anterior (SEBT-ANT), Biodex balance (static athlete single-leg overall stability index), figure 8 hop for time, triple crossover hop for distance, and dorsiflexion range of motion (DFROM). Along with the 5 clinical tests, we selected 7 clinical predictors to help predict group membership into certain kinematic movement pattern clusters including gender, number of failed trials during the clinical tests, body mass index (BMI), perceived instability scores on self-reported questionnaires (Foot and Ankle Ability

Measure-Activities of Daily Living [FAAM-ADL], FAAM-Sports subscale, and Modified Ankle Instability Index [MAII]), and number of previous ankle sprains.

This study aimed to identify multiple movement pattern clusters during jump landing/cutting from 100 patients with CAI and to find clinical predictors that would help identify multiple movement clusters. Based on the success of our recent unpublished work on movement pattern clusters, we hypothesized that each CAI patient would show an independent kinematic movement pattern during the task, based on the curve's shape of lower extremity joint kinematics and values of 12 clinical predictors, and that we would identify multiple kinematic movement pattern subgroups (or clusters). We also hypothesized that clinical predictors would help predict kinematic movement clusters to which each CAI patient would be assigned—either frontal or sagittal movement pattern subgroups, respectively.

METHODS

Research Design

This study was a controlled laboratory trial. Each subject reported to the biomechanics laboratory for 2 sessions, 2–3 days apart. The first session was a practice session to familiarize subjects with the clinical tests (e.g., SEBT-ANT, Biodex static balance, figure 8 hop, triple crossover hop, and DFROM). Subjects performed 6 practice trials of each clinical test, which took about 40 minutes. The purpose of the practice session was to minimize learning and fatigue effects on clinical tests. Multiple trials of the hop tests would be too demanding to perform practice and testing trials in the same day. The second session was a testing data collection session where each subject performed 3 testing trials of each clinical test followed by 10 trials of single-leg maximal vertical forward jump landing/cutting. Total time for the data collection session was about 2 hours. Independent variables were (i) lower extremity frontal and sagittal kinematics during landing/cutting and (ii) values of 12 clinical predictors: gender, SEBT-ANT reach distance (% of leg length), Biodex static balance (single-leg overall stability index), figure 8 hop for time (sec), triple crossover hop for distance (m), DFROM (deg), number of failed trials, BMI (kg/m^2), FAAM-ADL (%), FAAM-Sports (%), MAII (number of "yes" responses on questions 4–8; a feeling of instability during functional tasks), and number of previous ankle sprains. Dependent variables were (i) multiple movement pattern clusters, (ii) results of post hoc pairwise comparisons and group characteristics (% of values), and (iii) prediction model accuracy for frontal and sagittal kinematic movement pattern clusters, respectively.

Subjects

One hundred patients with CAI, recruited from a university population, participated in this study. Table 1 contains subject demographics. Subjects were identified in accordance with endorsed inclusion and exclusion criteria for CAI defined in the International Ankle Consortium.[60] Subjects were selected using self-reported function questionnaires including a FAAM-ADL,[61] FAAM-Sports,[61] and MAII.[62] Specific subject inclusion criteria included (i) a history of at least one significant ankle sprain with a first sprain 12 months before the study enrollment, and the injury was related to inflammatory symptoms (e.g., pain, swelling, etc.) and created at least one interrupted day of desired physical activity, (ii) a history of at least 2 "giving way" episodes in the past 6 months and at least 2 "yes" responses on questions 4–8 on the MAII, (iii) a score of < 90% on the FAAM-ADL and < 80% on the FAAM-Sports, and (iv) a history of a moderate level of weight-bearing physical activity at least 3 days per week for a total of 90 min in the previous 3 months. Specific subject exclusion criteria included (i) a history of lower extremity surgeries to the musculoskeletal structures (e.g., bones, joint structures, and nerves), (ii) a history of a fracture in lower extremity, and/or (iii) acute musculoskeletal injury to lower extremity joints in the previous 3 months. Thirty-four CAI subjects had unilateral ankle sprains and the remaining 66 CAI subjects had bilateral ankle sprains. For subjects with bilateral ankle sprains, the subject chose the involved limb based on a greater perceived feeling of instability. The Institutional Review Board (F16455) approved this study and each subject provided informed consent prior to the study enrollment.

Experimental Procedures

Each subject visited the biomechanics laboratory 2–3 days prior to testing data collection to become familiar with 5 clinical tests (e.g., SEBT-ANT, Biodex static balance, figure 8 hop, triple crossover hop, and DFROM). We instructed subjects to wear their own athletic shorts, shirts and shoes and performed 6 trials of each clinical test for practice. Subjects reported back to the biomechanics laboratory 2–3 days later for testing data collection. After changing into athletic spandex clothing (HeatGear, Under Armour, Baltimore, MD) provided by investigators, subjects performed 3 trials of each clinical test in a random order to reduce the order effect. Subjects performed 3 clinical tests barefoot (e.g., SEBT-ANT, Biodex static balance, and DFROM) and performed 2 clinical tests (e.g., figure 8 hop and triple crossover hop) with athletic shoes (T-Lite XI, Nike, Beaverton, OR), provided by investigators. There was a 3-minute rest between each clinical test to minimize fatigue effects and a 30-second rest between each trial. Upon completion of the clinical tests, subjects performed 10 trials of a single-leg maximal vertical forward jump landing/cutting task (Figure 1).

Clinical Test Procedures

For a SEBT-ANT measure,[66-68] subjects performed 3 trials of the test barefoot in an anterior direction. We instructed subjects to place the tested foot on a tape measure (cm) and to perform maximal anterior direction reaches with the opposite foot followed by a single, light toe touch on the tape measure while keeping both hands on their waist. Failed trials were counted if the hands did not remain on their waist, the position of the stance foot was not maintained, the heel did not remain on the floor, or subjects did not maintain a single-leg stance position during the test. Subjects performed the test until they completed 3 successful trials. Distances were measured in cm (nearest 0.5 cm) and normalized by dividing by the subject's lower limb length (e.g., from anterior superior iliac crest to distal end of the medial malleolus) and multiplying by 100 (% of leg length).[67] As subjects had the practice session 2–3 days prior, subjects performed 1 practice trial and 3 testing trials. There was a 30-second rest between each trial. The mean of the best 2 trials was used for data analysis. The previous study demonstrated that the intraclass correlation coefficient (ICC) for intra-rater (between sessions) reliability for SEBT-ANT was 0.92, confidence interval (CI: 0.86–0.96), and the ICC for inter-rater (between assessors) reliability was 0.88 (CI: 0.80–0.94).[69]

For an ankle DFROM measure,[25,70,71] the test was performed using the knee-to-wall measurement in which subjects were instructed to stand facing a wall with the tested foot parallel with a tape measure secured to the floor with the second toe, center of the heel and knee perpendicular to the wall while placing their hands on the wall and the opposite limb approximately 1 foot-length behind. Subjects performed a forward lunge in which both knees were flexed, but the knee in the tested limb was required to contact the wall while keeping the heel planted on the floor. Subjects performed the test until they achieved maximum distances from the wall and continued to maintain knee contact without lifting the heel. A digital inclinometer (Digital Protractor Angle Finder Level Inclinometer Magnetic V-Groove, RISEPRO, Amazon, Seattle, WA) was used to measure DFROM, and the top edge of the inclinometer was aligned with the tibial tuberosity.[72] Subjects performed 1 practice trial and 3 testing trials. There was a 30-second rest between each trial. We used the mean of the best 2 trials for data analysis. The previous study showed that the ICCs for intra-rater reliability for the digital inclinometer was 0.98 (CI: 0.95–0.99), and the ICCs for inter-rater reliability was 0.90 (CI: 0.43–0.97).[70,72]

For a Biodex Balance System measure,[73,74] static athlete single-leg overall stability index was used to quantify single-leg static postural control as a sum of anterior-posterior and medial-lateral stability index. Subjects performed the test barefoot on the Biodex platform. We instructed subjects to maintain a single-leg stance position with the tested limb in full knee extension while holding the opposite knee to 90° flexion and keeping both hands on their waist. We instructed subjects to position the tested foot at the center of the platform, to look ahead at the visual feedback display, adjusted at their eye level to prevent vestibular distraction and head movement, while adjusting their foot position to a comfortable standing position and maintaining the moving pointer at or near the center point of the visual feedback display. The position of the foot remained constant throughout the static balance test. Subjects performed 1 practice trial and 3 testing trials. Each trial was 3 sessions for 20 seconds each (a total of 9 individual testing trials per subject). There was a 30-second rest between each trial. During the 30-second rest, subjects were encouraged to bear their weight on the opposite limb to minimize fatigue on the tested limb. The mean of the best 2 trials of static athlete single-leg overall stability index was used for data analysis, which was automatically calculated by the Biodex Balance System. The previous study revealed that the ICC for intra-rater reliability was 0.85 (CI: 0.61–0.94) regarding static athlete single-leg overall stability index.[73]

For a figure 8 hop for time (seconds) measure,[75] subjects performed the test with athletic shoes. We instructed subjects to maintain a single-leg stance position on the tested limb only while holding the opposite knee to 90° flexion. Subjects performed a single-leg hop twice as quickly as possible on a 5-m course outlined by 2 cones in a figure 8 pattern. An investigator recorded the total time with a handheld stopwatch to the nearest 0.01 sec. We used a 50-cm long plastic stick adjusted at subject's chest level, to determine when subjects crossed the finish line. Failed trials were counted if subjects put the contralateral limb down, fell, touched the cones, or did not complete the course twice. Subjects performed the test until they completed 3 successful trials. Subjects performed 1 practice trial and 3 testing trials. There was a 1-minute rest between each trial. We used the mean of the best 2 trials for data analysis. The previous study showed that the ICC for inter-rater reliability was 0.95 (standard error of measurement 1.66 seconds).[76]

For a triple crossover hop for distance (m) measure,[77,78] subjects performed the test with athletic shoes. We instructed subjects to maintain a single-leg stance position on the tested limb only, while their opposite knee was flexed to 90°. Subjects performed 3 consecutive hops on the tested limb in a zigzag pattern, crossing over a 15-cm wide line on the floor as a maximal effort. The first and final hops were towards the lateral side of the tested limb. We measured the distance using a tape measure (nearest 0.01 m) from the start line to where the heel landed on the third hop. Failed trials were counted if subjects put the contralateral limb down, fell, touched the 15-cm wide tape, or did not complete the test. Subjects performed the test until they completed 3 successful trials. Subjects performed 1 practice trial and 3 testing trials. There was a 1-minute rest between each trial. We used the mean of the best 2 trials for data analysis. The previous studies reported that the ICC for inter-rater reliability was 0.94–0.96; no studies reported 95% CIs.[79-81]

