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RESEARCH ARTICLE

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Kinematics observed during ACL injury are associated with large early peak knee abduction moments during a change of direction task in healthy adolescents

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Abstract

Cluster analysis of knee abduction moment waveforms may be useful to examine biomechanical data. The aim of this study was to analyze if the knee abduction moment waveform of early peaks, consistent with anterior cruciate ligament injury mechanisms, was associated with foot-trunk distance, knee kinematics, and heel strike landing posture, all of which have been observed during anterior cruciate ligament injuries. One hundred and seventy-seven adolescent athletes performed cutting maneuvers, marker-based motion capture collected kinetic and marker data and an 8-segment musculoskeletal model was constructed. Knee abduction moment waveforms were clustered as either a large early peak, or not a large early peak using a two-step process with Euclidean distances and the Ward-d2 cluster method. Mediolateral distance between foot and trunk was associated with the large early peak waveform with an odds ratio (95% confidence interval) of 3.4 (2.7–4.4). Knee flexion angle at initial contact and knee flexion excursion had odds ratios of 1.9 (1.6–2.4) and 1.6 (1.3–2.0). Knee abduction excursions had an odds ratio of 1.8 (1.1–2.4) and 1.8 (1.4–2.4), respectively. Heel strike landings and anteroposterior distance between foot and trunk were not associated with the large early peak waveform with odds ratios of 1.2 (0.9–1.7) and 1.1 (0.8–1.3), respectively. The knee abduction moment waveform is associated with several kinematic variables observed during ACL injury. The results support intervention programs that can modify these kinematics and thus reduce early stance phase knee abduction moments.

KEYWORDS

anterior cruciate ligament, biomechanics, cluster analysis, injury prevention, knee

1 | INTRODUCTION

Anterior cruciate ligament (ACL) injuries are serious injuries that result in a large societal burden due to the high treatment cost and disease progression.[1] Consequently, efforts to prevent ACL injuries have led to the development of effective intervention programs.[2] These programs have not been widely adopted at least partly due to the time they take,[3] and research has yet to identify a plausible biomechanical effect of these programs, that is, linked to the ACL injury mechanism.[4,5]

Cadaveric impact simulators have reproduced the clinical presentation of ACL rupture by using a combination of an external knee abduction moment (KAM), an anterior tibial shear, and an internal tibial rotation moment together with an axial impact.[6] Consistent with being an impact injury, both cadaveric studies[7] and video analyses of injuries in vivo[8] have demonstrated that the ACL injury occurs within 100 ms after initial contact with the ground. While cadaveric studies often analyze the KAM and internal tibial rotation moments separately, they are interdependent.[9] The KAM is likely a key component of the injury,[6] as it leads to greater compression of the femur on the lateral tibial plateau and subsequently to an internal rotation of the tibia.[7,10] Studies analyzing video recordings of ACL injuries in vivo have identified kinematics associated with the ACL rupture such as a heel strike landing[11] and a large base of support to the center of mass distance.[12] These kinematics may increase the likelihood of high impact forces that are subsequently transmitted to the ACL.

There is a methodological gap between studies on the ACL injury mechanism and prospective studies evaluating the risk of injury,[13] resulting in heterogeneous results. The KAM has been identified as a potential risk factor for ACL injury in a prospective study which reported a sensitivity of 78% and specificity of 73%.[14] However two studies with similar methods have failed to corroborate that finding.[15,16] Prospective biomechanical studies[14–16] have focused on peak values over the whole weight acceptance phase of a bilateral drop-jump, despite evidence indicating that the injury results from an impact during the early stance of a single leg motion.[17] The peak KAM during weight acceptance only moderately correlates with the KAM observed during the first 100 ms,[18] indicating that the prospective studies have not analyzed impact forces such as those that lead to injury.

