Koga, H., Nakamae, A., Shima, Y., Bahr, R., Krosshaug, T. (2017). Hip and Ankle kinematics in noncontact anterior cruciate ligament injury situations: video analysis using model-based image matching. *The American Journal of Sports Medicine*. doi: 10.1177/0363546517732750

Hip and Ankle Kinematics in Non-contact Anterior Cruciate Ligament Injury Situations – Video Analysis Using Model-based Image-matching

Running title: Hip and Ankle Kinematics in ACL injuries

Abstract

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 using 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: Case Series.

Methods: Ten ACL injury video sequences from women's handball and basketball were analyzed. Hip and ankle joint kinematics were obtained using MBIM.

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

Conclusions: Hip kinematics 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 non-injury game situations.

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

What is known about the subject:

Through the development of a novel model-based image-matching (MBIM) technique, detailed knee joint kinematics in actual anterior cruciate ligament (ACL) injury situations has been revealed. However, detailed kinematics in entire lower extremity has not been clarified.

What this study adds to existing knowledge:

Detailed hip and ankle kinematics from ACL injury situations were described. Hip kinematics was consistent; the hip joint remained unchanged in a flexed and internally rotated position in the phase leading up to injury, suggesting limited energy absorption of the hip. Foot contacted the ground with the heel strike. However, the anterior and lateral foot placement in ACL injury situations was not different from what can be expected in non-injury game situations.

Introduction

Knowledge about injury mechanisms is critical to develop more effective injury preventive measures. Although the last decade has provided new insights into the detailed mechanisms of non-contact 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 three-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 (ms) after initial ground contact (IC), coinciding with the peak vertical ground reaction force. These findings align well with key studies using 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]

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 motion analysis studies,[5, 30] cadaver studies,[9] and video analyses.[4, 17, 36] However, the validity of such approaches, i.e. not studying actual injury situations or using a simple two-dimensional approach, can be questioned.[14] Therefore, using the 3D MBIM technique using actual injury videos as input is required.

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 to the 3D MBIM technique.

The objective of this study was therefore to describe hip and ankle kinematics in actual ACL injury situations using the MBIM technique. 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 two cameras during TV broadcasts, were analyzed; all of them occurred during game situations. From handball the videotapes were supplied by the Norwegian Broadcasting Corporation in BetaSP PAL format and from basketball by the National Basketball Association in DigiBeta NTSC format. The quality of all the videotapes was generally very good, although fast-moving body parts could be somewhat blurry. The injured knee was partly occluded in one of the camera views in two cases, whereas the hip and ankle on the injured side were partly occluded in one of the camera views in two and three cases, respectively. In such cases, a spline interpolation technique was applied to the affected camera view, and joint kinematics was 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 using Adobe Premiere Pro (version 1.5; Adobe

Systems Inc., San Jose, California, USA) and were deinterlaced to achieve an effective frame rate of 50 Hz (team handball videos) or 60 Hz (basketball videos) using Adobe Photoshop (version CS; Adobe Systems Inc.). Lens distortions were corrected using Andromeda LensDoc filter (version 1.1; Andromeda Software Inc., Westlake Village, California, USA). To synchronize the camera views from the same injury sequence, a manual synchronization was performed using key events in each camera view, e.g. foot strike and ball catching.

Model-based image matching

To reconstruct the three-dimensional kinematics of the injured players, we utilized a MBIM technique.[15, 18] The matchings were performed using the commercially available program Poser® 4 and the Poser® Pro Pack (Curious Labs Inc., Santa Cruz, California, USA). A model of the surroundings was built and manually matched to the background for each frame in every camera view, using a key frame and spline interpolation technique, by adjusting the camera calibration parameters (position, orientation and focal length). The surroundings were modeled using points, straight lines and curved lines (see Fig. 1 for an example of how key lines and other fixed objects on the handball court were matched). We utilized a skeleton model from Zygote Media Group Inc. (Provo, Utah, USA) 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 three rotational and three translational degrees of freedom. The motions of the remaining segments were then described with three rotational degrees of freedom relative to their parent, e.g. 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 one, experienced examiner, and to minimize bias resulting from single-operator judgement, three experts gave their opinion on the goodness of the fit until we reached a consensus. The validation studies have shown that root mean square differences for hip flexion, abduction and rotation with two or three cameras were less than 6°, 14° and 15°, respectively,[15] and for ankle less than 3° in all motions.[26] The matching procedure has been described in detail in the 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 using 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 anthropometrical measurements were available for cases 4, 5, 9 and 10. In these cases, the segment dimensions were iteratively adjusted during the matching process until, finally, 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 kinematics as well as ground reaction forces from the 10 cases were reported in the previous study.[12] IC was defined as the first frame where the foot contacted the ground prior to 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 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 two components ($\mathrm{COM\_BOSsum} = \sqrt{\mathrm{COM\_BOSx}^2 + \mathrm{COM\_BOSy}^2}$), normalized by the femur length.[31]