The Rationale for 12 Clinical Predictors for the Current Study

Based on the success of our unpublished work on identifying multiple kinematic movement patterns (6 movement pattern clusters from 200 CAI patients), this study leveraged previous findings to identify kinematic movement pattern clusters using values of clinical predictors. As such, we selected 12 clinical predictors including gender, SEBT-ANT, Biodex static balance (athlete single-leg overall stability index), figure 8 hop for time, triple crossover hop for distance, DFROM, number of failed trials, BMI, FAAM-Sports score, FAAM-ADL score, MAII responses (“yes” responses on questions 4–8) and number of previous ankle sprains. We selected each predictor based on whether the predictor might be directly or indirectly associated with risk factors for CAI. Specifically, gender was included in this study because there were gender differences between males and females for functional performance[82] and physiological characteristics (e.g., strength, mobility, alignment, etc.).[83,84] We included 5 clinical tests—SEBT-ANT, Biodex static balance, figure 8 hop, triple crossover hop and DFROM—that were commonly used in clinical settings to examine the risk of injury,[33,84-86] mechanical or sensorimotor deficits caused by injury,[17,75,87,88] or improvements following the rehabilitation interventions.[66,89,90] Specifically, SEBT-ANT was included because short reach distance indicates poor dynamic postural control, which is often observed in CAI patients[32,91] and more importantly was identified as a predictor for ankle reinjury[85] and for a development of CAI.[92] The SEBT-ANT is a measure of dynamic postural control, and the Biodex balance system is a measure of static postural control using a static athlete single-leg overall stability index (anterior-posterior and medial-lateral postural control stability).[93,94] The figure 8 hop for time test was included as Docherty et al[75] reported a significant correlation (r = 0.31) between self-reported instability index and time to complete the task, indicating that CAI patients took a longer time to complete the test relative to controls. We also saw this functional performance deficit in the injured ankles relative to the uninjured ankles of CAI patients during single-leg multiplanar hop.[95] The triple crossover hop for distance test was identified as a predictor for lower extremity strength and power.[96] The test could increase stress on the lateral structures of the ankle as it has side-to-side motion. This would have a potential benefit from this test relative to the other hop tests (e.g., single hop for distance, triple straight hop for distance, side hop for time and up-down hop, etc.) that use only sagittal-plane motion.[75,77,78] Moreover, the number of failed trials during the clinical tests was included because more numbers of failed trials may suggest sensorimotor impairments in the global and/or local system to cope with clinical tasks during SEBT, Biodex balance, figure 8 hop, and triple crossover hop tests. Further, as mechanical and/or sensorimotor impairments are thought to be related to perceived self-reported function[97] and repeated ankle sprains,[17,33,75,84-88] we included 3 self-reported function questionnaires: FAAM-ADL, FAAM-Sports and MAII, and the number of previous ankle sprains. Lastly, a recent prospective study concluded that BMI may be a risk factor for repeated ankle sprains, as higher BMI is associated with greater risk of ankle reinjury and overall lower extremity injury.[85,98,99]

Single-Leg Maximal Vertical Forward Jump Landing/Cutting Task

Subjects were instructed to perform “double-leg maximal vertical forward jump as high as they can,” “land on the force plate with the test leg only,” and “side-cutting jump at 90° to the contralateral side as quickly as possible” in a maximal effort while facing forward during the task (Figure 1). We allowed up to 10 practice trials, gradually increasing vertical jump height, to reduce learning effects for subjects prior to testing data collection. Subjects then performed 10 testing trials of single-leg maximal vertical forward jump landing/cutting. Subjects stood at a distance that was 50% of their height from the center of the force plate (Figure 1A). Subjects performed a double-leg maximal vertical forward jump (Figure 1B), landed on the force plate with the test leg only (Figure 1C), and immediately transitioned to a side-cut jump at 90° to the contralateral side (Figures 1D and 1F). We marked 3 target locations: the starting position, the landing position on the force plate and the side-cut jump landing position (standardized to 60–70% of subject's height) to ensure consistency across all trials of the task. The first 5 trials were used to estimate a range of maximal vertical jump heights by adding ± 5% to the average maximal vertical jump height. We calculated and confirmed the maximal vertical jump height using a sacral marker (posterior superior iliac crest) in Vicon Nexus software during a 1-min rest between each trial. The next 5 successful trials were used for data analysis. We discarded and repeated a trial if the subject missed any of the target locations or the maximal vertical jump height was outside of the range determined in the first 5 trials. There was a 1-min rest between each trial.

Motion Analysis

We collected motion data using 12 high-speed cameras (250 Hz; Vicon, Oxford, UK) during the stance phase of jump landing/cutting. We placed 44 reflective markers on each subject's anatomical landmarks. A single marker was placed bilaterally over anterior and posterior superior iliac spine, greater trochanter, medial and lateral femoral condyle, medial and lateral malleoli, posterior heel, dorsal midfoot, middle forefoot (head of second metatarsal), medial and lateral forefoot. Four rigid clusters with 4 markers were placed bilaterally over the lateral midthigh and midshank.

Data Processing

We collected spatial trajectories from 44 reflective markers using Vicon Nexus software, and imported them into Visual 3D (C-Motion, Germantown, MD). The trajectories data were smoothed using a fourth-order low-pass Butterworth filter; a cutoff frequency of 10 Hz was determined by residual analyses[100] for all jump landing/cutting trials. We used the smoothed marker coordinates to calculate 3D ankle, knee and hip joint kinematics for jump landing/cutting tasks. We created a static model for each subject using previously described methods.[82] Joint kinematics were calculated using a Cardan rotation sequence of flexion-extension, abduction-adduction, and internal-external rotation.[101]

Functional Statistical Analysis

Functional Principal Component Analysis. There were 6 "dimensions" of data that were used in this study: ankle, knee and hip angles in both the frontal and sagittal planes. Within each "dimension," a subject had 5 iterate curves (e.g., 5 trials of landing/cutting), making a total of 30 curves per subject (6 dimensions × 5 trials of the task). The goal was to have a single representative curve for analysis per subject in each of frontal and sagittal planes. Of the 5 available curves for a given subject and dimension, 4 curves were registered to a selected reference curve; typically the curve had the largest data points (e.g., the longest stance time). All curves started at time point zero and end points were based on the curve to which the replicate curves were registered. If the number of observed points varied from curve to curve within a subject, then points were interpolated using time-warping splines.[102,103] The resulting 5 curves were identical in length and very similar in shape, so an average at each point was taken to obtain a single curve per subject per dimension, making a total of 6 curves per subject, 3 for each of the frontal and sagittal planes. Next, using functional principal component analysis, we reduced the ankle, knee and hip kinematic curves to one in each of the frontal and sagittal planes. This process took a "variance-maximizing average" highlighting important and informative features found in the input curves. We registered the remaining curves in that plane to the reference curve and the resulting curves were the final representative curves used in analysis. In short, to obtain representative curves we registered and averaged within-subject dimension curves, did functional principal component analysis on within-subject plane curves on 5 groups of 2 curves per subject, and then registered between-subject plane curves.

Hierarchical Bayesian Model with a Product Partition Model. We used a hierarchical Bayesian model that employed a product partition model, to cluster movement curves. A feature of the procedure was the probabilistic assignment of individuals to cluster based on shape of the representative curve and the similarity of 12 clinical predictor values. For example, if we cluster one of the dependent variables, a sagittal representative curve using the functional principal component analysis, yit is denoted as a sagittal representative curve and the measurement was taken on the i-th subject at time t. In this proposal $i = 1, 2, 3, \ldots, 100$ and $t = 1, \ldots, ni$ where ni denotes the number of time points for the i-th subject. Measurements of a sagittal representative curve during landing/cutting were realizations of subject-specific functions resulting in the following equation:

$$yit = \beta 0i + fi(zit) + \epsilon it. \tag{1.1}$$

Here zit references time at which yit was measured, $fi(\,)$ denoted each subject's (i-th) sagittal representative curve, $\beta 0i$ denoted a vertical shift to the i-th subject's curve, and ϵit was an idiosyncratic error or deviation from the subject-specific curve $fi(\,)$. The error term followed a normal distribution with mean 0 and variance σ^2 (in notation $\sigma^2 \sim N(0, \sigma^2)$). In this proposal, there was negligible deviations from the curve and σ^2 was very small. In model 1.1, $fi(\,)$ was unknown for each subject, so it was estimated using the data. This seemingly challenging problem was greatly simplified when instead of considering $fi(\ )$ directly we considered an approximation of $fi(\ )$ which was expressed as a simple linear combination of basis functions. We used the following equation for this process:

$$fi(zi\mathrm{t}) = h(zit)\,\beta i \tag{1.2}$$

where $h(\ )$ was a known basis function and βi denoted the corresponding "regression" coefficients. Instead of estimating $fi(\ )$, we estimated βi which was much simpler.

Predictor Dependent Product Partition Model. The method employed to include values of 12 clinical predictors in clustering of curves (in addition to the curve shape which was carried out using the coefficients in equation 1.2), was through a predictor-dependent product partition model.[104] The predictor dependent product partition model was a probability distribution that assigned probabilities to all the possible ways that n subjects can be collected into κ groups. It gets its name because distribution was based on a product called cohesion functions that measured the "compactness" of subjects in a cluster and a "similarity" function that measured the similarity among subject 12 clinical predictor values. In what follows, the cohesion function was denoted by $c(\cdot)$ and the similarity by $g(\cdot)$. We used ρ to denote a partition of the n subjects into κ groups. That was if $S1$ denoted the collection of subjects in the first group, and $S2$ the second up to $S\kappa$, then $\rho = \{S1, S2, S\kappa\}$. A predictor dependent product partition model equation had the following form:

$$Pr(\rho = \{S1, S2, \ldots, S\kappa\}) = \frac{1}{C}\prod_{j=1} c(Sj)\,g(x\frac{*}{j}) \tag{1.3}$$

where C was a normalizing constant ensuring the probabilities associated with all the possible partition sums to 1 and $x\frac{*}{j}$ was a collection of cluster specific clinical predictor values. More specifically, if we let $xi = (x1i, x2i, \ldots, x\mathrm{p}i)$ denote the i-th subjects p predictor values (e.g., $x1i$

= gender for the i-th subject, $x2i$ = SEBT-ANT for the i-th subject, $x3i$ = Biodex balance for the i-th subject . . ., etc.), then x^*_j was the collection of all the xi's that belong to cluster j. The specific form of (•) was dependent on the application, but had to produce larger values when the clinical predictor values included in the cluster were more "similar." In this way, subjects that have similar values of clinical predictors had a higher probability of being assigned to the same cluster *a priori*. The partition equation in model 1.3 together with the data equation 1.1 and function equation 1.2 modeled subject response curves flexibly, yet still have the ability to cluster subjects based on shape of the representative curve and 12 clinical predictor values. We refer to the model detailed in equations 1.1 to 1.3 as the prediction model, and was a simplified version of that found in a previous paper.[105]

RESULTS

Characteristics of Frontal Kinematic Movement Pattern Clusters

We used the product partition model to estimate the number of frontal movement clusters, and partitions that contained 4 frontal clusters were identified to have the highest posterior probability (Figure 3). The number of subjects in each of 4 frontal clusters are presented in Table 2. Six clinical predictors, including gender (p = 0.00), SEBT-ANT (p = 0.03), figure 8 hop (p = 0.00), triple crossover hop (p = 0.00), DFROM (p = 0.01) and FAAM-ADL (p = 0.03) appeared to be influential for group assignment of 4 frontal clusters (Table 2); there are statistically significant differences in the cluster specific means for each of 6 clinical predictors between 4 frontal clusters. Table 2 has the results of post hoc pairwise comparisons. Table 3 shows the characteristics of each of 4 frontal clusters. For example, in frontal cluster 1, the value of 45.7% indicates that 45.7% of the subjects in frontal cluster 1 were females who performed the triple crossover hop that ranged from 2.38–4.3 m.

