Hip and Ankle Kinematics in Noncontact Anterior Cruciate Ligament Injury Situations

Video Analysis Using Model-Based Image Matching

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Background: Detailed kinematic descriptions of real anterior cruciate ligament (ACL) injury situations are limited to the knee only.

Purpose: To describe hip and ankle kinematics as well as foot position relative to the center of mass (COM) in ACL injury situations through use of a model-based image-matching (MBIM) technique. The distance between the projection of the COM on the ground and the base of support (BOS) (COM_BOS) normalized to the femur length was also evaluated.

Study Design: Descriptive laboratory study.

Methods: Ten ACL injury video sequences from women's handball and basketball were analyzed. Hip and ankle joint kinematic values were obtained by use of MBIM.

Results: The mean hip flexion angle was 51° (95% CI, 41° to 63°) at initial contact and remained constant over the next 40 milliseconds. The hip was internally rotated 29° (95% CI, 18° to 39°) at initial contact and remained unchanged for the next 40 milliseconds. All of the injured patients landed with a heel strike with a mean dorsiflexion angle of 2° (95% CI, –9° to 14°), before reaching a flatfooted position 20 milliseconds later. The foot position was anterior and lateral to the COM in all cases. However, none of the results showed larger COM_BOS than 1.2, which has been suggested as a criterion for ACL injury risk.

Conclusions: Hip kinematic values were consistent among the 10 ACL injury situations analyzed; the hip joint remained unchanged in a flexed and internally rotated position in the phase leading up to injury, suggesting that limited energy absorption took place at the hip. In all cases, the foot contacted the ground with the heel strike. However, relatively small COM_BOS distances were found, indicating that the anterior and lateral foot placement in ACL injury situations was not different from what can be expected in noninjury game situations.

Keywords: anterior cruciate ligament (ACL); injury mechanism; video analysis; hip kinematics, ankle kinematics

Knowledge about injury mechanisms is critical to develop more effective injury prevention measures. Although the past decade has provided new insights into the detailed mechanisms of noncontact anterior cruciate ligament (ACL) injury, important knowledge gaps still exist. Through the development of a novel model-based image-matching (MBIM) technique, it has been possible to reconstruct 3-dimensional (3D) motion and extract detailed knee joint kinematics from video recordings of actual injury situations.[15] Analyses of ACL injury situations in handball and basketball[12] as well as soccer[11] and alpine skiing[3] reveal that sudden valgus development coupled with internal rotation and anterior translation of the tibia occurs during the first 40 milliseconds after initial ground contact, coinciding with the peak vertical ground-reaction force. These findings align well with key studies that used other, more indirect research approaches to investigate ACL injury mechanisms[10,24,32,34] and hence lend support to the focus on avoiding valgus motion in injury prevention training.[27,28]

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However, since the lower extremities act as a kinetic chain during dynamic tasks, control of the hip and ankle joint will interact with knee motion. Researchers have tried to investigate the potential relationships between hip and/or ankle biomechanics and ACL injury risk by using motion analysis studies,[5,30] cadaver studies,[9] and video analyses.[4,17,36] However, the validity of such approaches (ie, using a simple 2-dimensional (2D) analysis, or not studying actual injury situations) can be questioned.[14] A more valid analysis would entail use of the 3D MBIM technique with actual injury videos as input.

In addition, excessive anterior foot position relative to the projection of the center of mass (COM) has been suggested to be associated with higher risk of ACL injuries[31]; however, the previous study was performed with a 2D approach, which is likely to be less accurate compared with the 3D MBIM technique.

The objective of this study was to use the MBIM technique to describe hip and ankle kinematics in actual ACL injury situations. We also analyzed foot position relative to the COM to examine how foot position could affect ACL injury situations.