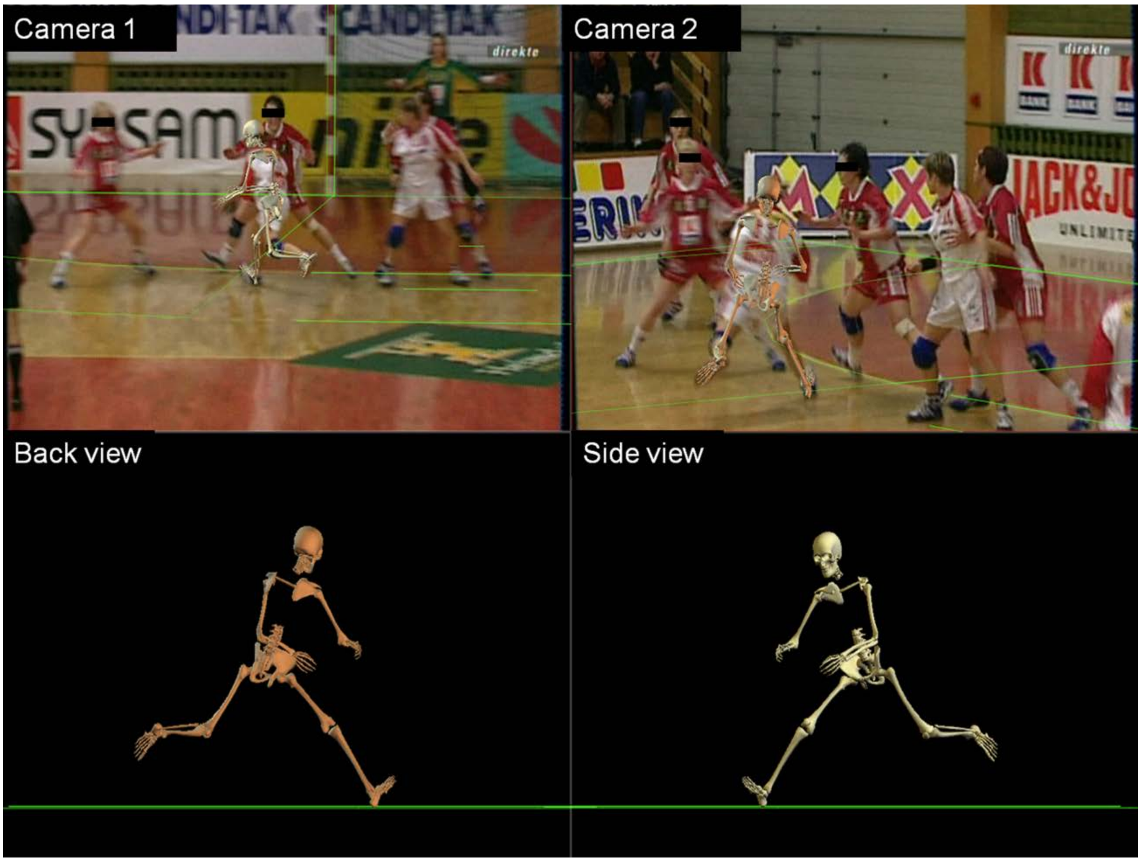

Figure 1. An example of a video matched in Poser. Case number 4, two-camera team handball injury situation at IC. The two top panels show the customized skeleton model and the handball court model superimposed on and matched with the background video image from camera 1 and 2. The bottom two panels show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

Statistical analysis

We used paired t-tests to compare hip and ankle joint angle changes between different time points, IC and 40 ms after IC (and 20 ms after IC for ankle flexion only), based on the previous study documenting the timing of ACL rupture.[12] A two-sided p-value of less than 0.05 was considered significant. The results are shown as the mean with 95% confidence intervals (CI) or range, as noted.