Prediction Model Accuracy for Frontal Kinematic Movement Pattern Clusters

The multinomial regression model revealed 2.2 times chance (55.7%) of prediction model accuracy in assigning each of 97 CAI subjects into 1 of 4 frontal clusters. Due to a small sample size in frontal cluster 5 (n = 2) and 6 (n = 1), 97 CAI subjects were used for prediction model accuracy. Initially, the prediction model allocated each subject to 1 of 4 frontal clusters based on lower extremity frontal kinematics and values of 12 clinical predictors. Then, we treated each subject's cluster assignment as the response in a multinomial regression model. We obtained the out-of-sample prediction by excluding a subject's predictor values and a cluster label when fitting the multinomial regression model and then using the fitted model to predict group assignment for the excluded subject using the excluded subject's predictor values. We did this for each of the 97 CAI subjects. Table 4 details prediction model accuracy for 4 frontal clusters.

Characteristics of Sagittal Kinematic Movement Pattern Clusters

We used the prediction model to determine an optimal number of sagittal movement clusters, and we identified partitions that contained 5 sagittal clusters as having the highest posterior probability (Figure 7). The number of subjects in each of 5 sagittal clusters are presented in Table 5. Ten clinical predictors appeared to be influential for group assignment of 5 sagittal clusters in the same sense as described for 4 frontal clusters, including gender ($p = 0.00$), SEBT-ANT ($p = 0.00$), figure 8 hop ($p = 0.00$), triple crossover hop ($p = 0.00$), DFROM ($p = 0.00$), the number of failed trials during the clinical tests ($p = 0.00$), BMI ($p = 0.00$), FAAM-Sports score ($p = 0.00$), FAAM-ADL score ($p = 0.00$) and MAII "yes" responses on questions 4–8 ($p = 0.03$) (Table 5). Results of post hoc pairwise comparisons are presented in Table 5. Characteristics of each of 5 sagittal clusters (% of values) are presented in Table 6. For example, in sagittal cluster 1, the value of 65.6% indicates that 65.6% of the subjects in sagittal cluster 1 were female who performed triple crossover hop that ranged from 2.38–4.3 m.

Prediction Model Accuracy for Sagittal Kinematic Movement Pattern Clusters

A multinomial regression model used the predictors (or covariates) of gender, SEBT-ANT, Biodex balance, figure 8 hop, triple crossover hop, DFROM, the number of failed trials during the clinical tests, BMI, FAAM-ADL score, FAAM-Sports score, MAII "yes" responses and the number of previous ankle sprains, produced an out-of-sample prediction rate of 3.0 times chance (59%) in assigning each of 100 CAI subjects into 1 of 5 sagittal clusters. Initially, the prediction model allocated each subject to 1 of 5 sagittal clusters using lower extremity sagittal kinematics and values of 12 clinical predictors. Then, we treated each subject's cluster assignment as the response in the multinomial regression model. We obtained the out-of-sample prediction by excluding a subject's predictor values and cluster label when fitting the multinomial regression model, and then using the fitted model to predict group assignment for the excluded subject using the excluded subject's predictor values. We did this for each of the 100 CAI subjects. We presented the details of prediction model accuracy for sagittal clusters in Table 7.

DISCUSSION

Patients with CAI demonstrated multiple kinematic movement patterns during a single-leg landing/cutting task (Figure 1). We identified 4 subgroups of frontal movement patterns and 5 subgroups of sagittal movement patterns, respectively, based on shape of the each patient's representative curve and values of 12 clinical predictors. Our data suggest that 6 clinical predictors (e.g., gender, SEBT-ANT, figure 8 hop, triple crossover hop, DFROM, and FAAM-ADL score; Table 3) provided insight of group membership in assigning each CAI patient to 1 of the 4 frontal clusters with 2.2 time chances (55.7% accuracy; Table 2), while 10 clinical predictors (e.g., minus Biodex balance and the number of previous ankle sprains; Table 7) provided insight of group membership in assigning each CAI patient to 1 of the 5 sagittal clusters with 3.0 time chance (59% accuracy; Table 6). The current study provides novel findings about the presence of multiple movement patterns within a homogeneous CAI population through the self-reported function. More importantly, clinical tests may help identify specific movement patterns in clinical settings without using laboratory-based tools like a motion capture system and force plates.

The Importance of Identifying Multiple Movement Patterns in a CAI Population

Previous epidemiology studies[6,106,107] reported that a majority of ankle sprains occur during jump-landing, hopping, cutting, or twisting (direction changes). It is believed that altered movement patterns during these dynamic tasks could predispose CAI patients to vulnerable positions and loads of the foot, which could increase risk of ankle sprains.[47,48,63] As such, rehabilitation interventions could focus on these altered movement patterns to reduce the prevalence of ankle reinjury. However, substantial CAI research has been focused on examining alterations in each component of mechanical and sensorimotor impairments: pathological laxity,[20,108,109] arthrokinematic restrictions,[16,17] osteokinematic restrictions,[25,33,71] strength,[33,88,110-113] proprioception,[114-116] reflex reactions[33,35,117-126] and postural control,[32,91,127,128] while relatively few studies have examined altered movement patterns during landing or cutting.[47-51,129-132] Due to the nature of a static measurement position of mechanical and sensorimotor impairments, these studies give us limited perspectives about dynamic characteristics of neuromuscular control during functional tasks in an active CAI population.

Researchers have reported altered movement patterns during various landing tasks in CAI patients compared to controls and/or ankle sprain copers.[47,50,51,59,133] However, findings are conflicting between studies—demonstrating greater inversion kinematics,[49,63,64] less inversion kinematics,[47] or no difference in kinematics[48,50,53] during prelanding and/or postlanding. Conflicting findings between studies may be due to varied jump tasks, but more likely is due to multiple movement patterns that naturally exist given various constraints among CAI patients who would exhibit varied mechanical and/or sensorimotor impairments.[56,65] It is important to note that most CAI studies selected CAI patients using a subjective self-reported function defining this injured group as homogeneous.[25,42,47,60,92] However, considering the varying severity of mechanical and/or sensorimotor impairments along with the Dynamic System Theory, this injured population could be heterogeneous in terms of multiple movement patterns. This assumption led us to conduct a multiple movement pattern study recently, and the results of our unpublished work successfully identified 6 kinematic movement pattern clusters during a jump landing/cutting task (Figure 1). Since identification of these movement patterns is difficult, there is a need to find clinical tests that help identify multiple movement patterns in clinical settings, and the results of this study confirmed that multiple movement patterns can be predicted by clinical tests (e.g., SEBT-ANT, figure 8 hop, triple crossover hop, and DFROM).

It is worth noting that the current rehabilitation interventions have focused on reducing symptoms caused by ankle sprains (e.g., pain, swelling, effusion, etc.)[134,135] and on improving outcomes associated with risk factors of ankle sprains (e.g., diminished strength, impaired postural control, reduced reflex reactions, reduced proprioception and decreased range of motion).[66,89,90,136] Since these interventions were designed based on the existing literature on risk factors for recurrent ankle sprains, clinicians provide similar or the same rehabilitation protocols for all CAI patients, which are not individualized nor focused on altered movement patterns during functional tasks (e.g., jump-landing and cutting). Because of this, rehabilitation interventions appeared to be effective in some CAI studies,[12,13,137,138] but not all studies.[12,13,139] As mentioned previously, mechanical and/or sensorimotor impairments contribute to developing multiple movement patterns during functional tasks, which potentially predispose this patient population in different ways to repeated ankle sprains. To reduce risk of ankle sprains, identifying multiple movement patterns is of utmost importance, and if a certain movement pattern places this patient population at risk, the interventions should be developed and addressed to correct the specific movement patterns during functional tasks. This study is the first step in finding clinical predictors that would help identify specific movement patterns during a maximal single-leg jump landing plus cutting in a CAI population.

Multinomial Regression for Prediction Model Accuracy for Frontal and Sagittal Clusters

We used a multinomial regression model to quantify the influence of each predictor on cluster membership probabilities and to make predictions for frontal and sagittal kinematic clusters, respectively. The prediction model revealed 55.7% and 59% out-of-sample prediction rates for frontal and sagittal clusters, respectively. However, its clinical utility is questionable due to low prediction accuracy for which subject is assigned to a certain cluster. Greater than 75% of accuracy (3 in 4 cases correct accuracy) may provide more confidence in its clinical utility in clinical settings. It is worth noting that researchers should consider a few important things to improve the prediction model accuracy in any future study. First, 12 clinical predictors included in this study were chosen based on scientific evidence associated with a risk factor or a strong predictor for CAI. However, among 12 clinical predictors, only 4 predictors included in this study seemed to be highly supported by prospective data as a strong predictor for recurrent ankle sprains including SEBT[68,85,92,140] (or a similar Y-balance test),[141,142] DFROM,[33,86] BMI,[99,106,107] and FAAM-ADL score.[92] As such, more prospective data with a larger sample size is needed to identify other strong predictors for ankle reinjury that would help predict multiple movement patterns for any future study. Interestingly, BMI, defined as a strong predictor for ankle reinjury in previous studies, was not an influential predictor in predicting kinematic movement patterns in this study relative to other influential predictors such as SEBT, DFROM and FAAM-ADL score. There are two possible reasons. First, the current study may have a relatively small sample size compared to previous BMI studies: n = 152,[98] n = 539[85] and n = 11918.[99] There were only 8% of obese subjects (BMI, ≥ 30)[143] and 27% of overweight subjects (BMI, 25–29.9)[143] in this study. Due to the smaller ratio of higher BMI, BMI may not have been influential in the current study. Second, while the current study was conducted in a university setting; most subjects were college students (mean age of 21.8 ± 2.3); the previous BMI studies were completed in a high school population.[85,98,99] The findings of this study showed that some predictors (e.g., Biodex index, failed trials, FAAM-Sports, MAII and number of previous ankle sprains) did not play an important role in predicting kinetics movement patterns. Future studies should include other high differential predictors along with the influential predictors included in this study (e.g., gender, SEBT, figure 8 hop, triple crossover hop, DFROM and FAAM-ADL score). As the purpose of the prediction model was to predict lower extremity kinematic movement patterns by using values of clinical tests, future work should include movement-related measures including calcaneal eversion ROM, tibial varum ROM and talar tilt ROM as potential clinical predictors as suggested in previous data.[84]

Characteristics of Sagittal Kinematic Movement Pattern Clusters

We identified 5 sagittal kinematic pattern clusters in this study based on shape of the representative curve (e.g., ankle, knee and hip angles during landing/cutting) and values of 12 predictors. Sagittal clusters 1, 2, 3, and 5 seemed to have an adequate number of varied subjects (17–32 subjects), while sagittal cluster 4 had only 6 subjects. Not surprisingly, a smaller sample size increased characteristics of the cluster to find similarities within the cluster between subjects (% of values; Table 6), which may be attributed to less between-subject variability. For example, 100% of subjects in sagittal cluster 4 (n = 6) were characterized by gender and self-reported function. A trend of characteristics of each cluster (% of values) was reduced by having more subjects in each sagittal cluster: sagittal cluster 5 (n = 17; 82.3% of values), sagittal cluster 3 (n = 22; 72.7% of values) and sagittal cluster 1 (n = 32; 65.6% of values) (Table 6).