METHODS

Video Material

Ten ACL injury situations from women's handball (n = 7) and basketball (n = 3), recorded with at least 2 cameras during television broadcasts, were analyzed; all of them occurred during game situations. The video recordings of handball were supplied by the Norwegian Broadcasting Corporation in BetaSP PAL format, and the videos of basketball were from the National Basketball Association in DigiBeta NTSC format. The quality of all the video recordings was generally very good, although fast-moving body parts could be somewhat blurry. The injured knee was partly occluded in 1 of the camera views in 2 cases, whereas the hip and ankle on the injured side were partly occluded in 1 of the camera views in 2 and 3 cases, respectively. In such cases, a spline interpolation technique was applied to the affected camera view, and joint kinematic values were estimated based on the frames before and after partial occlusion.

Video Editing

The video recordings were transformed from their original format into uncompressed AVI sequences before further processing to avoid loss of quality. The sequences were converted to uncompressed TIFF files by use of Adobe Premiere Pro (version 1.5; Adobe Systems Inc) and were deinterlaced to achieve an effective frame rate of 50 Hz (team handball videos) or 60 Hz (basketball videos) by means of Adobe Photoshop (version CS; Adobe Systems Inc). Lens distortions were corrected by use of Andromeda LensDoc filter (version 1.1; Andromeda Software Inc). To synchronize the camera views from the same injury sequence, manual synchronization was performed by use of key events in each camera view (eg, foot strike and ball catching).

Model-Based Image Matching

To reconstruct the 3D kinematics of the injured players, we used an MBIM technique.[15,18] The matchings were performed with the commercially available program Poser 4 and the Poser Pro Pack (Curious Labs Inc). A model of the surroundings was built and manually matched to the background for each frame in every camera view, via a key frame and spline interpolation technique, by adjustment of the camera calibration parameters (position, orientation, and focal length). The surroundings were modeled by use of points, straight lines, and curved lines (see Figure 1 for an example of how key lines and other fixed objects on the handball court were matched). We used a skeleton model from Zygote Media Group Inc for the player matching. This model consisted of 21 rigid segments with a hierarchical structure, using the pelvis as the parent segment. Pelvic motion was described by 3 rotational and 3 translational degrees of freedom. The motions of the remaining segments were then described with 3 rotational degrees of freedom relative to their parent (eg, the shank relative to the thigh). In the matchings, we allowed for 57 degrees of freedom. For the tibia, we distributed the rotation evenly between the knee and ankle joint, using foot orientation as guidance. The matchings were performed by 1 experienced examiner, and to minimize bias resulting from single-operator judgment, 3 experts gave their opinion on the goodness of the fit until we reached a consensus. Validation studies have shown that root mean square differences for hip flexion, abduction, and rotation with 2 or 3 cameras were less than 6°, 14°, and 15°, respectively,[15] and for ankle were less than 3° in all motions.[26] The matching procedure has been described in detail in previous studies.[6,11,12,15,18,25,26] An example of a matched video is shown in Figure 1.

Anthropometric measurements were obtained from players for cases 1, 2, and 3, where body segment parameters were calculated by use of a modified version[15] of Yeadon's inertia model.[39] The skeleton model segment dimensions were set based on these measurements. For cases 6, 7, and 8, only player height and body mass were available, and no anthropometric measurements were available for cases 4, 5, 9, and 10. In these cases, the segment dimensions were iteratively adjusted during the matching process until a fixed set of scaling parameters was determined.

We used Woltring's Generalized Cross Validation Spline package[37] with a 7-Hz cutoff to obtain velocity and acceleration estimates for the COM translation. The hip and ankle joint angles were reported according to the recommendations of the International Society of Biomechanics.[38] Knee kinematic values as well as ground-reaction forces from the 10 cases were reported in the previous study.[12] Initial contact was defined as the first frame in which the foot contacted the ground before the injury.

