

Mechanisms for Noncontact Anterior Cruciate Ligament Injuries

Knee Joint Kinematics in 10 Injury Situations From Female Team Handball and Basketball

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Background: The mechanism for noncontact anterior cruciate ligament injury is still a matter of controversy. Video analysis of injury tapes is the only method available to extract biomechanical information from actual anterior cruciate ligament injury cases.

Purpose: This article describes 3-dimensional knee joint kinematics in anterior cruciate ligament injury situations using a model-based image-matching technique.

Study Design: Case series; Level of evidence, 4.

Methods: Ten anterior cruciate ligament injury video sequences from women's handball and basketball were analyzed using the model-based image-matching method.

Results: The mean knee flexion angle among the 10 cases was 23° (range, 11°-30°) at initial contact (IC) and had increased by 24° (95% confidence interval [CI], 19°-29°) within the following 40 milliseconds. The mean valgus angle was neutral (range, -2° to 3°) at IC, but had increased by 12° (95% CI, 10°-13°) 40 milliseconds later. The knee was externally rotated 5° (range, -5° to 12°) at IC, but rotated internally by 8° (95% CI, 2°-14°) during the first 40 milliseconds, followed by external rotation of 17° (95% CI, 13°-22°). The mean peak vertical ground-reaction force was 3.2 times body weight (95% CI, 2.7-3.7), and occurred at 40 milliseconds after IC (range, 0-83).

Conclusion: Based on when the sudden changes in joint angular motion and the peak vertical ground-reaction force occurred, it is likely that the anterior cruciate ligament injury occurred approximately 40 milliseconds after IC. The kinematic patterns were surprisingly consistent among the 10 cases. All players had immediate valgus motion within 40 milliseconds after IC. Moreover, the tibia rotated internally during the first 40 milliseconds and then external rotation was observed, possibly after the anterior cruciate ligament had torn. These results suggest that valgus loading is a contributing factor in the anterior cruciate ligament injury mechanism and that internal tibial rotation is coupled with valgus motion. Prevention programs should focus on acquiring a good cutting and landing technique with knee flexion and without valgus loading of the knee.

Keywords: anterior cruciate ligament (ACL); injury mechanism; video analysis; knee kinematics

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One or more authors has declared a potential conflict of interest: The Oslo Sports Trauma Research Center has been established at the Norwegian School of Sport Sciences through grants from the Royal Norwegian Ministry of Culture, the South-Eastern Norway Regional Health Authority, the International Olympic Committee, the Norwegian Olympic Committee and Confederation of Sport, and Norsk Tipping AS.

It is well established that female athletes have a higher risk for anterior cruciate ligament (ACL) injury than male athletes.^{1,27} Although different ACL injury prevention programs have been developed successfully,^{6,12,20,29,31} it is not well understood how the different elements in these multicomponent programs affect injury risk. Anterior cruciate ligament injuries in women predominantly result from a noncontact mechanism and occur during cutting or 1-legged landing maneuvers.^{1,4,18,30} However, to develop more targeted injury prevention programs, a more detailed description of the mechanism(s) of noncontact ACL injuries is needed.

Several theories of noncontact ACL injury mechanisms have been proposed, such as the quadriceps drawer hypothesis (where the quadriceps muscle generates anterior shear forces on the tibia because of the patellar tendon angle),⁸ internal tibial rotation on a relatively straight leg,² knee valgus with internal rotation,³⁵ knee valgus with external rotation (which may involve impingement of the ACL against the intercondylar notch),¹¹ and tibiofemoral compression loading.²⁸ However, for lack of evidence, these hypotheses are still a matter of controversy,¹⁵ with some favoring sagittal and others nonsagittal plane knee joint loading.^{8,25,26,32,41}

Several different approaches have been used to describe ACL injury mechanisms, including athlete interviews, clinical studies, laboratory motion analysis, cadaver studies, or mathematical simulations.¹⁵ Among these, video analysis of injury tapes is the only method available to extract kinematic data from actual injury situations. However, video analyses have so far been limited to simple visual inspection,^{4,7,30} and the accuracy of this method has been shown to be poor, even among experienced researchers.¹⁷ In addition, simple visual inspection is not sufficient to extract a time course for joint angles, velocities, and accelerations.

Therefore, a model-based image-matching (MBIM) technique has been developed to extract joint kinematics from video recordings using 1 or more uncalibrated cameras.¹⁶ This technique has been validated in noninjury situations in a laboratory environment¹⁶ and also has been found to be feasible for use in actual ACL injury situations.¹⁹ The objective of this study was to describe knee joint kinematics in actual ACL injury situations using the MBIM technique.