One reason for this discrepancy is the technical difficulty in extracting biomechanical data from ground impact forces using traditional three-dimensional (3D) motion analysis. The ground impact is a high-frequency signal, but it also generates high-frequency artifacts from marker oscillations and movement of the skin relative to the bone.[19] To calculate joint moments, the segmental position is derived twice leading to an amplification of the high-frequency component of the signal.[20] With respect to filtering strategies, marker data requires a much lower cut-off frequency than force plate data,[21] but filtering them unevenly produces artificially large impact artifacts while filtering both signals equally removes the impact peak.[20] The only prospective study that found a link between knee KAM and ACL injury risk used an uneven filtering strategy[14] that produces artificially large impact artifacts, and was, therefore, more likely to identify the KAM peak in the early stance that is consistent with the timing of injury.[22]

An alternative to the magnitude of peak KAM is to categorize the different waveforms of KAM according to the presence or absence of a peak KAM using cluster analysis.[23] Using cluster analysis it's possible to identify trials that present with an early peak KAM with timing consistent with ACL injury.[22] Analyses using videos of actual ACL injuries have identified postures associated with the time and occurrence of ACL rupture. If the early peak KAM waveform identified with cluster analysis is associated with ACL injury, it might also be associated with kinematics observed during ACL injury, even in noninjury situations. The aim of this study was to assess if kinematics associated with ACL injury would also be associated with an early peak KAM waveform.

We hypothesized that the following positions at initial contact (IC) would be associated with an early peak knee KAM; (1a) a heel strike landing pose,[11] (1b) greater anteroposterior (AP) distance between the base of support and the trunk center of mass,[12] (1c) greater mediolateral (ML) distance between the base of support and the trunk center of mass,[12] (1d) smaller knee flexion angle.[11] We further hypothesized that the following kinematics during the first 15% of the stance phase would be associated with the early peak KAM; (2a) greater knee abduction excursion,[24] (2b) less knee flexion excursion,[17] (2c) greater knee extension excursion,[25] and (2d) greater trunk lateral flexion excursion.[24]

2 | METHODS

This is a cross-sectional laboratory study (level of evidence: III). Subjects were recruited from local handball and soccer clubs aged 9–12 (first phase) years, and followed up 5 years later at 14–18 (second phase) years of age. Of the 293 subjects originally recruited, 174 (59%) consented to the follow-up investigation. This study uses data from the second phase only. All participants, together with a guardian, signed informed consent. The study was approved by the Icelandic national bioethics committee, approval code VSNb2012020011/03.07.

The data collection process has been previously reported.[26] In short, participants wore shorts, and girls additionally wore athletic tops. A 5-min stationary bicycle warm-up preceded isometric strength measures of the hip abductors and external rotators. A total of 46 markers were placed on participants by the same researcher (HBS), a licensed physical therapist. A static measurement was captured to define the musculoskeletal model after which 12 markers were removed. Participants performed bilateral drop jumps and cutting maneuvers in randomized order with two familiarization attempts and at least five recorded trials. Cutting maneuvers were performed in a planned direction against a dummy opponent using a self-selected angle from a ready position without a running start. Participants then underwent a 5-min progressive skateboard exercise intervention before the drop-jumps and cutting maneuvers were repeated in reverse order. An optical motion capture system was used where retro-reflective markers were tracked using the QTM software (Qualisys AB; Gotherborg) and an 8 camera Oqus 300 system sampling at 400 Hz. Ground reaction force data were collected using an AMTI force plate (AMTI; Watertown) sampling at 2000 Hz. For this analysis, only the cutting maneuver task was used, and attempts before and after the skateboard intervention were pooled.

2.1 | Data analysis

Data were exported from the QTM software and imported to Visual3D (C-Motion; Germantown) where model construction and calculations were performed. An 8 segment skeletal model was constructed with joint centers estimated from marker locations.

where ankle joint centers were placed midway between malleolar markers,[27] knee joint center midway between epicondylar markers,[28] the hip joint centers were located 25% of the distance between trochanter markers,[29] and trunk motion was simplified as one segment connected to the pelvis by a joint located midway between the iliac crest markers. A static trial was used to define each segments' local coordinate system and inertial parameters were assigned using the Visual3D defaults.[30] Gap filling was performed using polynomial smoothing, automatically for gaps smaller than 30 frames and manually for gaps larger than 29 frames. Similar methods have been found reliable with intraclass correlation ranging from 0.74[31] to 0.93.[32]

Signal processing was done with the aim of retaining the waveform of the KAM during the early stance phase. Unfiltered markers were used to calculate kinematics using the 6-DOF method, and unfiltered force plate data and kinematics were used for kinetics using the inverse dynamics method and normalized by body weight. Joint moments are reported as external moments such that the KAM is the force acting to abduct the knee. Using unfiltered signals for the calculations preserves both the impact peak data and congruity between force data and segmental accelerations.[21] The resulting calculated signals were then low pass filtered using a single bidirectional pass Butterworth filter at 6 Hz. Using a low-frequency cut-off creates a smooth signal that can be used to cluster analyze the curve shape even though it does introduce an under-estimation of the force magnitudes.[20,33]