The distance between the vertical projection of the COM on the ground and vertical projection of the center of foot segment automatically defined in the Poser program (base of support, BOS) (COM_BOS), normalized to the femur length, was also calculated to examine how foot positioning may affect ACL injury situations. We defined the COM_BOSx as the component along the COM velocity

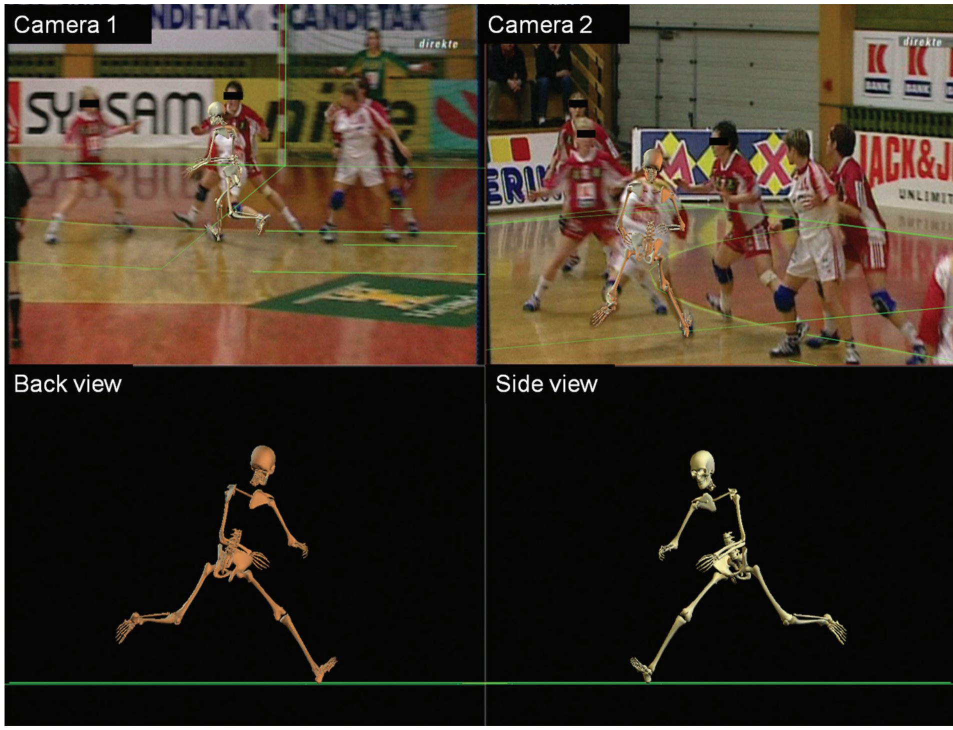

Figure 1. An example of a video matched in Poser. Case 4: two-camera team handball injury situation at initial contact. The 2 top panels show the customized skeleton model and the handball court model superimposed on and matched with the background video image from cameras 1 and 2. The bottom 2 panels show the skeleton model from back (left panel) and side (right panel) views created in Poser.

vector direction (forward direction was defined as positive). We defined COM_BOSy as the line perpendicular to COM_BOSx in the horizontal plane so that the COM_BOSy would be positive if the foot was located lateral for the COM. The COM_BOS was then calculated for each axis (COM_BOSx and COM_BOSy) as well as the sum of the 2 components ($\text{COM\_BOSsum} = \sqrt{\text{COM\_BOSx}^2 + \text{COM\_BOSy}^2}$), normalized by the femur length.[31]

Statistical Analysis

We used paired t tests to compare hip and ankle joint angle changes between different time points—initial contact and 40 milliseconds after initial contact (and 20 ms after initial contact for ankle flexion only)—based on the previous study documenting the timing of ACL rupture.[12] A 2-sided P value less than .05 was considered significant. The results are shown as the mean with 95% CI, as noted.

RESULTS

Player Characteristics

The characteristics of the 10 players are shown in Table 1. All the players were handling the ball in the injury situation; 7 were in possession of the ball at the time of injury, 2 had shot, and 1 had passed the ball. In 6 cases, player-to-player contact with an opponent occurred at the time of injury; all of these contacts entailed the torso being pushed or held. No direct contact to the knee occurred. The injury situations could be classified into 2 groups: 7 players were injured during cutting and 3 were injured during 1-legged landings.