Results

Player characteristics

The characteristics of each of the ten cases are shown in Table 1. All the players were handling the ball in the injury situation; seven were in possession of the ball at the time of injury, two had shot and one had passed the ball. In six cases, there was player-to-player contact with an opponent at the time of injury, all of them to the torso being pushed or held. There was no direct contact to the knee. The injury situations could be classified into two groups; seven cases occurred when cutting and three during one-leg landings.

Table 1. Player characteristics.

Case	Maneuver	Sport	Height (cm)	Femur length[b] (cm)	Injured leg	Ball handling	Contact[a]
1	Cutting	Handball	173	41	Rt	In possession	No
2	Cutting	Handball	176	45	Rt	In possession	No
3	Cutting	Handball	166	41	Lt	In possession	Yes
4	Cutting	Handball	172[b]	43	Rt	In possession	Yes
5	Cutting	Handball	177[b]	43	Lt	In possession	Yes
6	Cutting	Basketball	168	41	Rt	Has passed	No
7	Cutting	Basketball	175	43	Lt	In possession	Yes
8	One-leg landing	Basketball	193	48	Lt	In possession	Yes
9	One-leg landing	Handball	170[b]	41	Lt	Has shot	No
10	One-leg landing	Handball	178[b]	43	Lt	Has shot	Yes

BW; body weight, Rt; right, Lt; left.

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

[b]Estimate by Poser.

Hip and ankle kinematics

As shown in Table 2 and Figure 2, the hip kinematics for each of the cases were consistent. The hip had an average flexion angle of 51° at IC, and hip flexion stayed constant over the next 40 ms. The hip was internally rotated 29° at IC, and hip rotation also remained unchanged for the next 40 ms. The hip abduction angle was 21° at IC, but decreased by 5° ($p=0.002$) 40 ms later.

The ankle kinematics for each of the cases were also quite consistent (Table 2, Figure 3). All cases landed with a heel strike, with an average dorsiflexion angle of 2°. All cases reached a flatfooted position relative to the floor 20 ms later, with the ankle plantarflexion angle increasing by 12°, although not significantly ($p=0.096$). During the next 20 ms, the ankle was abruptly dorsiflexed again by 12° ($p<0.001$), while the foot remained flat on the floor. The ankle supination angle increased from 7° at IC to 12° ($p=0.005$) 40 ms later. The ankle was externally rotated 5° at IC, but rotated internally by 7° ($p=0.025$) 40 ms later. A representative case is shown in Figure 4, focusing on hip and ankle kinematics.

Table 2. Hip and ankle joint kinematics (°) at IC, 20 ms and 40 ms after IC.

case	Hip						Ankle						
	Flexion		Abduction		IR		Dorsiflexion			Supination		IR	
	IC	40ms	IC	40ms	IC	40ms	IC	20ms	40ms	IC	40ms	IC	40ms
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)	(41~63)	(42~64)	(13-29)	(7~24)	(18~39)	(26~36)	(-9~14)	(-2~-16)	(-6~9)	(1~12)	(12-25)	(-9~-2)	(-2~6)
Difference	1.7		-6.1		2.5		-12.1		11.5	11.9		7.6	
(95% CI)	(-2.8~6.2)		(-8.9~-3.3)		(-3.9~8.9)		(-24.8~0.6)		(8.6~14.4)	(5.5~18.3)		(2.1~13.1)	
P value	0.480		0.002		0.465		0.096		<0.001	0.005		0.025	

IC, initial ground contact; IR, internal rotation; ms, milliseconds; CI, confidence interval.