Among the 5 sagittal clusters, clusters 4 and 5 appeared to have a high risk of ankle reinjury. For example, sagittal cluster 4 (n = 6, 100% female) demonstrated several distinctive characteristics in negative ways including the most restricted DFROM (38.58 deg), the highest BMI (29.05 kg/m^2), the lowest self-reported function on the FAAM-Sports (48.83%), FAAM-ADL (72%) and MAII (4.67 "yes" responses), the longest figure 8 hop time (15.11 sec), the shortest triple crossover hop distance (3.47 m) and the largest number of failed trials during the clinical tests (8.5 times), compared to other sagittal clusters (Table 6). In addition, sagittal cluster 5 (n = 17, 100% male) also exhibited distinctive negative characteristics, including the shortest SEBT-ANT reach distance (56.36% of leg length), the second lowest DFROM (39.31 deg), and the second lowest self-reported function on the MAII (3.71 "yes" responses).

These findings from sagittal clusters 4 and 5 suggest 3 important clinical implications. First, poor performance on SEBT-ANT was identified as a strong predictor for risk of ankle reinjury.[68,85] Short reach distances are indicative of poor dynamic postural control, which has been observed in patients with CAI in meta-analyses.[32,91] Reduced performance on SEBT-ANT in sagittal cluster 5 could be due to diminished lower extremity strength,[144] mobility,[71,145] balance,[146] and coordination[147] because these factors are responsible for maintaining control of the body during the test. Specifically, short reach distances were associated with restricted DFROM (28% of the variance in a SEBT-ANT performance),[71] and reduced knee and hip flexion kinematics (49% of the variance in a SEBT-ANT performance).[148,149] Second, we observed a reduced DFROM in sagittal cluster 5, which was defined as a predictor for risk of CAI.[33,86,150] Pope et al[86] reported that limited dorsiflexion ROM (34 deg) results in 5 times greater risk of ankle sprains compared to normal DFROM (45 deg) during an intensive 12-week training in 1093 Australian Army recruits,[86] and further restricted DFROM has been reported in CAI patients during walking,[27] landing,[47,48] cutting,[47] running[26] and a static weight-bearing lunge test.[25,71,136] It is believed tension force during sudden inversion stress can result in an anterior positional fault of the talus,[21,22] which prevents the tibiotalar joint from reaching its rigid, stable, close-packed position (full dorsiflexion); thereby restricting dorsiflexion ROM.[22,87] This idea is supported by a recent study[25] suggesting a relationship between the reduced SEBT-ANT reach distance and restricted DFROM. Third, studies show that higher BMI increased the risk of ankle reinjury 2-fold in 539 high school football players, and increased the risk of reinjury 19 times when a higher BMI player (e.g., BMI for age and gender, ≥ 95th percentile)[143] player had a previous ankle sprain(s).[98] Further, even higher BMI (obese, e.g., BMI for age and gender, ≥ 95th percentile)[143] high school athletes sustained increased ankle/foot injuries compared to normal weight (e.g., BMI for age and gender, 15–85th percentile)[143] athletes that participated in sports such as wrestling, volleyball and football.[99] Future work should support a relationship between poor performance on clinical predictors and actual incidence of ankle injury. When it comes to a rehabilitation perspective, interventions should focus on increasing DFROM like talar glide[136] and calf stretching,[151] and increasing dynamic postural control like neuromuscular training (e.g., balance, strength, proprioception, power, agility, etc.).[66,89,90]

On the other hand, sagittal cluster 3 seemed to be the most physically functional group as indicated by the longest triple crossover hop distance (5.97 m), the fastest figure 8 hop time (9.70 sec), the second highest DFROM (47.71 deg), the second longest SEBT-ANT reach distance (65.20% of leg length) and the least failed trials during the clinical tests (3.73 times) among all sagittal clusters. Although good performance on the hop tests may be attributed to the high male ratio (91%)—because males have better performance measures than females due to physiological differences (e.g., strength and muscle fiber characteristics)[83]—other values of the predictors (e.g., DFROM, SEBT-ANT, and number of failed trials) indicate this group to be the most physically functional group among all sagittal clusters. Future research should examine a relationship between a better performance and risk of ankle reinjury.

Characteristics of Frontal Kinematic Movement Pattern Clusters

Like the sagittal clusters, a small sample size seemed to be associated with higher characteristics of the cluster (% of values). For example, frontal clusters 2 and 4 had a relatively small sample size of 8 and 14 subjects, respectively, which resulted in a better percentage of values that ranged from 62.5–64.2% when compared to frontal cluster 1 (n = 35) and 3 (n = 40) that ranged from 37.5–45.7% (Table 3). Frontal cluster 4 appeared to be the most physically functional group as indicated by the longest SEBT-ANT reach distance (65.29% of leg length), the fastest figure 8 hop time (10.02 sec), the longest triple crossover hop distance (5.92 m), the largest DFROM (47.59 deg), and the highest FAAM-ADL scores (88.21%). As the hop tests (e.g., figure 8 hop and triple crossover hop) are dependent on physical capacity (e.g., strength and muscle fiber characteristics),[83] a better performance on the hop tests in frontal cluster 4 could be due to a higher male ratio (79%), but values of other clinical predictors suggest that frontal cluster 4 seems to be the most physically functional group among all frontal clusters (Table 2). On the other hand, frontal cluster 2 seemed to be the least physically functional group. While frontal cluster 4 exhibited the best values on several predictors (e.g., SEBT-ANT, figure 8 hop, triple crossover hop, DFROM, and FAAM-ADL score), values of aforementioned predictors for frontal cluster 2 were completely opposite (e.g., the least values). A poor performance on the hop tests may result from a higher female ratio (88%) and/or the observed lowest self-reported function on the FAAM-ADL score (80.5%) and FAAM-Sports score (67.75%). Greater perceived instability of the ankle may decrease physical performance due to fear of ankle reinjury as reported by reduced function on the Disablement in the Physically Active Scale, increased Tampa Scale of Kinesiophobia-11, and increased Fear-Avoidance Beliefs Questionnaire.[97] As frontal cluster 4 seemed to be the most physically functional, and frontal cluster 2 seemed to be the least physically functional, prospective data should examine whether physical functionality is associated with risk of ankle reinjury.

High vs. Low Characteristics Between Sagittal and Frontal Clusters

Among 12 clinical predictors included in this study, 6 predictors (e.g., gender, SEBT-ANT, figure 8 hop, triple crossover hop, DFROM and FAAM-ADL) appeared to be influential for group membership of both frontal and sagittal clusters (Tables 2 and 5). We identified 4 frontal clusters in this study. In frontal cluster 4, 64.2% of subjects were characterized by gender (male), figure 8 hop (8.3–10.3 sec) and triple crossover hop (5.56–7.79 m). In frontal cluster 2, 62.5% of subjects were characterized by gender (female), triple crossover hop (2.38–4.3 m) and

Biodex balance (0.25–0.75 index stability). On the other hand, 5 sagittal kinematic movement pattern clusters were identified in this study. Sagittal clusters with a range from 30.4–100% was better characterized compared to frontal clusters which ranged from 37.5–64.2%. A possible explanation for this result is the fact that the sagittal representative curves displayed far less individual variability in shape, and, as a result, the clinical predictors had more influence on the resulting cluster configuration. In sagittal cluster 3, 72.7% of subjects were characterized by triple crossover hop (5.56–7.79 m) and figure 8 hop (8.3–10.3 sec). In sagittal cluster 4, 100% of subjects were characterized by gender (female) and FAAM-Sports (28–69%) and 82.3% of subjects were characterized by gender (male) and SEBT-ANT (46.7–59.5% of leg length). Among 6 frontal clusters, frontal clusters 5 (n = 2) and 6 (n = 1) were not included in further analyses (e.g., pairwise comparisons, post hoc pairwise comparison, and prediction model accuracy) due to a small sample size. Each of 4 frontal clusters were characterized by 2 predictors with a range of 37.5–64.2%, while each of 5 sagittal clusters were characterized with a range of 30.4–100%. On the basis of these findings observed higher characteristics of sagittal clusters (% of values presented in Table 6) may be attributed to lower between-subject variability in lower extremity sagittal kinematics during jump landing/cutting compared to frontal kinematics. For example, during landing, sagittal kinematics at the ankle, knee and hip involve a uniplanar direction towards increasing flexion angles (e.g., dorsiflexion, knee flexion and hip flexion) so that no opposite direction of sagittal kinematics (e.g., plantarflexion, knee extension and hip extension) would occur. As such, there are only uniplanar differences in kinematics (more or less angles) between subjects. Further, during side-cutting, sagittal kinematics at the ankle, knee and hip would also occur in a uniplanar direction towards increasing extension angles (e.g., plantarflexion, knee extension and hip extension). However, lower extremity frontal kinematics could occur in biplanar directions like inversion or eversion at the ankle and adduction or abduction at the knee and hip. Changes in the magnitude of frontal kinematics (angle differences) and biplanar directions of 3 lower extremity joints would lead to higher between-subject variability during jump landing/cutting, which potentially reduces the ability to characterize each frontal cluster. Greater variability between subjects in frontal kinematics may be associated with mechanical and/or sensorimotor impairments reported in CAI patients. From a mechanical impairment perspective, changes in pathological laxity and arthrokinematic restrictions may contribute to a greater variability of frontal kinematics, especially at the ankle. Substantial evidence has shown increased ankle ligament laxity (e.g., inversion and/or anterior direction) as measured by an ankle arthrometer in CAI patients,[19,43,108-110,152,153] while a few studies reported no increased ankle laxity in patients with CAI.[154,155] Conflicting results may support the idea of between-subject variability in a CAI population, suggesting that not all CAI patients have the same impairments.

Damage to lateral ankle ligaments (e.g., anterior talofibular, calcaneofibular, and posterior talofibular) and mechanoreceptors results in articular deafferentation (reduced sensory feedback),[156,157] which potentially decreases dynamic ankle joint stabilization (reduced motor function) of ankle musculatures (e.g., peroneal muscle groups).[158] It is believed greater ankle ligament laxity would reduce mechanical stability at the ankle,[19,156] which would place the foot into a more inverted position during initial landing, which is thought to increase risk of repeated ankle sprains.[20,108,109] For a sensorimotor perspective, relating to ligament laxity, it may be possible that a patient with high inversion ligament laxity would use a movement strategy to increase eversion angle as a self-protective motor strategy to avoid repeated ankle sprains as increased inversion laxity is a less stable, loose-packed, more vulnerable position to lateral ankle sprains, which is supported by a recent landing study.[47] Considering all possible ways to cope with mechanical and sensorimotor impairments during landing/cutting, greater between-subject variability of frontal kinematics are likely present in a CAI population. In addition, sensorimotor impairments in evertors, including slower reflex reactions,[35-37] arthrogenic muscle inhibition,[38] and diminished strength[39,40] are substantially reported in CAI patients. Conversely, some studies have reported no sensorimotor impairments in patients with CAI including strength,[152,159-161] reflex reactions,[32,40,84] and muscular activation.[52,124] Due to evertor impairments, each CAI patient would utilize his/her own movement strategy to accomplish desired movement tasks in a variety of ways, which ultimately result in higher variance of frontal kinematics between subjects, and further it would reduce the ability to characterize frontal kinematic movement pattern clusters.