Hip and Ankle Kinematics

As shown in Table 2 and Figure 2, the hip kinematic values for the players were consistent. The hip had a mean flexion angle of 51° at initial contact, and hip flexion stayed constant over the next 40 milliseconds. The hip was internally rotated 29° at initial contact, and hip rotation also remained unchanged for the next 40 milliseconds. The hip abduction angle was 21° at initial contact but had decreased by 6° (P = .002) 40 milliseconds later.

The ankle kinematic values for all players were also quite consistent (Table 2, Figure 3). All players landed with a heel strike, with a mean dorsiflexion angle of 2°. All players reached a flatfooted position relative to the floor 20 milliseconds later, with the ankle plantarflexion angle increasing by 12°, although not significantly (P = .096). During the next 20 milliseconds, the ankle was abruptly dorsiflexed again by 12° ($P < .001$), while the foot remained flat on the floor. The ankle supination angle increased from 7° at initial contact to 19° (P = .005) 40 milliseconds later. The ankle was externally rotated 5° at initial contact but

TABLE 1
Player Characteristics

Case No.	Maneuver	Sport	Height, cm	Femur Length, cm[a]	Injured Leg	Ball Handling	Contact[b]
1	Cutting	Handball	173	41	Right	In possession	No
2	Cutting	Handball	176	45	Right	In possession	No
3	Cutting	Handball	166	41	Left	In possession	Yes
4	Cutting	Handball	172[b]	43	Right	In possession	Yes
5	Cutting	Handball	177[b]	43	Left	In possession	Yes
6	Cutting	Basketball	168	41	Right	Had passed	No
7	Cutting	Basketball	175	43	Left	In possession	Yes
8	One-legged landing	Basketball	193	48	Left	In possession	Yes
9	One-legged landing	Handball	170[b]	41	Left	Had shot	No
10	One-legged landing	Handball	178[b]	43	Left	Had shot	Yes

[a]Estimate by Poser.
[b]Contact by other players (being hit, pushed, or held) to the body other than the lower extremity.

TABLE 2
Hip and Ankle Joint Kinematics at Initial Contact and at 20 and 40 Milliseconds After Initial Contact[a]

	Hip						Ankle						
	Flexion		Abduction		IR		Dorsiflexion			Supination		IR	
Case No.	IC	40 ms	IC	40 ms	IC	40 ms	IC	20 ms	40 ms	IC	40 ms	IC	40 ms
1	19	23	26	18	–16	11	39	4	20	4	14	0	3
2	44	50	14	14	39	37	–1	10	20	25	34	–12	1
3	39	47	11	0	28	34	–13	–22	–5	3	28	–1	4
4	65	61	29	21	39	34	19	–11	5	8	14	–11	–2
5	56	42	35	34	30	34	11	–22	–13	1	30	–10	–1
6	86	92	31	28	35	30	1	–20	–8	0	14	–7	10
7	58	60	35	21	43	37	–1	–17	–14	13	12	–5	12
8	42	44	24	21	29	22	–28	–8	3	15	24	–9	–3
9	59	55	13	9	24	34	9	–14	1	0	20	–4	7
10	49	60	–5	–14	35	38	–11	4	10	–2	–4	6	–8
Average	51	52	21	15	29	31	2	–10	2	7	19	–5	2
(95% CI)	(41 to 63)	(42 to 64)	(13 to 29)	(7 to 24)	(18 to 39)	(26 to 36)	(−9 to 14)	(−2 to −16)	(−6 to 9)	(1 to 12)	(12 to 25)	(−9 to −2)	(−2 to 6)
Difference	1.7		−6.1		2.5		−12.1		11.5	11.9		7.6	
(95% CI)	(−2.8 to 6.2)		(−8.9 to −3.3)		(−3.9 to 8.9)		(−24.8 to 0.6)		(8.6 to 14.4)	(5.5 to 18.3)		(2.1 to 13.1)	
P value	.480		.002		.465		.096		<.001	.005		.025	

[a]Kinematic values expressed as degrees. IC, initial ground contact; IR, internal rotation.

had rotated internally by 8° (P = .025) 40 milliseconds later. A representative case is shown in Figure 4, focusing on hip and ankle kinematics.