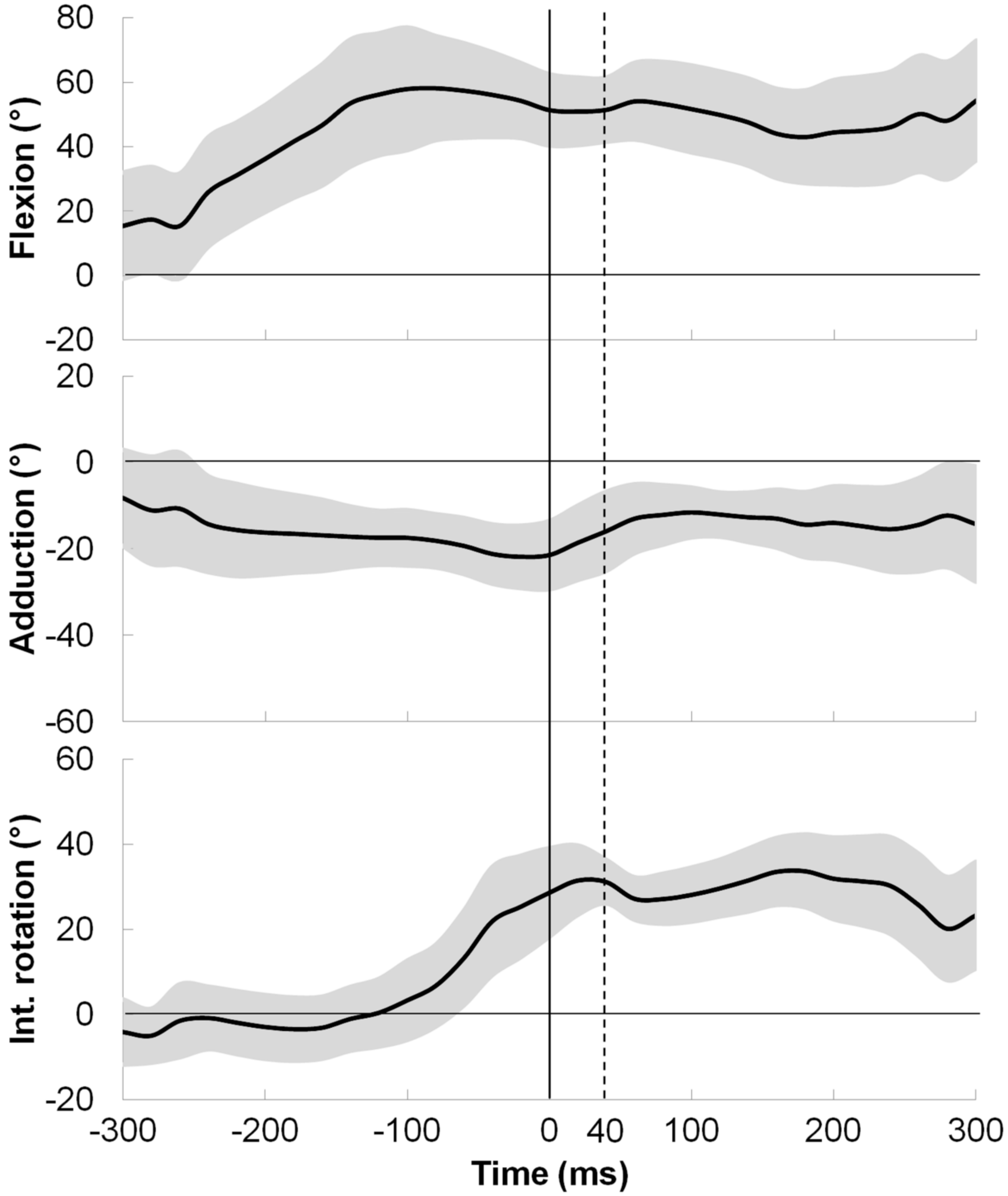

Figure 2. Time sequences of the mean hip angles of the 10 cases (black dotted line) with 95% CI (grey area). Time 0 indicates IC and the dotted vertical line indicates the time point 40 ms after IC.