Clinical Implications

When it comes to identifying kinematic movement patterns, the first step was to identify each movement pattern, which we successfully accomplished in our recent unpublished work. The second step, which was the purpose of the current study, was to find clinical predictors that help identify multiple movement patterns. The results of the current study revealed that kinematic movement patterns can be predicted using values of clinical predictors, however due to low prediction accuracy (55.7–59%), its clinical diagnostic utility remains questionable. However, prediction accuracy could be increased up to a desirable level (75% accuracy; 3 in 4 cases correct accuracy) if future work would include high influential predictors that were identified in the current study and would add other influential predictors that are movement-related measures. The third step is to identify altered movement patterns that place CAI patients at risk of ankle reinjury by measuring an actual incidence of injury as a follow-up study. The last step is to identify interventions to address altered-movement patterns and further to examine whether the interventions can actually reduce the risk of ankle reinjury. The end goal of this project is that clinicians can predict which altered-movement pattern is at risk of reinjury using a series of clinical tests without using high-cost biomechanical tools, and further provide target interventions to correct altered-movement patterns to minimize risk of reinjury. We characterized some clusters, including sagittal clusters 4 and 5, as being high risk of ankle reinjury (e.g., shorter SEBT-ANT reach distance, restricted DFROM, higher BMI, and higher perceived self-reported function). Prospective data should seek to support a potential relationship between poor motor performance on dynamic postural control (SEBT-ANT), ankle mobility (DFROM), hop tests (figure 8 hop and triple crossover hop) and higher BMI and an actual increased risk of reinjury.

Limitations of the Study

There are few limitations in the current study. First, altered movement patterns can be caused by various biomechanical parameters (e.g., ground reaction force, net internal joint moment, muscle activation, etc.). However, the current study only used lower extremity joint kinematics, which may provide limited information in understanding comprehensive altered movement patterns that would predispose a CAI population to risk of reinjury. Second, the predictor dependent clustering model identified 4 frontal clusters and 5 sagittal clusters. However, the number of subjects in frontal cluster 2 (n = 8), frontal cluster 4 (n = 14) and sagittal cluster 4 (n = 6) may not have a sufficient number of subjects for desired power (80%) to examine between-cluster differences in clinical predictors (e.g., post hoc pairwise comparisons, Tables 2 and 5). Third, we did not provide prospective data (e.g., actual incidences of ankle sprain injury, number of “giving way” episodes, exposure time to sports, type of participating sports, etc.) with the current subjects to quantify a relationship between altered movement patterns and risk of ankle reinjury. As such, as a 1-year follow up study, we are currently collecting prospective data to see which altered-movement patterns would have higher risk of reinjury. Fourth, although we collected data with 100 subjects in this study, since other prospective studies used a larger number of subjects: n = 152,[98] n = 539,[85] n = 1093[86] and n = 11918[99] to identify a risk factor for ankle reinjury, we may not have enough power to examine a relationship between altered-movement patterns and risk of ankle reinjury with the 100 subjects. Lastly, ankle sprains are observed across various ages from adolescence to elderly people, and, therefore, we can only generalize our findings to a college student population (mean age of 21.8 ± 2.3 years).

CONCLUSIONS

Statistical analyses—including the functional principal component analysis for a representative curve, product partition model for a subject assignment into the cluster and predictor dependent clustering model for the probability of the cluster—allowed us to predict kinematic movement patterns (which subject could be assigned to a certain cluster) using ankle, knee and hip kinematics as well as values of 12 clinical predictors. Six clinical predictors (e.g., gender, SEBT-ANT, figure 8 hop, triple crossover hop, DFROM, and FAAM-ADL score) were influential in predicting frontal kinematic movement pattern clusters (Table 2), while 10 clinical predictors (minus the Biodex balance and number of ankle sprains) were influential in predicting sagittal kinematic movement pattern clusters (Table 5). The end goal of this study is to identify altered movement patterns that predispose CAI patients to higher risk of ankle reinjury and to identify appropriate interventions to correct altered movement patterns to reduce the prevalence of ankle reinjury. The current findings of this study suggest that we were able to identify 4 frontal and 5 sagittal kinematic movement pattern clusters, and these movement pattern clusters seemed to be predicted using a series of clinical tests which ranged from 55.7 to 59% accuracy. Due to low prediction model accuracy in the current model, clinical practicality may be limited (40% errors). However, prediction model accuracy might be increased in future work by incorporating a different set of predictors by keeping the current high influential predictors (e.g., gender, SEBT-ANT, figure 8 hop, triple crossover hop, DFROM and FAAM-ADL score) used in this study and replacing the current low influential predictions (e.g., Biodex index, number of failed trials during the clinical tests, FAAM-Sports, MAII, and number of previous ankle sprains) with other new promising predictors (e.g., ROM measures of calcaneal eversion, tibial varum, and talar tilt).

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Table 1. Subject Demographics

Group	N	Age (yr)	Height (cm)	Mass (kg)	BMI[d] (kg/m^2)	FAAM[e]-ADL[f] (%)	FAAM[e]-Sports (%)	MAII[g] No. "yes" responses	No.[h] Ankle Sprains (n)	Duration since last ankle sprain (months)
CAI[a]	50 M[b]	21.8	174.4	74.1	24.3	85.3	68.5	3.5	3.5	11.6
	50 F[c]	(2.3)	(10.8)	(13.8)	(3.7)	(5.7)	(10.0)	(1.1)	(2.3)	(10.7)

Data are mean (SD).
[a]Chronic Ankle Instability
[b]Male
[c]Female
[d]Body Mass Index
[e]Foot and Ankle Ability Measure
[f]Activities of Daily Living
[g]Modified Ankle Instability Index
[h]No., number of

Table 2. Post Hoc Pairwise Comparisons Between Frontal Kinematic Movement-Pattern Clusters

Frontal Cluster	1	2	3	4	5	6
Number of Subjects	35	8	40	14	2	1

Cluster	Gender (M/F[a])	SEBT-ANT[b] (% LL)[c]	Biodex balance (index)	Figure 8 hop (sec)	Triple cross hop (m)	DFROM[d] (deg)	Failed trials	BMI[e] (kg/m²)	FAAM[f]-Sports (%)	FAAM[g]-ADL[f] (%)	MAII[h] "yes" responses	No.[i] ankle sprains
1	0.29[k,l]	65.27[k]	0.84	12.51[k,l]	4.42[k,l]	47.35[j]	4.94	23.84	69.69	86.09	3.54	3.43
2	0.12[m,n]	62.45	0.71	13.62[m,n]	4.20[n]	41.25[n]	5.50	24.52	67.75	80.50[n]	3.75	3.38
3	0.65	61.01	0.81	11.00	5.10[o]	43.46	4.72	24.74	68.55	85.08	3.40	3.83
4	0.79	65.29	0.74	10.02	5.92	47.59	4.00	23.42	70.36	88.21	3.57	2.71
p-value	0.00*	0.03*	0.31	0.00*	0.00*	0.01*	0.61	0.56	0.91	0.03*	0.84	0.50

Data are mean.

Frontal clusters 5 and 6 were not included in analyses for post hoc pairwise comparisons due to a small sample size.

[a]M = male (denote by 1); F, female (denoted by 0)
[b]SEBT-ANT = Star Excursion Balance Test–Anterior
[c]LL = Leg Length
[d]DFROM = dorsiflexion range of motion
[e]BMI = Body Mass Index
[f]FAAM = Foot and Ankle Instability Measure
[g]ADL = Activities of Daily Living
[h]MAII = Modified Ankle Instability Index
[i]No., number of

[j]indicates statistically significant differences between clusters 1 and 2.
[k]indicates statistically significant differences between clusters 1 and 3.
[l]indicates statistically significant differences between clusters 1 and 4.
[m]indicates statistically significant differences between clusters 2 and 3.
[n]indicates statistically significant differences between clusters 2 and 4.
[o]indicates statistically significant differences between clusters 3 and 4.

Table 3. Characteristics for Each of 4 Frontal Kinematic Movement Pattern Clusters

Cluster	Predictor 1	Predictor 2	% of values
1 (n = 35)	Triple cross hop (2.38–4.3 m)	Gender (female)	45.7%
	Figure 8 hop (12.2–20.7 sec)	Gender (female)	45.7%
	Triple cross hop (2.38–4.3 m)	Figure 8 hop (12.2–20.7 sec)	37.1%
	SEBT-ANT[a] (59.5–66.8% LL[b])	Gender (female)	28.5%
	FAAM[c]-ADL[d] (87–89%)	Gender (female)	28.5%
	Biodex balance (0.25–0.75)	Gender (female)	25.7%
2 (n = 8)	Biodex balance (0.25–0.75)	Gender (female)	62.5%
	Triple cross hop (2.38–4.3 m)	Gender (female)	62.5%
	No.[e] sprains (1–3 episodes)	Gender (female)	50%
	Figure 8 hop (12.2–20.7 sec)	Triple cross hop (2.38–4.3 m)	50%
	Figure 8 hop (12.2–20.7 sec)	Gender (female)	50%
	DFROM[f] (28.4–43.2 deg)	FAAM[c]-ADL[d] (60–87%)	50%
3 (n = 40)	Figure 8 hop (8.3–10.3 sec)	Gender (male)	37.5%
	Triple cross hop (5.56–7.79 m)	Gender (male)	35%
	FAAM[c]-ADL[d] (60–87%)	FAAM[c]-Sports (28–69%)	35%
	Triple cross hop (5.56–7.79 m)	Figure 8 hop (8.3–10.3 sec)	32.5%
	DFROM[f] (43.2–48.4 deg)	MAII[g] "yes" (2–4 responses)	27.5%
4 (n = 14)	Figure 8 hop (8.3–10.3 sec)	Triple cross hop (5.56–7.79 m)	64.2%
	Figure 8 hop (8.3–10.3 sec)	Gender (male)	64.2%
	FAAM[c]-ADL[d] (87–89%)	DFROM[f] (48.4–60.9 deg)	42.8%
	Biodex balance (0.75–0.9)	Gender (male)	35.7%
	Biodex balance (0.75–0.9)	Triple cross hop (5.56–7.79 m)	35.7%
	SEBT-ANT[a] (66.8–83.5 % LL[b])	DFROM[f] (48.4–60.9 deg)	35.7%

Clusters 5 and 6 were not included due to a small sample size (n = 3).
[a]SEBT-ANT = Star Excursion Balance Test-Anterior
[b]LL = Leg Length
[c]FAAM = Foot and Ankle Instability Measure
[d]ADL = Activities of Daily Living
[e]No., number of
[f]DFROM = Dorsiflexion Range of Motion
[g]MAII = Modified Ankle Instability Index

Table 4. Multinomial Regression of Prediction Model Accuracy for Frontal Kinematic Movement-Pattern Clusters

Frontal Cluster	1	2	3	4
Number of Subjects	35	8	40	14

	Prediction 1 (n)	Prediction 2 (n)	Prediction 3 (n)	Prediction 4 (n)	Actual Prediction (N)	Actual Unprediction (N)	Actual Prediction Model Accuracy (%)
Actual 1 (n)	**21**	3	9	2	**21 / 35**	14 / 35	60.0
Actual 2 (n)	5	**0**	3	0	**0 / 8**	8 / 8	00.0
Actual 3 (n)	10	0	**28**	2	**28 / 40**	12 / 40	70.0
Actual 4 (n)	5	0	5	**5**	**5 / 14**	10 / 14	35.7
					54 / 97	44 / 97	**55.7**

Data are the number of subjects in each of four clusters.
Clusters 5 and 6 were not included in analyses for prediction model accuracy due to a small sample size (n = 3).