To classify KAM waveforms the initial 15% of the time series of the stance phase was transformed into the sign of lagged differences since we have previously demonstrated that early peaks can be identified within this percentage of stance.[23] The similarity between observations was calculated as the Euclidean distance and then clustered into discrete shapes followed by clustering based on magnitude using the Ward-D2[34,35] method, as previously described.[23] The resulting clusters were categorized as either small or large early peaks, or other (non-early peak) shapes. The clustering process maximizes the similarity within clusters while minimizing the similarity between clusters, and this ratio is expressed as the C-index and used to evaluate the result of the cluster analysis procedure. Better clustering results result in lower C-index values. A previous study from our lab indicates that no elbow is formed in this procedure, and therefore a C-index cut-off value of 0.05 is used to determine the number of clusters.

The joint angles, and segment center of mass positions were identified at the time of IC, defined as the time when the vertical ground reaction force crossed a 10 N threshold. The distance between the center of mass of the trunk and stance leg foot was calculated as the distances in the AP and ML directions and normalized by the participants' thigh length. The joint excursions were calculated as the difference between the joint angle at IC, and the peak value observed within 15% of the stance phase duration. To identify a heel strike landing, the angle between the floor and the foot was calculated and negative values in the sagittal plane were taken to be a heel strike landing.

TABLE 1 Subject characteristics at the follow-up data collection and the number of valid trials analyzed (attempts)

Sex	Drop out	Height (mean, cm)	Weight (mean, kg)	Attempts (*n*)	Athletes (*n*)
Male	Yes	181	75.3	414	19
	No	177	71.0	871	38
Female	Yes	164	62.8	1108	52
	No	168	62.0	1234	59

2.2 | Statistical analysis

All variables except the heel strike landing were continuous. For those, a receiver operating characteristic curve (ROC) was first calculated by dividing the range of the variable into 100 equally sized segments and calculating the sensitivity and specificity for each value. Youden's Index[36] was used to establish a cut-off value for hypothesis testing. Hypothesis testing was done using the Fishers' exact test and reporting the odds ratio of a trial being classified as a large early peak if the kinematic variable is observed, or the cut-off reached. Due to the exploratory approach involving multiple hypotheses, a Bonferroni adjustment was used. α was set at 0.05.

3 | RESULTS

A total of 174 participants completed data collection, of which 73 had discontinued sports participation at the time of initiation of this investigation. Six subjects had incomplete or erroneous follow-up data and were excluded. The remaining 168 participants provided a total of 3626 trials that were used for analysis. The average number of trials included per subject is 10.7 (range 5–19). Subject characteristics are summarized in Table 1.

3.1 | Cluster analysis

A heat map of the Euclidean distances between transformed waveforms is displayed in Figure 1. In the initial step, five clusters were formed (Figure 2), out of which two (#3 & #4) were classified as having an early peak KAM through visual assessment. In the second clustering step, two sub-clusters were formed from the early peak cluster and classified as small or large (Figure 3). C-indices for step one and two were <0.05 and 0.15, respectively (Figure 4).

3.2 | Risk factors for large early peaks

Descriptive statistics of the kinematic variables are presented in Table 2. A total of 341 trials (9.2% of the total) had a large early peak waveform. ROC curves for the continuous variables are presented in

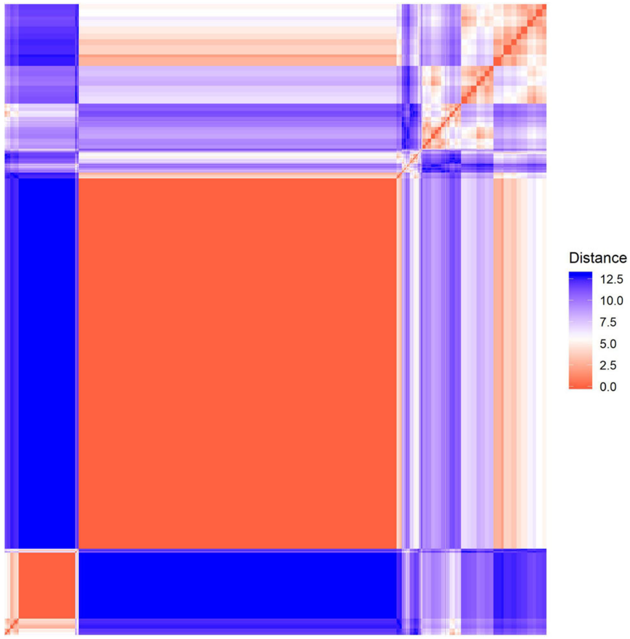

FIGURE 1 Heat map of Euclidean distances between direction reduced knee valgus moment time series. Both *x* and *y* axes are observations (a single cutting maneuver). Clusters present in the data emerge visually as red boxes (areas of low distance between observations) [Color figure can be viewed at wileyonlinelibrary.com]