METHODS

Video Collection

Ten ACL injury situations from women's team handball ($n = 7$) and basketball ($n = 3$), recorded with at least 2 cameras during television broadcasts, were analyzed. From team 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 1 of the camera views in 2 cases.

Video Editing

The video recordings were transformed from their original format into uncompressed AVI (audio video interleave) sequences before further processing to avoid loss of quality. The sequences were converted to uncompressed TIFF (tagged image file format) files using Adobe Premiere Pro (version 1.5, Adobe Systems Inc, San Jose, California) 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). Then, lens distortions were corrected using Andromeda LensDoc filter (version 1.1, Andromeda Software Inc, Westlake Village, California). To synchronize the camera views from the same injury sequence, a manual synchronization was performed using key events in each camera view (eg, foot strike and ball catching).

Model-Based Image Matching

To reconstruct the 3-dimensional kinematics of the injured players, we used a new photogrammetric MBIM technique.^{16,19} The matchings were performed using the commercially available program Poser 4 and the Poser Pro Pack (Curious Labs Inc, Santa Cruz, California). A model of the surroundings were 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 Figure 1 for an example of how key lines and other fixed objects on the handball court were matched). We utilized a skeleton model from Zygot Media Group Inc (Provo, Utah) 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 motion of the remaining segments was then described with 3 rotational degrees of freedom relative to their parent, for example 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 matching procedure has been described in detail in the previous studies.^{16,19} An example of a matched video is shown in Figure 1 (for supplemental video, see the online Appendix for this article at <http://ajs.sagepub.com/supplemental/>).

Anthropometric measurements were obtained from players for cases 1, 2, and 3, where body segment parameters were calculated using a modified version¹⁶ of Yeadon's inertia model.⁴⁰ 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, finally, a fixed set of scaling parameters was determined.

We used Woltring's generalized cross-validation spline package³⁹ with a 7-Hz cutoff to obtain velocity and acceleration estimates for the center of mass translation. Normalized ground-reaction forces were calculated based on estimated accelerations of the center of mass. The knee joint angles were converted into the joint coordinate system convention of Grood and Suntay.¹³

Statistical Analysis

We used paired t tests to compare knee joint angle changes between different time points. A 2-sided P value of $<.05$ was