Table 5. Post Hoc Pairwise Comparisons Between Sagittal Kinematic Movement-Pattern Clusters

Sagittal Cluster	1	2	3	4	5
Number of Subjects	32	23	22	6	17

Cluster	Gender (M/F[a])	SEBT-ANT[b] (% LL)[c]	Biodex balance (index)	Figure 8 hop (sec)	Triple cross hop (m)	DFROM[d] (deg)	Failed trials	BMI[e] (kg/m²)	FAAM[f]-Sports (%)	FAAM[f]-ADL[g] (%)	MAII[h] "yes" responses	No.[i] ankle sprains
1	0.03[j,k,l]	65.38[m]	0.75	13.18[j,k,l,m]	4.10[j,k,m]	47.84[l,m]	5.09[l]	23.17[l]	72.50[l]	86.88[l]	3.50	2.84
2	0.52[n,o,p]	63.41[p]	0.90	11.30[n,o]	4.80[n,o,p]	44.78[p]	4.35[o]	24.80	71.30[o]	87.00[o]	3.22[o]	3.61
3	0.91[q]	65.20[r]	0.76	9.70[q]	5.97[q]	47.71[q,r]	3.73[q]	23.59[q]	66.73[q]	85.64[q]	3.23[q]	3.55
4	0.00[s]	60.94	0.76	15.11[s]	3.47[s]	38.58	8.50[s]	29.05	48.83[s]	72.00[s]	4.67	5.50
5	1.00	56.36	0.86	10.27	5.66	39.31	4.53	24.98	69.29	86.00	3.71	3.82
p-value	0.00*	0.00*	0.09	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.03*	0.11

Data are mean.

[a]M/F = M = male (denoted by 1); F = female (denoted by 0)
[b]SEBT-ANT = Star Excursion Balance Test–Anterior
[c]LL = Leg Length
[d]DFROM = Dorsiflexion Range of Motion
[e]BMI = Body Mass Index
[f]FAAM = Foot and Ankle Instability Measure
[g]ADL = Activities of Daily Living
[h]MAII = Modified Ankle Instability Index
[i]No., number of

[j]indicates statistically significant differences between clusters 1 and 2.
[k]indicates statistically significant differences between clusters 1 and 3.
[l]indicates statistically significant differences between clusters 1 and 4.
[m]indicates statistically significant differences between clusters 1 and 5.
[n]indicates statistically significant differences between clusters 2 and 3.
[o]indicates statistically significant differences between clusters 2 and 4.
[p]indicates statistically significant differences between clusters 2 and 5.
[q]indicates statistically significant differences between clusters 3 and 4.
[r]indicates statistically significant differences between clusters 3 and 5.
[s]indicates statistically significant differences between clusters 4 and 5.

Table 6. Characteristics for Each of 5 Sagittal Kinematic Movement Pattern Clusters

Cluster	Predictor 1	Predictor 2	% of values
1 (n = 32)	Triple cross hop (2.38–4.3 m)	Gender (female)	65.6%
	MAII[a] "yes" (2–4 responses)	Gender (female)	56.2%
	No.[b] sprains (1–3 episodes)	Gender (female)	53.1%
	Biodex balance (0.25–0.75)	Gender (female)	46.8%
	FAAM[c]-Sports (76–79%)	Gender (female)	43.7%
	SEBT-ANT[d] (59.5–66.8 % LL)	Gender (female)	40.6%
2 (n = 23)	FAAM[c]-ADL[e] (89%)	SEBT-ANT[d] (59.5–66.8% LL)	30.4%
	FAAM[c]-ADL[e] (89%)	Biodex balance (0.75–0.9)	30.4%
	BMI (18.4–22.4 kg/m^2)	No.[b] sprains (1–3 episodes)	30.4%
	Figure 8 hop (8.3–10.3 sec)	Triple cross hop (5.56–7.79 m)	26%
	Figure 8 hop (8.3–10.3 sec)	Gender (male)	26%
3 (n = 22)	Triple cross hop (5.56–7.79 m)	Figure 8 hop (8.3–10.3 sec)	72.7%
	DFROM[g] (48.4–60.9 deg)	Gender (male)	50%
	No.[b] sprains (1–3 episodes)	Gender (male)	36.3%
	SEBT-ANT[d] (46.7–59.5 % LL)	Gender (male)	31.8%
	DFROM[g] (43.2–48.4 deg)	Gender (male)	31.8%
4 (n = 6)	FAAM[c]-Sports (28–69%)	Gender (female)	100%
	Figure 8 hop (12.2–20.7 sec)	Triple cross hop (2.38–4.3 m)	83.3%
	Figure 8 hop (12.2–20.7 sec)	Gender (female)	83.3%
	Figure 8 hop (12.2–20.7 sec)	FAAM[c]-Sports (28–69%)	83.3%
5 (n = 17)	SEBT-ANT[d] (46.7–59.5 % LL)	Gender (male)	82.3%
	DFROM[g] (28.4–43.2 deg)	Gender (male)	76.4%
	No.[b] sprains (3–5 episodes)	SEBT-ANT[d] (46.7–59.5 % LL)	58.8%
	No.[b] sprains (3–5 episodes)	Gender (male)	58.8%
	Figure 8 hop (8.3–10.3 sec)	Gender (male)	58.8%
	Triple cross hop (5.56–7.79 m)	Gender (male)	52.9%

[a]MAII = Modified Ankle Instability Index
[b]No., number of
[c]FAAM = Foot and Ankle Instability Measure
[d]SEBT-ANT = Star Excursion Balance Test–Anterior
[e]ADL = Activities of Daily Living
[f]BMI = Body Mass Index
[g]DFROM = Dorsiflexion Range of Motion

Table 7. Multinomial Regression of Prediction Model Accuracy for Sagittal Kinematic Movement-Pattern Clusters

Sagittal Cluster	1	2	3	4	5
Number of Subjects	32	23	22	6	17

	Prediction 1 (n)	Prediction 2 (n)	Prediction 3 (n)	Prediction 4 (n)	Prediction 5 (n)	Actual Prediction (N)	Actual Unprediction (N)	Actual Prediction Model Accuracy (%)
Actual 1 (n)	**25**	6	1	0	0	**25 / 32**	7 / 32	78.1
Actual 2 (n)	8	**7**	6	0	2	**7 / 23**	16 / 23	30.4
Actual 3 (n)	1	6	**11**	0	4	**11 / 22**	11 / 22	50.0
Actual 4 (n)	0	1	0	**5**	0	**5 / 6**	1 / 6	83.3
Actual 5 (n)	0	2	4	0	**11**	**11 / 17**	6 / 17	64.7
						59 / 100	41 / 100	**59.0**

Data are the number of subjects in each of 5 clusters.

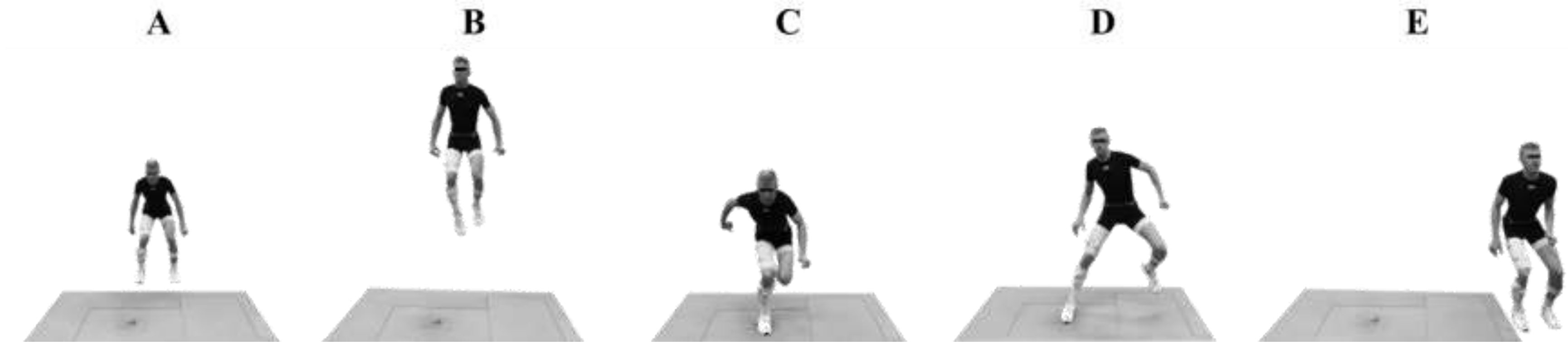

Figure 1. Single-leg maximal vertical forward jump landing/cutting task.

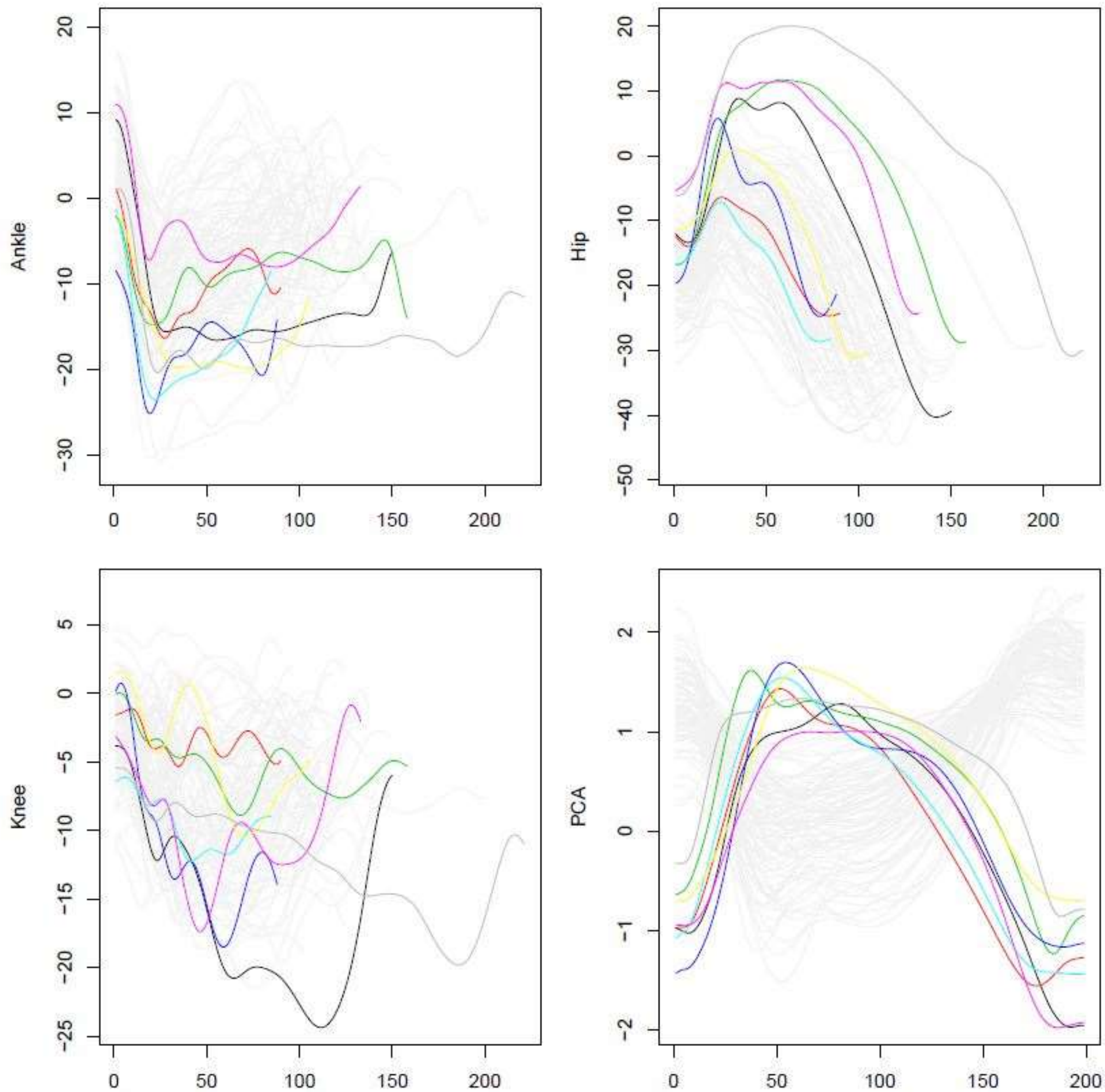

Figure 2. Frontal ankle, knee, and hip joint angles (x-axis) during the stance phase of landing/cutting (y-axis).