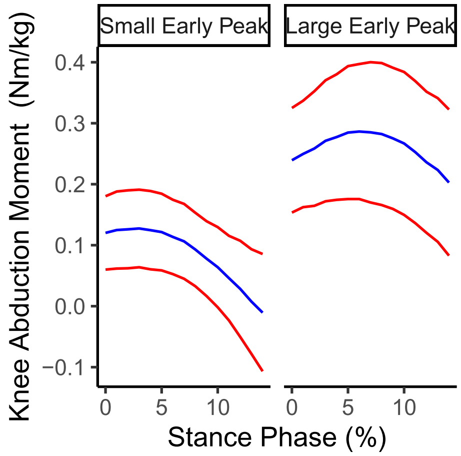

FIGURE 3 Clusters based on Euclidean distances of non-transformed time series of clusters classified as an early peak. The blue curves are the means and the red curves denote 1 standard deviation above and below the mean [Color figure can be viewed at wileyonlinelibrary.com]

Figures 5 (knee kinematics) and 6 (trunk related kinematics). A heel strike landing had a sensitivity of 0.18 and specificity of 0.85 ($p = 0.98$) for predicting a large early peak KAM. Five of the eight kinematic variables analyzed were associated with the large early peak KAM (Table 3), notably a knee flexion angle below 41° at IC had a sensitivity of 0.51 and specificity of 0.64 (Figure 5). Knee abduction excursions greater than 0.1° had the highest sensitivity at 0.8, and a specificity of 0.31 ($p < 0.0001$, Figure 5). The variables not associated

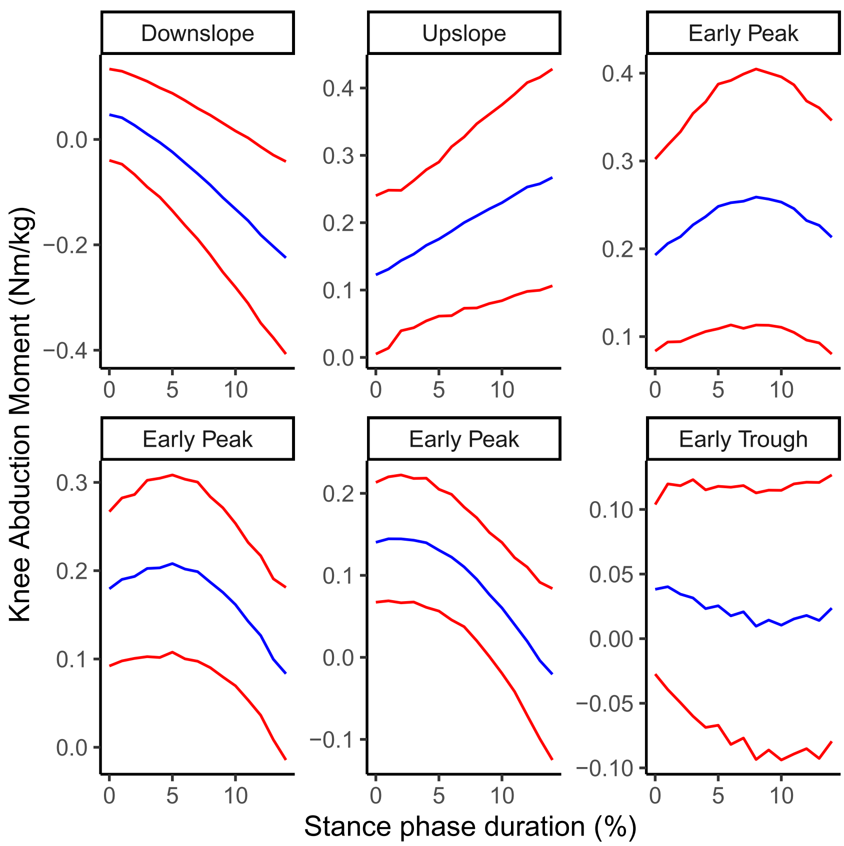

FIGURE 2 Six shapes from the clustering of transformed time series. Three of the clusters were classified as an early peak. Sign differences refer to the transformation of the time series where first the lagged difference is calculated and then keeping only the sign of the difference. The blue lines are the means, the red lines show 1 standard deviation above (higher line) and below (lower line) [Color figure can be viewed at wileyonlinelibrary.com]