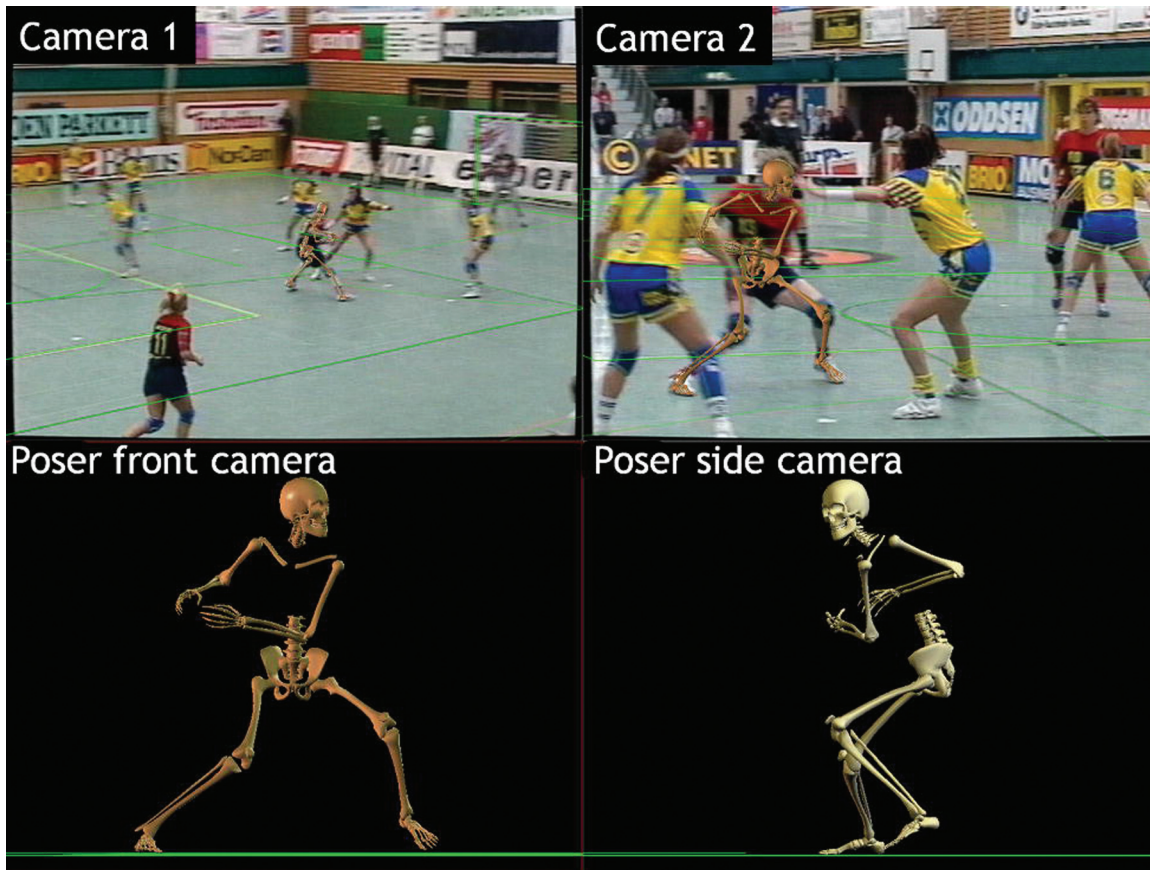


Figure 1. An example of a video matched in Poser. Case number 2, 2-camera team handball injury situation 40 milliseconds after initial contact (IC). The 2 upper panels show the customized skeleton model and the handball court model superimposed on and matched with the background video image from cameras 1 and 2. The bottom 2 panels show the skeleton model from a frontal (lower left) and side (lower right) view created in Poser.

considered significant. The results are shown as the mean with 95% confidence intervals (CI) or range, as noted.

RESULTS

Player Characteristics

Ten video sequences with at least 2 views of ACL injuries from women's handball ($n = 7$) and basketball ($n = 3$) were analyzed; all of them occurred during game situations. Four players injured their right knee and 6 injured their left knee. 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, 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 2 groups: 7 cases occurred when cutting and 3 during 1-legged landings. Initial contact (IC) was defined as the first frame where the foot contacted the ground before the injury. The characteristics of each of the 10 cases are shown in Table 1.

Knee Kinematics

As shown in Table 2, the knee kinematics for each of the cases was quite consistent. The knee was relatively straight, with a flexion angle of 23° (range, 11° - 30°) at IC and had increased by 24° (95% CI, 19° - 29° ; $P < .001$) 40 milliseconds later (Figure 2). The knee abduction angle was neutral, 0° (range, -2° to 3°) at IC, but had increased by 12° (95% CI, 10° to 13° ; $P < .001$) 40 milliseconds later (Figure 3). As for knee rotation angle, the knee was externally rotated 5° (range, -5° to 12°) at IC, but abruptly rotated internally by 8° (95% CI, 2° - 14° ; $P = .037$) during the first 40 milliseconds. From 40 milliseconds to 300 milliseconds after IC, however, we observed an external rotation of 17° (95% CI, 13° - 22° , $P < .001$) (Figure 4).

Ground-Reaction Force

The estimated peak vertical ground-reaction forces for each of the 10 cases are shown in Table 3. Peak vertical ground-reaction force was 3.2 times body weight (95% CI, 2.7-3.7), and occurred at 40 milliseconds (range, 0-83 milliseconds) after IC.

TABLE 1
Player Characteristics

Case	Maneuver	Sport	Height, cm	Body Weight, kg	Injured Leg	Ball Handling	Contact ^a
1	Cutting	Handball	173	75	R	In possession	No
2	Cutting	Handball	176	67	R	In possession	No
3	Cutting	Handball	166	64	L	In possession	Yes
4	Cutting	Handball	172 ^b	Unknown	R	In possession	Yes
5	Cutting	Handball	177 ^b	Unknown	L	In possession	Yes
6	Cutting	Basketball	168	62	R	Has passed	No
7	Cutting	Basketball	175	68	L	In possession	Yes
8	1-legged landing	Basketball	193	84	L	In possession	Yes
9	1-legged landing	Handball	170 ^b	Unknown	L	Has shot	No
10	1-legged landing	Handball	178 ^b	Unknown	L	Has shot	Yes

^aContact by other players (through being hit, pushed, or held) to the body other than the lower extremity.

^bEstimate by Poser.