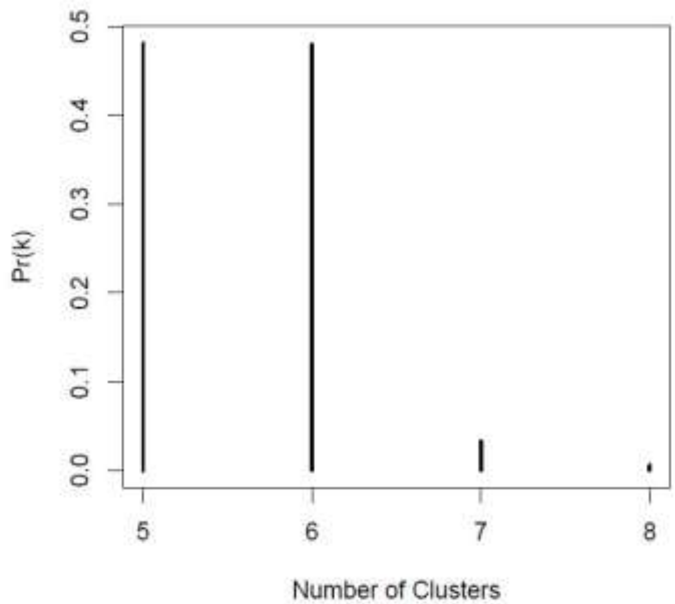

Figure 3. Frontal kinematic probability, Pr (k), for the number of frontal clusters.

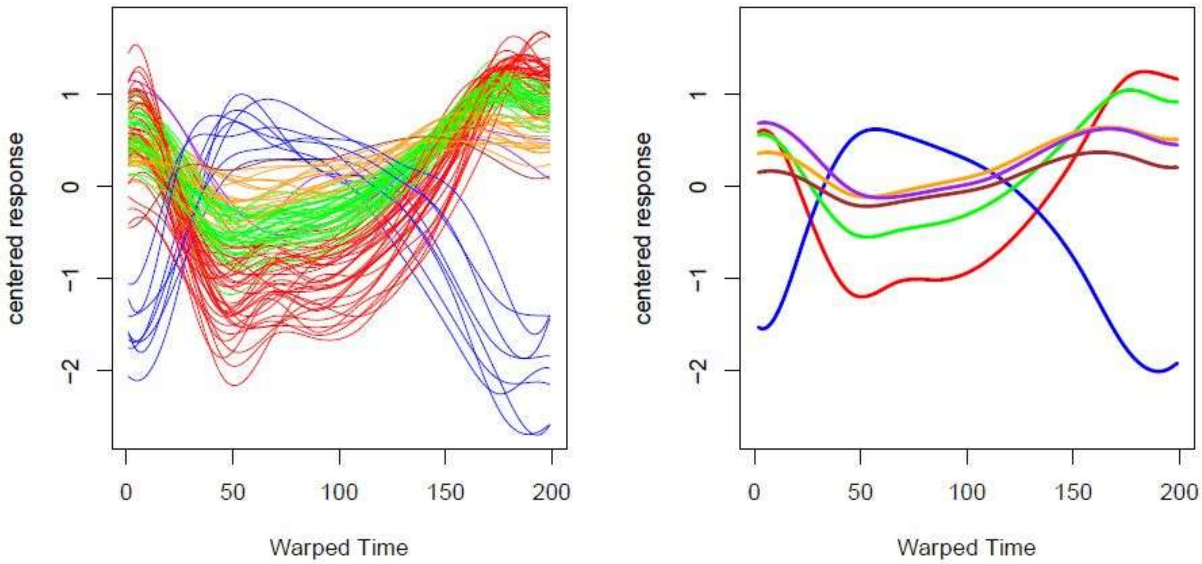

Figure 4. Frontal kinematic representative curves for CAI 100 subjects (left subplot).

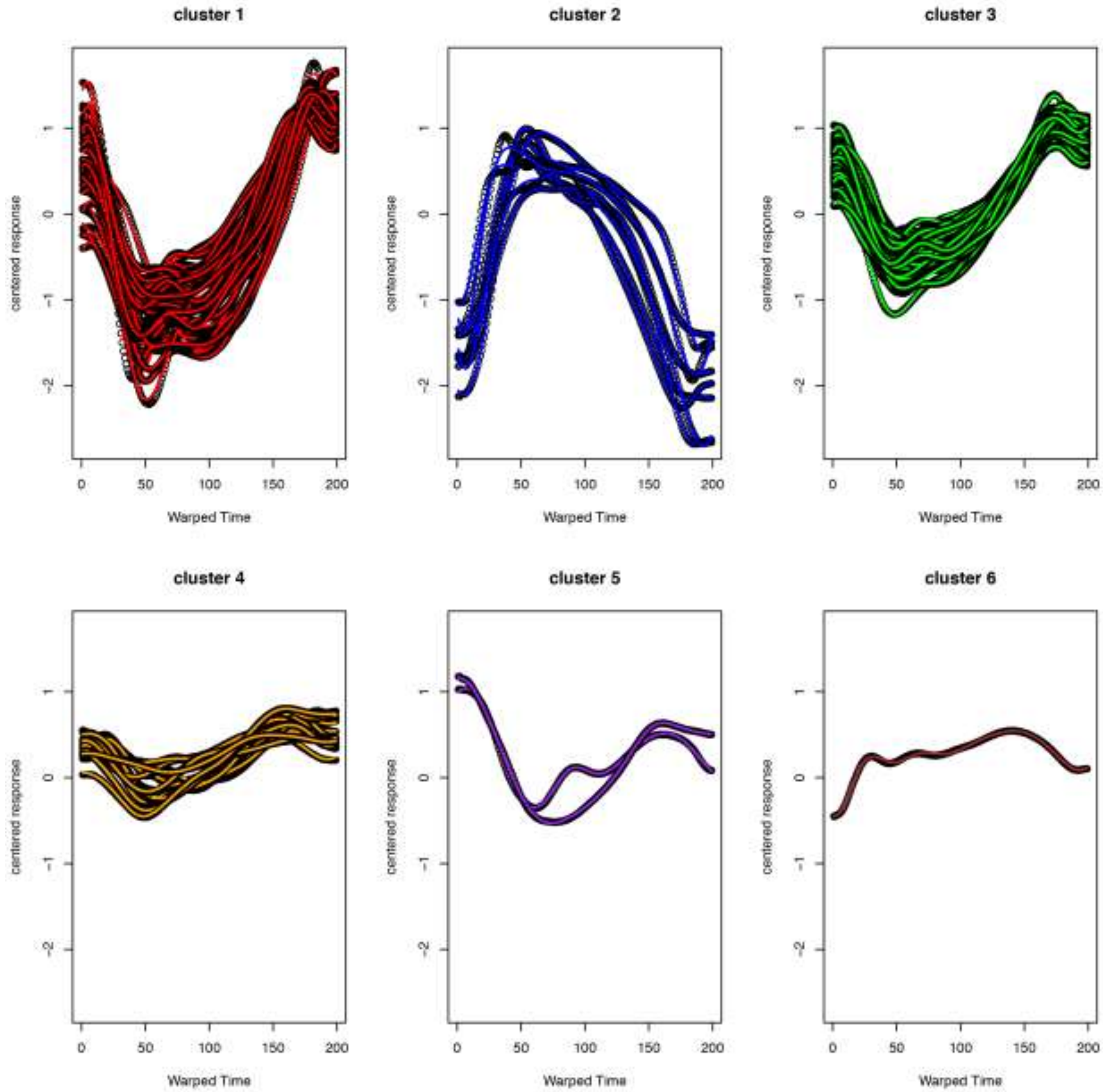

Figure 5. Frontal kinematic representative curves for each of 6 frontal clusters.