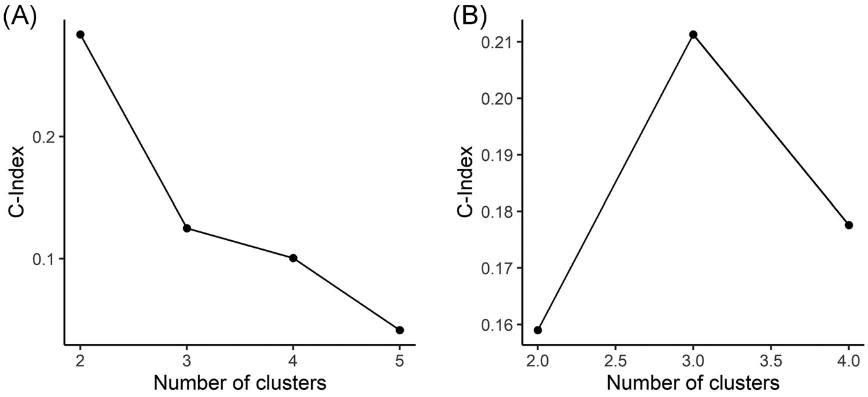

FIGURE 4 C-Index plots for the first (A) and second (B) cluster analysis steps. The C-Index is a ratio of how similar observations within a cluster are compared to how similar they are to other observations. A lower number indicates more clearly defined clusters

with the frequency of large early peak KAM ($p > 0.05$) were heel-strike landings, AP distance between stance leg and trunk center of mass (Figure 6), and knee extension excursion (Figure 5). Odds-ratios and their confidence intervals and P-values are presented in Table 4.

4 | DISCUSSION

A landing posture with a larger ML distance between foot and trunk center of mass (hypothesis 1c), and less knee flexion (hypothesis 1d) were associated with a greater frequency of large early peak knee KAM. Moreover, during the first 15% of the landing phase, movement into greater knee abduction (hypothesis 2a), knee flexion (hypothesis 2b), and trunk lateral flexion (hypothesis 2d) was associated with a greater frequency of large early peak KAM. Contrary to our hypotheses, a landing posture with a heel-strike (hypothesis 1a), greater AP distance between foot and trunk center of mass was not associated with large early peak KAM (hypothesis 1b), nor was movement into greater knee extension during the initial 15% of the stance phase (hypothesis 2c).

One potential risk factor for ACL injury is a stiff landing,[15] usually defined by high vertical ground reaction forces due to low knee flexion at initial contact and low flexion excursions with or without a heel strike landing. Our results demonstrate that variables relating to stiff landings have different relationships to KAM large early peaks which are not fully consistent with soft or stiff landings. Heel strike landings (hypothesis 1a) or knee extension excursions (hypothesis 2c) were not associated with a greater frequency of KAM early peaks, but controversially greater knee flexion excursion (hypothesis 2b) was, which potentially explains why a large intervention study emphasizing knee flexion excursions did not significantly reduce ACL injury frequency.[37]

Cadaver studies have demonstrated a mechanism by which the flexion angle at initial contact may affect ACL injury risk, because higher strains on the ACL have been reported with less knee flexion[38]—likely due to tibiofemoral geometry promoting a posterior femoral translation under compression.[39] Our results demonstrate a second mechanism through increasing the frequency of KAM impact loading, as lower flexion angles at IC were associated with a greater frequency of large early peak KAM (hypothesis 1d). However, knee

TABLE 2 Means, standard deviations (SD), and number of valid trials (*n*) for study variables

Variables	Mean	SD	*n*
COM lateromedial (% thigh length)	0.2	0.16	3602
COM anteroposterior (% thigh length)	1.0	0.15	3602
Knee flexion (IC) (°)	45	10.92	3627
Knee abduction excursion (°)	−1	1.26	3627
Trunk lateral flexion excursion (°)	4.34	2.92	3601
Knee flexion excursion (°)	3	4.10	3627
Knee extension excursion (°)	−2	2.50	3627
Thigh length (m)	0.41	0.03	3627

Abbreviations: COM, center of mass; IC, initial contact.