TABLE 2
Knee Kinematics at Initial Ground Contact (IC) and 40 Milliseconds After IC

Case	Maneuver	Knee Flexion		Knee Adduction/Abduction ^a		Knee Rotation ^b		
		IC	40 ms	IC	40 ms	IC	40 ms	External Rotation Increase, deg ^c
1	Cutting	11	31	-2	-15	-1	7	21
2	Cutting	30	56	-3	-12	-10	-3	16
3	Cutting	14	46	2	-10	-1	6	10
4	Cutting	28	54	2	-11	-12	0	21
5	Cutting	18	26	2	-7	-10	3	5
6	Cutting	27	48	0	-10	-7	11	17
7	Cutting	30	53	-3	-13	-4	13	33
8	1-legged landing	19	38	0	-12	-6	-5	19
9	1-legged landing	27	61	2	-14	-4	4	19
10	1-legged landing	24	55	2	-9	5	-11	12

^aAdduction/abduction of tibia relative to femur. Negative values represent abduction from neutral, positive adduction.

^bRotation of tibia relative to femur. Negative values represent external rotation from neutral, positive internal rotation.

^cIncrease of external rotation from 40 ms after IC to the time when maximum external rotation occurred within 300 ms.

DISCUSSION

This is the first study to quantify knee joint motions in real ACL situations using a sophisticated computerized 3-dimensional analysis technique; previous studies are based on simple visual analyses alone.^{4,7,18,30} Our results showed rapid valgus development of 12° within 40 milliseconds after IC, suggesting that valgus loading is a key factor in the ACL injury mechanism. At the same time, the knee rotated internally, indicating that valgus and internal rotation were coupled motions. The low flexion angle observed (~23°) suggests that a quadriceps drawer mechanism may also contribute to ACL injury. Although the quadriceps effect at different knee flexion angles seems to vary considerably between studies, they agree in that the anterior shear component will be large at such a low angle.^{9,21}

However, some limitations must be kept in mind when interpreting the results from the present study. First, the MBIM technique is subjective, in the sense that it is dependent on the operator's ability to perform the model matching consistently. To minimize the bias resulting from single-operator judgment, 3 experts gave their opinion on the

goodness of the fit until we reached a consensus. Second, the estimates, especially the angular estimates, may contain errors. As it was difficult to assess axial shank rotation accurately, we distributed axial rotation evenly between the knee and ankle joint. Obviously, there is a limit to how accurately joint kinematics can be estimated from standard television broadcasts, and in the sequences that were available it was not possible to assess tibial translation. Nevertheless, the MBIM technique has shown to be much more accurate than the simple visual inspection approach,¹⁷ and the validation study has shown that root mean square differences for knee flexion, abduction, and rotation with 2 or 3 cameras were less than 10°, 6°, and 11°, respectively.¹⁶ Moreover, the motion estimates obtained across the 10 cases were remarkably consistent, which suggests that the trends observed do indeed reflect the true events.

The estimates of the ground-reaction forces may also contain errors. They were calculated based on estimated accelerations of the center of mass, and the validation study has shown that estimates for acceleration are reasonably accurate (root mean square differences less than 6 m/s²).¹⁶ However, the relatively low frame rate in