COM_BOS Evaluation

The COM_BOS, normalized to femur length, is shown for each player in Table 3. All players showed a positive value both in COM_BOSx and COM_BOSy: That is, COM was posterior and medial to the foot. However, the largest COM_BOSsum was not more than 1.00 (case 1).

DISCUSSION

This is the first study to quantify hip and ankle joint motions in real ACL situations by use of a sophisticated, computerized 3D analysis technique; previous studies were based on simple visual analyses alone.[4] Our analysis showed that hip kinematic values were consistent; hip flexion and rotation remained unchanged when the hip was internally rotated, with slight adduction motion, during the first 40 milliseconds after initial contact, the period when the ACL was likely to have ruptured.[12] The ankle kinematic values were also consistent; the ankle showed slight dorsiflexion at initial contact, plantarflexion over the next 20 milliseconds, and then dorsiflexion until 40 milliseconds after initial contact. The initial ground contact was with a heel strike for all 10 athletes; the foot reached a flatfooted position within 20 milliseconds and remained flat on the floor until 40 milliseconds after initial contact. COM was posterior and medial to the foot in all cases. However, none of the cases showed larger COM_BOSsum than 1.2, when normalized to femur length, which was proposed as a high-risk criterion by Sheehan et al.[31]

The results from the current study support the theory that restricted hip flexion during landing may contribute to ACL injury. The static hip position seen in ACL injury

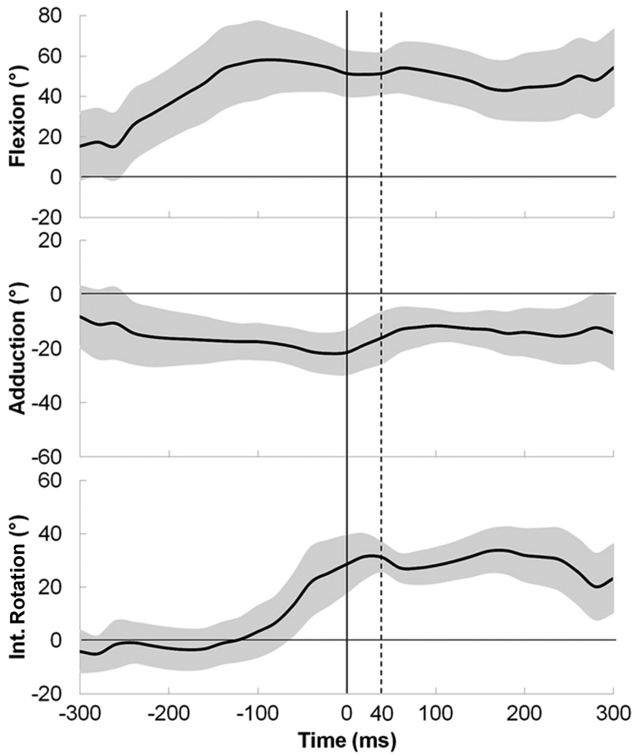

Figure 2. Time sequences of the mean hip angles of the 10 cases (black dotted line) with 95% CI (gray area). Time 0 indicates initial contact, and the dotted vertical line indicates the time point 40 milliseconds after initial contact.