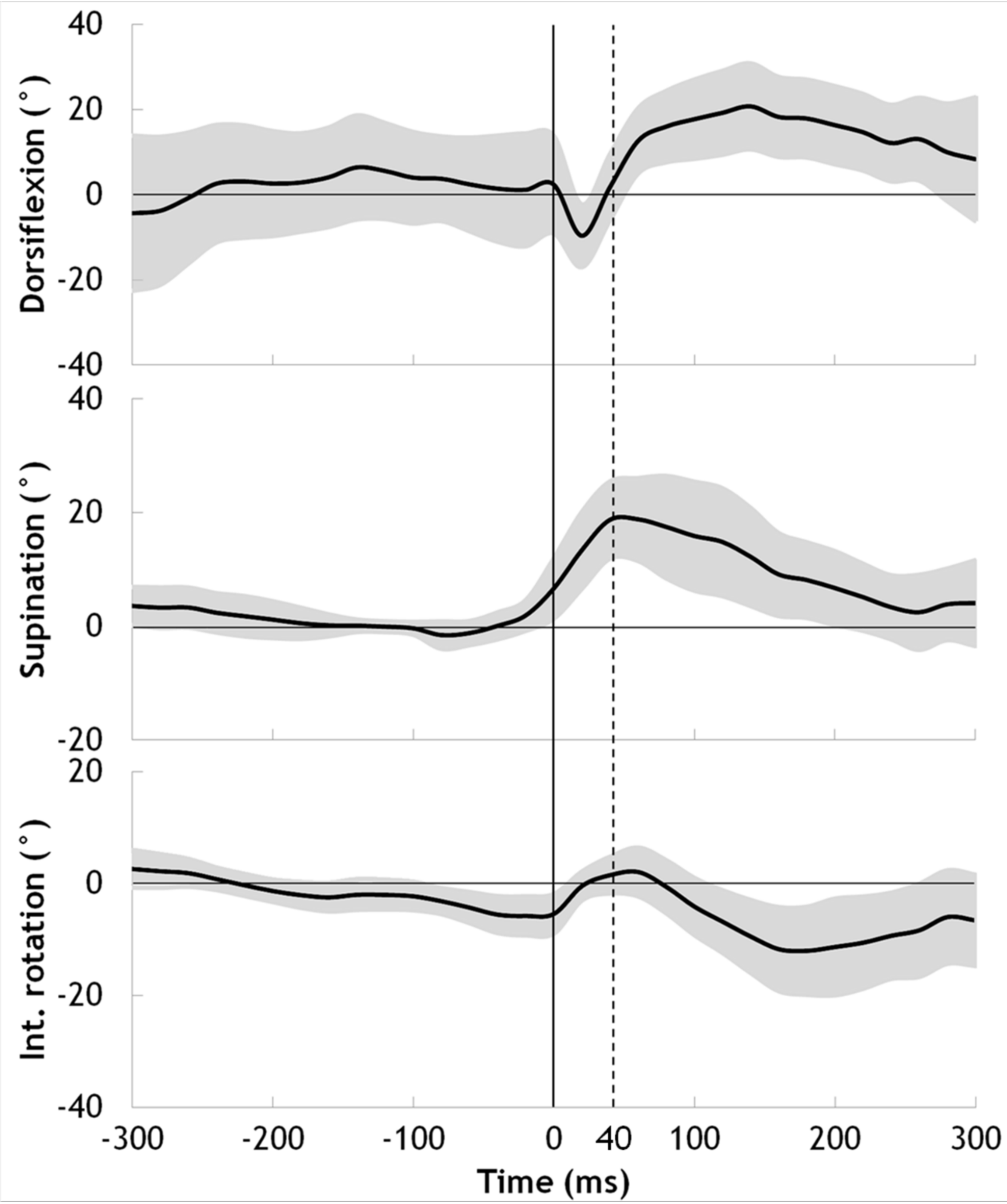

Figure 3. Time sequences of the mean ankle angles of the 10 cases (black dotted line) with 95% CI (grey area). Time 0 indicates IC and the dotted vertical line indicates the time point 40 ms after IC.