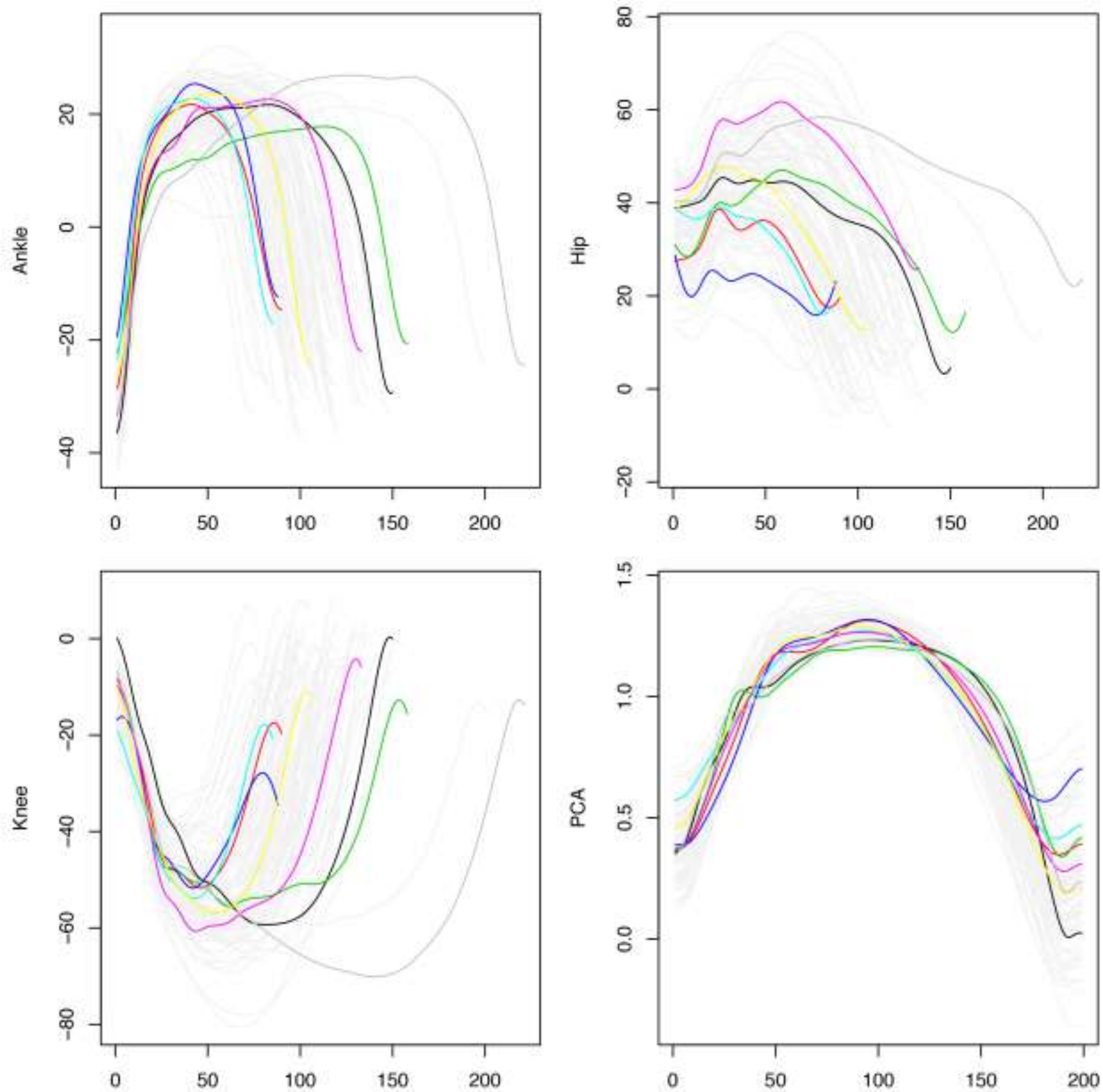

Figure 6. Sagittal ankle, knee, and hip joint angles (x-axis) during the stance phase of landing/cutting (y-axis).

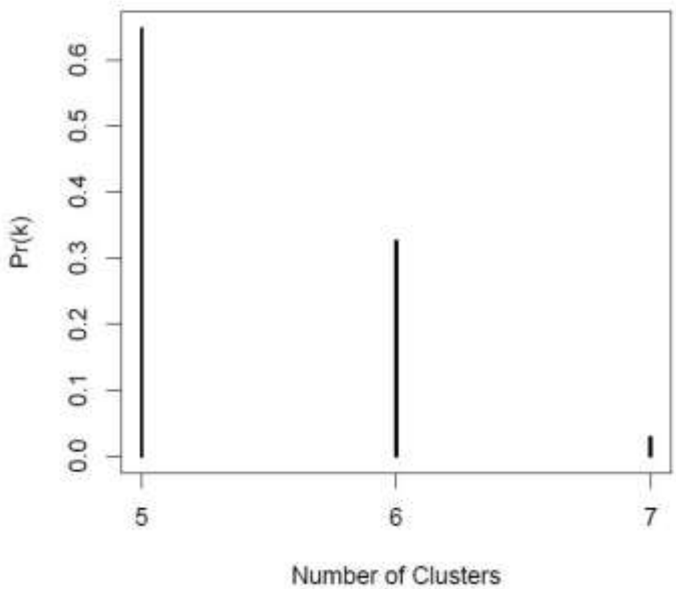

Figure 7. Sagittal kinematic probability, Pr(k), for the number of sagittal clusters.

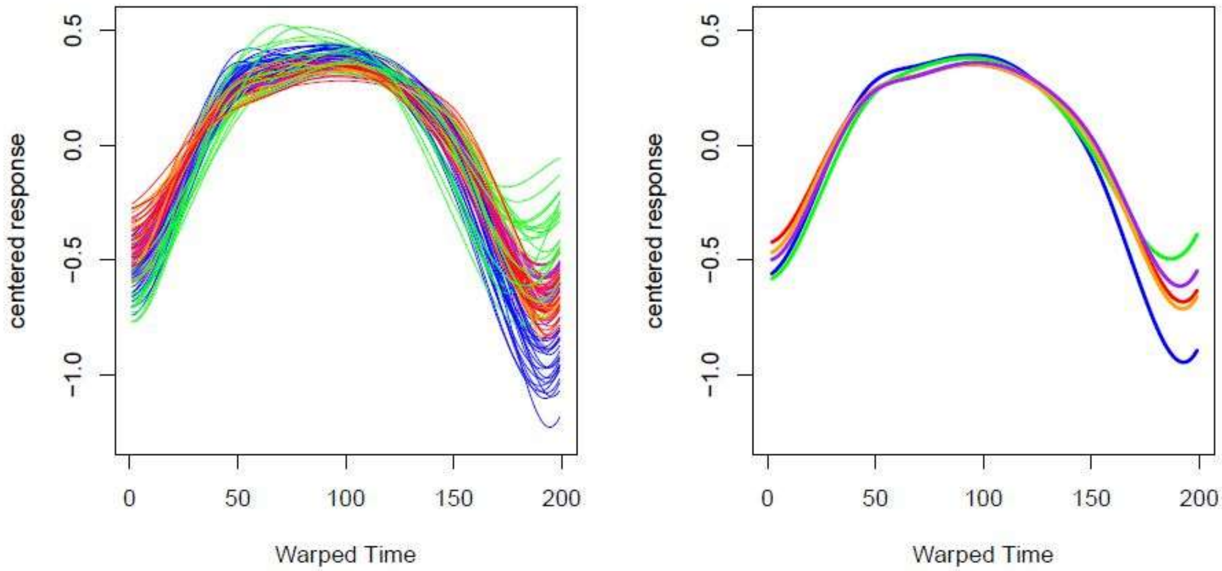

Figure 8. Sagittal kinematic representative curves for 100 CAI subjects (left subplot).

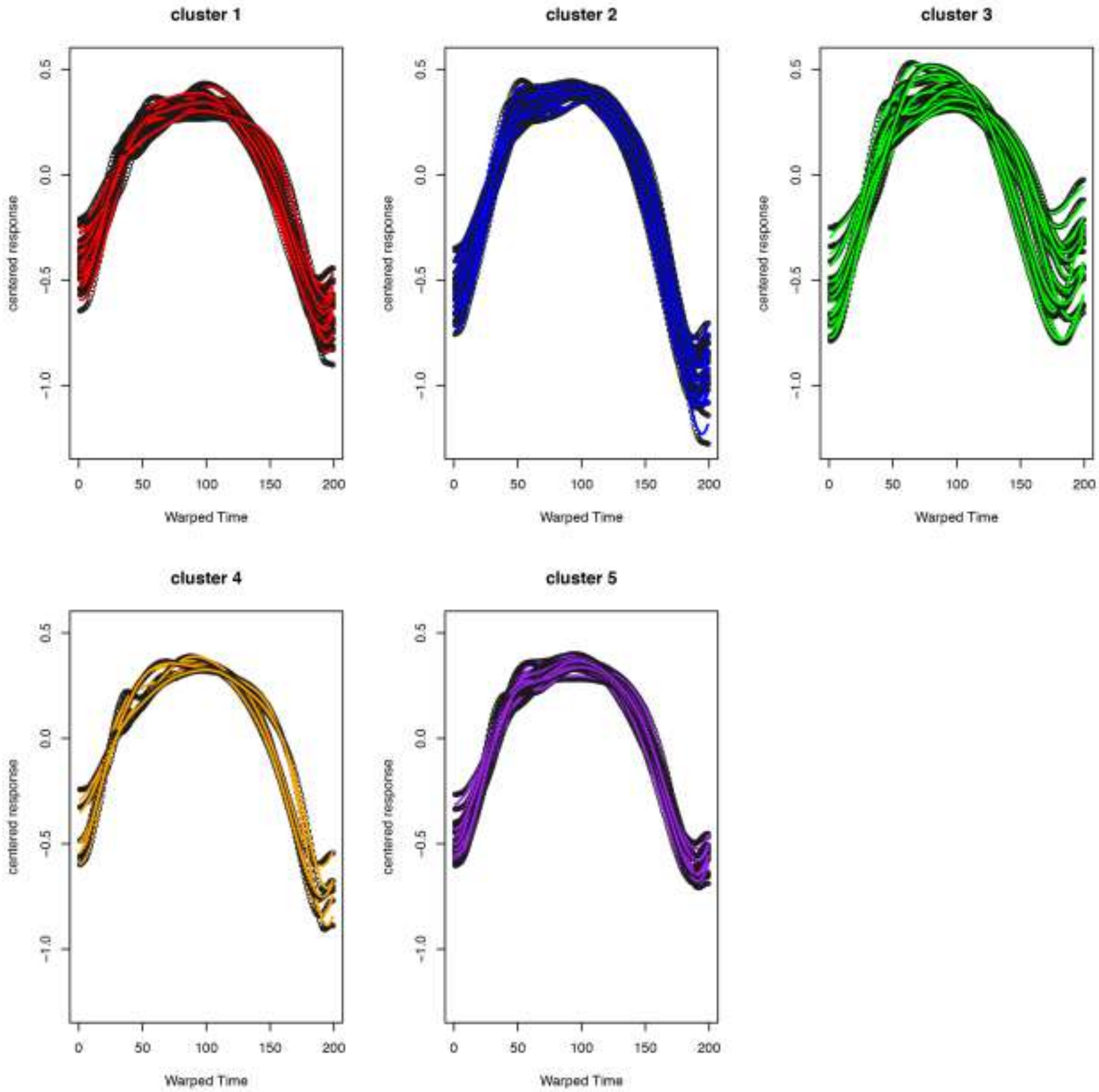

Figure 9. Sagittal kinematic representative curves for each of 5 sagittal clusters.

Figure Captions

Figure 1. Single-leg maximal vertical forward jump landing/cutting task. A, a double-leg standing position; B, a maximal vertical forward jump; C, a single-leg landing; D, a single-leg side-cutting jump to the contralateral side; E, a double-leg landing position.

Figure 2. Frontal ankle, knee, and hip joint angles (x-axis) during the stance phase of landing/cutting (y-axis). The functional principle component analysis produced a frontal kinematic representative curve for each subject using shape and length of the curve. When the frontal kinematic representative curve is close to zero (y-axis), the probability is reduced.

Figure 3. Frontal kinematic probability, Pr (k), for the number of frontal clusters. The product partition model indicated that 5 or 6 clusters had the highest probability to determine the optimal number of frontal kinematic movement-pattern clusters.

Figure 4. Frontal kinematic representative curves for CAI 100 subjects (left subplot). Mean of frontal kinematic representative curves for each of 6 frontal clusters (right subplot).

Figure 5. Frontal kinematic representative curves for each of 6 frontal clusters.

Figure 6. Sagittal ankle, knee, and hip joint angles (x-axis) during the stance phase of landing/cutting (y-axis). The functional principle component analysis produced a sagittal kinematic representative curve for 100 subjects using shape and length of the curve. When the sagittal kinematic representative curve is close to zero (y-axis), the probability is reduced.

Figure 7. Sagittal kinematic probability, Pr(k), for the number of sagittal clusters. The product partition model indicated that 5 clusters had the highest probability to determine the optimal number of sagittal kinematic movement-pattern clusters.

Figure 8. Sagittal kinematic representative curves for 100 CAI subjects (left subplot). Mean of sagittal kinematic representative curves for each of 5 sagittal clusters (right subplot).

Figure 9. Sagittal kinematic representative curves for each of 5 sagittal clusters.