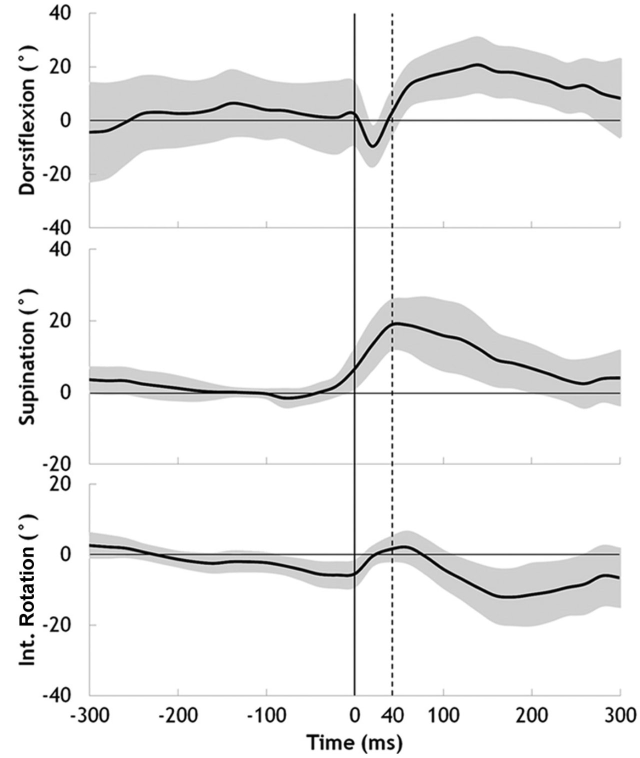

Figure 3. Time sequences of the mean ankle angles of the 10 cases (black dotted line) with 95% CI (gray area). Time 0 indicates initial contact, and the dotted vertical line indicates the time point 40 milliseconds after initial contact.

situations is strikingly different from what has been observed in noninjury situations of cutting[29,33] and landing[5,20] maneuvers, where the hip displayed a smooth transition into flexion after initial contact. Hashemi et al[9] suggested, based on a cadaver study, that restricted flexion of the hip at 20° combined with low quadriceps and hamstrings force levels in simulated single-legged landings could induce anterior tibial translation and a subsequent ACL injury. On the basis of this finding, the investigators proposed a mechanism called the "hip extension, knee flexion paradox," whereby a mismatch between hip and knee activation, and thus joint flexion, in landing is the cause of ACL injury.[8,23] It seems that such movement patterns are more likely to exist in females. Decker et al[5] reported that energy absorption at the hip joint was lower and, moreover, that the hip flexion angle at initial contact was lower in females than in males during a drop landing. Schmitz et al[30] reported that in a single-legged landing, energy absorption at the hip and the total hip flexion displacement were lower in females, even though the peak vertical ground-reaction force was larger when compared with males, implicating a stiffer landing in females. Landry et al[19] reported that female athletes performed an unanticipated side-cut maneuver with less hip flexion than male athletes. The current findings are supported by other observations from actual injury situations. In a previous study, based on visual assessments of injury videos, it was suggested that ACL-injured athletes had relatively constant hip flexion and abduction during the first 100 milliseconds after initial contact, whereas uninjured players flexed the hip by 15° in the same time period.[4]

Our data reveal that a large internal rotation of the hip was present, which indicates that internal rotation loads may have contributed to the injury. Previous studies have shown that limited hip internal rotation can result in greater load transfer to the knee, thereby increasing ACL strain[1] and ACL injury risk.[2,21,35] Correspondingly, it has been suggested that ACL-injured patients may have limited internal rotation range of motion,[7] although this is yet to be confirmed in a prospective study.[11,12] Finally, in our primary analysis of knee kinematics,[12] we observed internal knee rotation that corresponded with the internal hip and ankle rotation reported in the current study. A high degree of internal rotation in the hip and ankle suggests that all joints in the lower extremity, including the knee, experienced internal rotation loads. We did not observe any sliding or rotations between the shoe and the floor in any of the situations, suggesting that shoe-surface friction may have been high. Interestingly, previous studies have also reported a coupling between high knee valgus moments and hip internal rotation during a cutting motion, suggesting that both frontal plane and transverse plane loads may contribute to strain the ACL in sporting activities.[13,22]