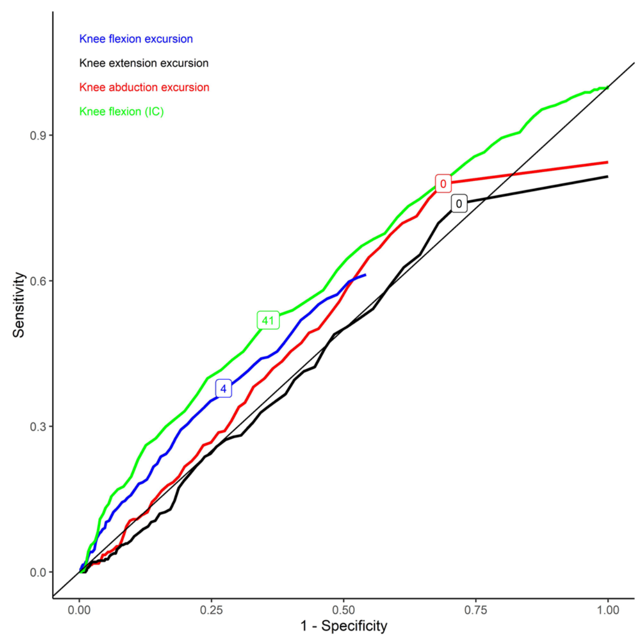

FIGURE 5 ROC of knee angles and excursions. Numeric labels on the line refers to the cut-off with the high Youden's Index. IC, initial contact; ROC, receiver operating characteristic curve [Color figure can be viewed at wileyonlinelibrary.com]

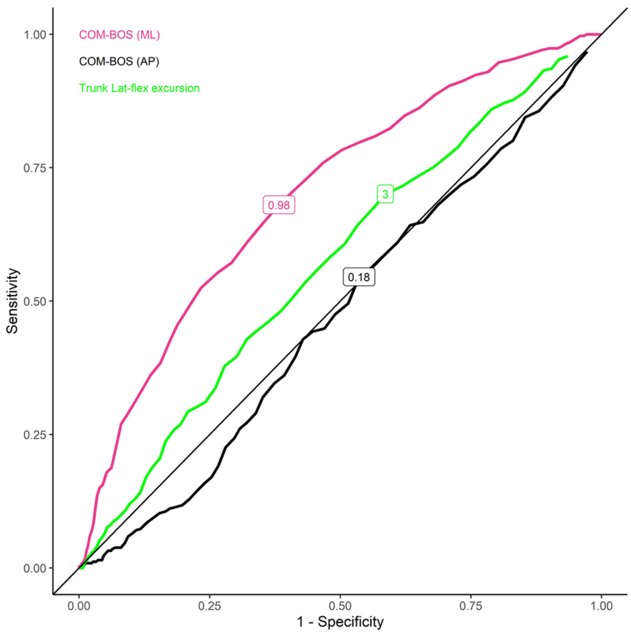

FIGURE 6 Receiver operating characteristic curve of trunk related variables. Numeric labels on the line refers to the cut-off value with the highest Youden's Index. Distances expressed as % of thigh length. BOS, base of support; COM, center of mass [Color figure can be viewed at wileyonlinelibrary.com]

extension excursions, indicating a concentric quadriceps contraction immediately after IC and a stiffer landing, were not associated with increased large early peak KAM frequency (hypothesis 2c). If KAM loading is an important component of the ACL injury mechanism,[10] interventions should emphasize greater knee flexion at initial contact, but not flexion excursions after initial contact.

A larger distance between the foot and trunk center of mass in the ML direction was associated with greater frequency of large early peak KAM (hypothesis 1c), while AP direction distance was not (hypothesis 1b). Sheehan et al.[12] found that during ACL injury, athletes landed with a greater AP distance between the foot and trunk center of mass, however, the change of direction task in the current study is more of a ML movement and this is reflected in the findings of the present study. To minimize the early stance KAM, the athlete must push actively into the ground away from the body center of mass. When a relatively greater downwards force is acting, consistent with less push laterally into the ground, an early peak KAM is more likely. As the distance between the foot and trunk center of mass increases, it may be increasingly demanding to push laterally into the ground and thus the chance of an early peak KAM may increase. As opposed to a landing or rapid deceleration, an ACL injury during side-stepping may be a predominantly valgus collapse injury mechanism and unaffected by the AP distance between foot and trunk center of mass.