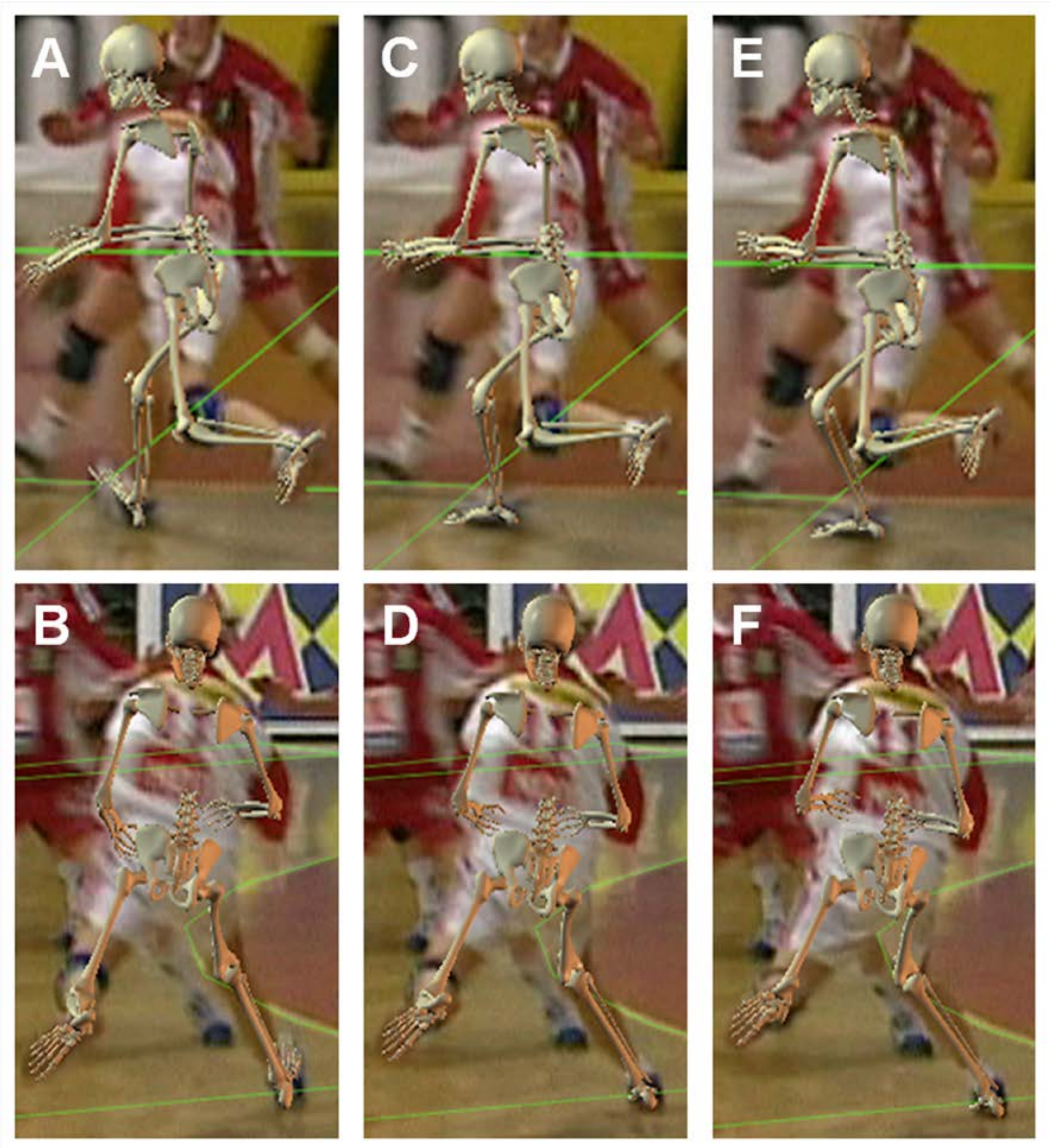

Figure 4. Case number 4 at IC (A and B), 20 ms later (C and D) and 40 ms later (E and F) after IC. Hip kinematics was constant at relatively flexed and largely internally rotated with the abduction angle slightly towards adduction during the 40 ms after IC. The foot position at IC was the hindfoot and reached a flatfooted position 20 ms later. The ankle was dosiflexed at IC, plantarflexed at 20 ms and dorsifixed at 40 ms again as the plantarfoot was fixed to the ground.