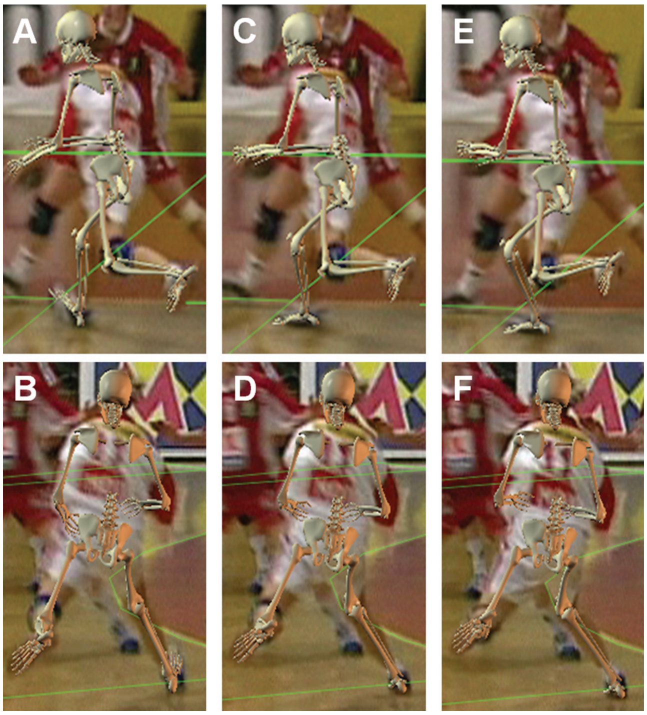

Figure 4. (A and B) Case 4 at initial contact, (C and D) 20 milliseconds later, and (E and F) 40 milliseconds later after initial contact. Hip kinematic values were constant at relatively flexed and largely internally rotated positions, with the abduction angle slightly toward adduction during the 40 milliseconds after initial contact. The foot position at initial contact was the hindfoot and reached a flatfooted position 20 milliseconds later. The ankle was dorsiflexed at initial contact, plantarflexed at 20 milliseconds, and dorsiflexed at 40 milliseconds again as the sole of the foot was fixed to the ground.

The ankle flexion kinematics observed in the current study agree well with previous video analyses that used simple visual inspection. Boden et al[4] reported that ACL-injured athletes landed on their heel or flatfooted to a larger degree than control players. However, since the movements that are performed will largely determine whether a toe or heel strike is natural, these must be matched for such a comparison to be meaningful. In the study by Boden et al,[4] information about such matching was not available; thus, the conclusions must be interpreted with care. In contrast, Waldén et al,[36] in their video analysis of ACL injuries among male professional football players, reported that the majority of players (8/11) landed with a heel strike or flatfooted in the pressing action, whereas only 1 player landed on his forefoot. A motion analysis study of sidestep cutting documented that a toe landing was one of the most significant predictors of lower knee abduction moments.[13]

In the current study, COM was posterior and medial to the foot in all cases, represented by positive values for COM_BOSx and COM_BOSy. However, none of the players showed larger COM_BOS than 1.2 when normalized to femur length, which was proposed by Sheehan et al[31]

TABLE 3
COM_BOS Normalized to Femur Length in 10 Cases[a]

Case No.	Maneuver	COM_ BOSx	COM_ BOSy	COM_ BOSsum
1	Cutting	0.88	0.46	1.00
2	Cutting	0.47	0.67	0.82
3	Cutting	0.74	0.31	0.80
4	Cutting	0.78	0.42	0.89
5	Cutting	0.90	0.28	0.95
6	Cutting	0.72	0.69	0.99
7	Cutting	0.84	0.03	0.84
8	One-leg landing	0.50	0.01	0.50
9	One-leg landing	0.62	0.54	0.83
10	One-leg landing	0.27	0.09	0.28