A valgus collapse mechanism has been proposed to explain ACL injuries.[40] The valgus collapse movement pattern is the combination of ankle pronation, knee abduction, hip adduction and internal rotation, and lateral trunk flexion towards the stance leg. The resulting KAM will stretch the ACL and compress the lateral compartment of the tibiofemoral joint, leading to an internal tibial rotation due to the lateral tibial plateau being more posteriorly rotated compared with the medial tibial plateau.[9] We found that knee abduction excursion and trunk lateral flexion excursion were associated with a greater frequency of large early peak KAM (hypotheses 2a and 2d). Rather than increasing the landing impact, the knee abduction and lateral trunk flexion excursions can increase the moment arm of the landing force and may therefore result in a larger early peak KAM.

4.1 | Limitations

This is the second study to use this cluster analysis method to classify joint moment waveforms. While it has been proposed that research in the area of biomechanics can benefit from data mining techniques (systematically searching data sets for previously

TABLE 3 Odds ratios and *p* values for the relationship between variables and the early peak KAM waveform

	Odds ratio	95% Confidence Interval		*p* value	Adjusted *p*
		Lower	Upper		
Heel strike landing	1.2	0.9	1.67	0.12	0.98
COM ant-post	1.05	0.8	1.3	0.6	>0.99
COM med-lat	3.4	2.7	4.4	0.00	<0.01
Knee extension excursion	1.2	1.0	1.6	0.1	0.8
Knee flexion excursion	1.6	1.3	2.0	<0.01	<0.01
Knee flexion at IC	1.9	1.6	2.4	<0.01	<0.01
Knee abduction excursion	1.8	1.4	2.4	<0.01	<0.01
Trunk lateral flexion excursion	1.7	1.3	2.1	<0.01	<0.01

Note: Adjusted *p* value was calculated using a Bonferroni correction.

Abbreviations: ant-post, anterior to posterior; COM, center of mass; IC, initial contact with the ground; med-lat, medial to lateral.

unknown relationships) such as cluster analysis,[41] it is a technique that has not been validated against a hard end-point such as an ACL injury. The present study demonstrates that cluster analysis of the KAM results in categories that have an association with kinematics observed during ACL injury and is congruent with the proposed mechanism of ACL injury. This is consistent with other works where cluster analysis has revealed clinically interesting patterns.[42,43] However, prospective studies that examine the relationship between the early peak waveform and subsequent injury are needed.

The use of digital filters on biomechanical data is a source of continued debate[44,45] and may have affected the shape of the curve. Rather than focus on the accuracy of inverse dynamics joint moment magnitudes, we propose that data should be processed in a way that preserves the usefulness of the data. The usefulness of any biomechanical variable of interest, and the experimental procedures that generated the variable, ultimately needs to be validated against meaningful endpoints such as an ACL injury.

Visual-3D default settings were used for segment inertial properties. The magnitude of joint moments are dependent on inertial properties, but it is unknown to what extent, if any, the KAM waveform is altered.

Kinematics were calculated using estimated joint center locations based on marker locations. While knee flexion angles are reliable to within 5°,[46] validity studies have demonstrated systematic errors in the knee abduction and knee rotations that depend on the knee flexion angle.[47] The cross-talk between axes of rotation is one source of error exacerbated by inaccuracies in marker placements but may be corrected with a PCA.[48] The PCA correction has also been suggested to decrease the effects of potential marker misplacements.[49] To assess the effects of this potential source of error, a sensitivity analysis was conducted with artificially induced errors in knee marker placement (Appendix A). The sensitivity analysis demonstrated that cluster assignment was the same in 80% of attempts despite marker errors. The results of Fisher's exact hypothesis tests were robust to this error, except for the relationship between knee flexion angles and the large early peak. The effects of this source of error in the original analysis are minimized by the use of a single physical therapist with over 5 years of clinical experience to place all markers.