COM_BOS evaluation

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

Table 3. COM_BOS normalized to femur length in 10 cases

Case	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

Discussion

This is the first study to quantify hip and ankle joint motions in real ACL situations using a sophisticated computerized 3D analysis technique; previous studies are based on simple visual analyses alone.[4] Our analysis showed that hip kinematics were consistent; hip flexion and rotation remained unchanged in an internally rotated position, with slight adduction motion, during the first 40 ms after IC, the period when the ACL was likely to have ruptured.[12] The ankle kinematics were also consistent, i.e. a slight dorsiflexion at IC, initially plantar flexing over the next 20 ms, then dorsiflexing until 40 ms after IC. The initial ground contact was with a heel strike for all 10 athletes, and foot position reached a flatfooted position within 20 ms, and remained flat on the floor until 40 ms after IC. In addition, 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 positions seen in ACL injury situation is strikingly different from what is observed in non-injury situations of cutting[29, 33] and landing[5, 20] maneuvers, where the hip displayed a smooth transition into flexion after IC. 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-leg landings could induce anterior tibial translation and a subsequent ACL injury. Based on this finding, they proposed a mechanism called the "hip extension, knee flexion paradox", i.e. that 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 IC was lower in females than in males during a drop landing. Schmitz et al.[30] reported that in a single-leg landing, energy absorption at the hip and the total hip flexion displacement were lower in females, even though the peak vertical GRF was larger when compared with males, implicating a stiffer landing in females. Landry et al.[19] also reported that female athletes performed an unanticipated side-cut maneuver with less hip flexion than male athletes. The current findings are also 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 subjects had relatively constant hip flexion and abduction during the first 100 ms after IC, whereas uninjured subjects flexed the hip by 15° in the same time period.[4]

Moreover, 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]

The ankle flexion kinematics observed in the current study agree well with previous video analyses using simple visual inspection. Boden et al.[4] reported that ACL-injured subjects to a larger degree than control subjects landed on their heel or flat-footed. 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 of Boden et al.[4] information about such matching was not available; thus, the conclusions must be interpreted with care. On the other hand, Waldén et al.,[36] in their video analysis of ACL injuries among male professional football players, also reported that the majority cases (8 of 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 also documented that a toe landing was one of the most significant predictors for lower knee abduction moments.[13]

In the current study, COM was posterior and medial to the foot in all cases, represented by a positive value of COM_BOSx and COM_BOSy. However, none of the cases showed larger COM_BOS than 1.2, when normalized to femur length, which was proposed as the criteria for risk of ACL injuries by Sheehan et al.[31] 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 the hip and knee kinematics in non-injury situations using the MBIM technique showed that non-injury situations may have COM_BOS greater than 1.2 (Sasaki, personal communication). These data indicate that the COM_BOS distance may not be as important as suggested by Sheehan et al.[31]

There are some limitations which should be borne in mind when interpreting the results. Most importantly, there is a limit to how accurately joint kinematics can be estimated from standard TV 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 one of the camera views in some cases. In such cases, a spline interpolation technique was applied to the affected camera view, and joint kinematics were estimated based on the frames before and after partial occlusion. However, the time periods of occlusion were generally short (typically less than 20 ms). Since the estimated kinematics were also based on one or two other camera views, such partial occlusion did not have a great impact on the analysis. Secondly, 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 improved over the simple visual inspection approach.[16] Furthermore we consistently observed simultaneous internal rotation at the hip, knee and ankle during the first 40 ms after IC, with narrow confidence intervals, providing confidence that the results may be accurate and that internal tibial rotation may contribute to ACL injury.

Thirdly, although the current study focused on hip and ankle biomechanics in "non-contact" ACL injury situations, 6 of the cases involved indirect contact (contact to the body other than the lower extremity). However, it has been repeatedly reported that player movements prior to injury is not only perturbed by body contact, but also by non-contact actions by opponents and team mates[12, 17, 36]. Hence, in both “indirect contact” and noncontact” situations, the injury is likely at least partly caused by the player being out of balance or having inadequate neuromuscular control due to various forms of perturbations. Therefore, we decided to include those 6 cases with indirect contact as "non-contact" ACL injury. In addition. Sub-group analyses were performed to evaluate whether indirect contact affected hip and ankle kinematics during ACL injuries. The 10 cases were divided into 2 groups, the "indirect contact" group and the "noncontact" group based on Table 1. There were no differences in hip and ankle kinematics between the 2 groups (Supplemental table).

Another limitation is that we did not include controls, i.e. players who performed cutting or landing maneuver 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 the hip and knee kinematics in non-injury 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 (Sasaki, personal communication).

In conclusion, hip kinematics 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 non-injury game situations.

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