[a]Data presented as relative ratios, normalized to femur length. COM_BOS, center of mass base of support; COM_BOSx, COM_BOS for x-axis; COM_BOSy, COM_BOS for y-axis; COM_ BOSsum; sum of COM_BOSx and COM_BOSy.

as the criterion for risk of ACL injuries. The 3D technique used in the current study will generally be more precise and result in larger distance than a 2D video analysis, because the analyses do not suffer from off-axis perspective errors. In addition, data from an unpublished study investigating hip and knee kinematics in noninjury situations using the MBIM technique showed that noninjury situations may have COM_BOS greater than 1.2 (S. Sasaki, personal communication, 2017). These data indicate that the COM_BOS distance may not be as important as suggested by Sheehan et al.[31]

Some limitations of the current study should be borne in mind when interpreting the results. First, there is a limit to how accurately joint kinematics can be estimated from standard television broadcasts. Although the method has been validated for knee and hip kinematics[15] as well as ankle kinematics,[6,25,26] it is worth noting that estimating hip joint kinematics is challenging, as it is difficult to assess pelvic orientation accurately.[15] In addition, the injured lower extremity was partly occluded in 1 of the camera views in some cases. In such cases, a spline interpolation technique was applied to the affected camera view, and joint kinematic values were estimated based on the frames before and after partial occlusion. However, the time periods of occlusion were generally short (typically <20 ms). Since the estimated kinematic values were also based on 1 or 2 other camera views, such partial occlusion did not have a great effect on the analysis.

Second, although the MBIM technique is a sophisticated method for quantifying 3D kinematics in real injury situations, it still involves some degree of subjective assessment. Although the positioning of the skeletal bones and joints can be verified by simultaneous matching in several camera views, the rotation of the bones such as the pelvis and femur can be difficult. Still, the MBIM technique has been shown to be superior to the simple visual inspection approach.[16] Furthermore, we consistently observed simultaneous internal rotation at the hip, knee, and ankle during the first 40 milliseconds after initial contact, with narrow CIs, providing confidence that the results may be accurate and that internal tibial rotation may contribute to ACL injury.

Third, although the current study focused on hip and ankle biomechanics in "noncontact" ACL injury situations, 6 of the cases involved indirect contact (contact to the body other than the lower extremity). However, other studies have reported that player movements before injury are perturbed not only by body contact but also by noncontact actions by opponents and teammates.[12,17,36] Hence, in both indirect contact and noncontact situations, the injury is likely caused, at least partly, by the player being out of balance or having inadequate neuromuscular control due to various forms of perturbations. Therefore, we decided to designate those 6 cases with indirect contact as "noncontact" ACL injury. In addition, subgroup analyses were performed to evaluate whether indirect contact affected hip and ankle kinematics during ACL injuries. The 10 cases were divided into 2 groups, an "indirect contact" group and a "noncontact" group, based on the information in Table 1. No differences in hip and ankle kinematics were found between the 2 groups (see Appendix Table A1, available in the online version of this article).

Another limitation is that we did not include controls; that is, players who performed cutting or landing maneuvers without injury. However, to ensure validity, a matched control must do the same task under the same game environment, which is difficult to arrange. In addition, data from the unpublished study investigating hip and knee kinematics in noninjury situations using the MBIM technique suggest that the motions we observed in the injury situations differ substantially from what can be observed in regular cutting or landing maneuvers (S. Sasaki, personal communication, 2017).

In conclusion, hip kinematic values were consistent among the 10 ACL injury situations analyzed; the hip joint remained unchanged in a flexed and internally rotated position in the phase leading up to injury, suggesting that limited energy absorption took place at the hip. In all cases, the foot contacted the ground with the heel strike. However, relatively small COM_BOS distances were found, indicating that the anterior and lateral foot placement in ACL injury situations was not different from what can be expected in noninjury game situations.

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