A decision was made to use the large early peak as the reference group for the calculation of sensitivity and specificity. The large early peak pattern emerged from the cluster analysis method, and no clear point of differentiation exists between the early peak categories, which is reflected in the higher C-Index. The large early peak may not be the only shape of importance in light of the multiplanar nature of an ACL rupture, and a small peak observed during laboratory testing may translate to more frequent and larger KAM early peaks during sports. The choice of using the large early peaks was to create the best conditions to test for the relationship between the kinematic factors and the KAM waveform. To validate a certain magnitude or shape requires the use of hard end-points such as an ACL injury.

5 | CONCLUSIONS AND CLINICAL RELEVANCE

The main findings of this study demonstrate that kinematic factors that have been observed during ACL injury are associated with an early peak KAM waveform in a mixed cohort of teenagers performing a change of direction task—a movement where a large portion of ACL injuries occur.[50]

These findings provide convergent validity to cluster analysis of the KAM waveform in the early stance phase and support the use of interventions that train athletes to change direction on the balls of the feet, with the foot close to the trunk, with a flexed knee, and to minimize lateral trunk flexion excursions and knee flexion excursions.

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AUTHOR CONTRIBUTIONS

Collected data, performed data analysis, and drafted the manuscript: Haraldur B. Sigurðsson. *Designed the study and critically revised the manuscript*: Kristín Briem. *Critically revised the manuscript*: Jón Karlsson and Lynn Snyder-Mackler.

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APPENDIX A: SENSITIVITY ANALYSIS

Methods

The sensitivity analysis was carried out to illustrate the role of random variation in marker placement on the results of our analysis. All methods are identical to those of the main manuscript, with the only difference that a random noise of up to 0.5 cm was added to the location of the knee markers used to define the proximal shank location (medial and lateral femoral condyles) of the right leg. The left leg was left unchanged.

TABLE A1 Number of trials receiving each cluster classification in the original and the sensitivity analysis

Original cluster	Random noise cluster	Leg	*N*
Large	Large	Left	194
Others	Others	Left	1299
Small	Small	Left	223
Others	Large	Left	50
Small	Large	Left	58
Others	Small	Left	13
Small	Others	Left	8
Others	Others	Right	1350
Large	Large	Right	72
Small	Small	Right	39
Large	Others	Right	67
Others	Large	Right	46
Small	Others	Right	135
Others	Small	Right	80
Small	Large	Right	40
Large	Small	Right	8

Note: Large and small refer to a large and small early peak shape, respectively. Others refers to all other shapes. Gray shaded areas emphasize the matching classifications, the non-shaded areas show where the classifications differ. The results of Fisher's exact hypothesis tests between the original and second analysis are presented in Table A2. The biggest difference was related to knee flexion angles. The knee extension excursion odds ratio could not be calculated as the highest Youden's index was at specificity = 1. The knee flexion excursion was not associated with a greater odds ratio of having a large early peak in the original analysis but was in the sensitivity analysis.

Results

A comparison between the original and the random noise cluster analyses is presented in Table A1. On the left side, 93% of attempts received the same classification in both analyses. On the right side, 79% of attempts received the same classification in both analyses.

Tables A1–A2.

TABLE A2 Comparison between the original and error induced (sensitivity analysis) results

Sensitivity analysis						Original analysis				
Odds ratio (95% CI)			*p* value			Odds ratio (95% CI)			*p* value	
OR	Lower	Upper	Regular	Adj		OR	Lower	Upper	Regular	Adj
1.15	0.88	1.49	0.29	1	Heel strike landing	1.26	0.94	1.68	0.12	0.98
3.27	2.66	4.03	<0.001	<0.001	COM Medio-lateral	3.47	2.74	4.42	<0.001	<0.001
Inf	0.37	Inf	0.12	0.87	COM ant-post	1.06	0.84	1.32	0.63	1
1.86	1.52	2.27	<0.001	<0.001	Knee flexion excursion	0.81	0.62	1.04	0.10	0.84
2.16	1.76	2.64	<0.001	<0.001	Knee flexion	1.94	1.55	2.43	<0.001	<0.001
1.61	1.30	2.01	<0.001	<0.001	Knee abduction excursion	1.81	1.38	2.40	<0.001	<0.001
1.37	1.12	1.67	0.002	0.02	Trunk lateral flexion excursion	1.68	1.32	2.15	<0.001	<0.001

Note: The adjusted *p* value uses the Bonferroni correction. The gray shading denotes the row where the odds ratio from the sensitivity analysis is outside the 95% CI of the original analysis.

Abbreviations: ant-post, anterior to posterior direction; COM, center of mass; CI, confidence interval.