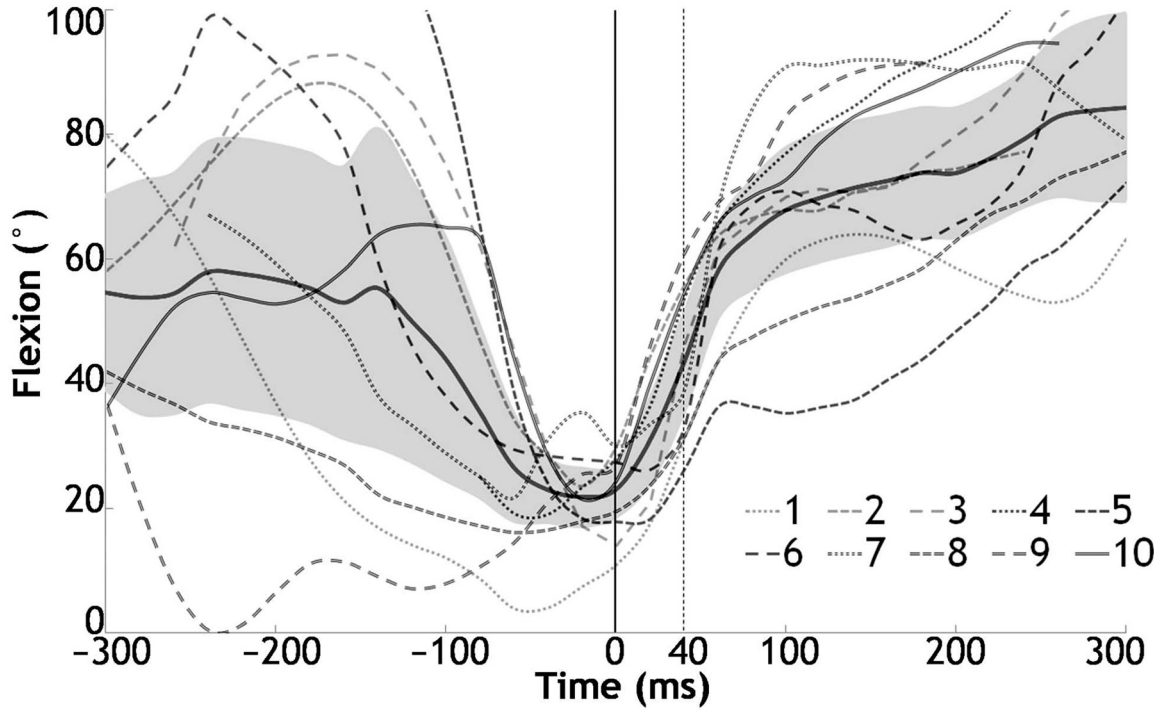


Figure 2. Time sequences of knee flexion angles (in degrees) of each of 10 cases, as well as the mean (thick black line) with 95% confidence intervals (CI) (gray area). Time 0 indicates initial contact (IC) and the dotted vertical line indicates the time point 40 milliseconds after IC. Case numbers correspond to Tables 1 through 3.

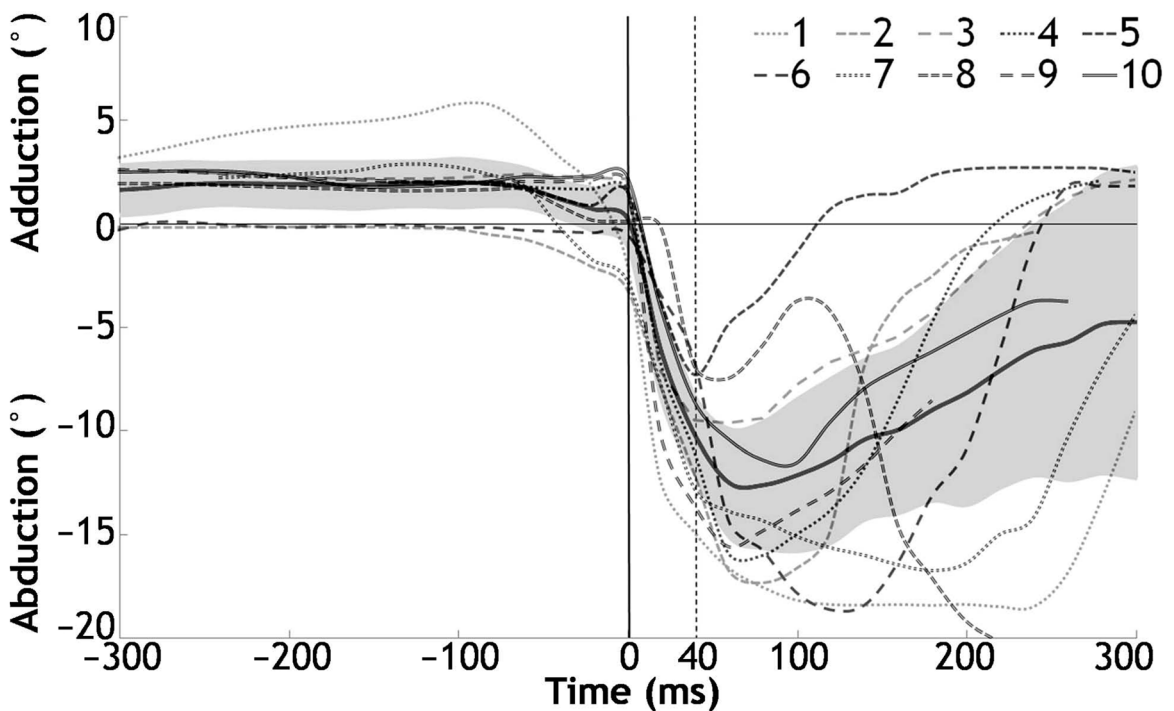


Figure 3. Time sequences of knee adduction/abduction angles (in degrees) of each of 10 cases, as well as the mean (thick black line) with 95% confidence intervals (CI) (gray area). Time 0 indicates initial contact (IC) and the dotted vertical line indicates the time point 40 milliseconds after IC. Case numbers correspond to Tables 1 through 3.

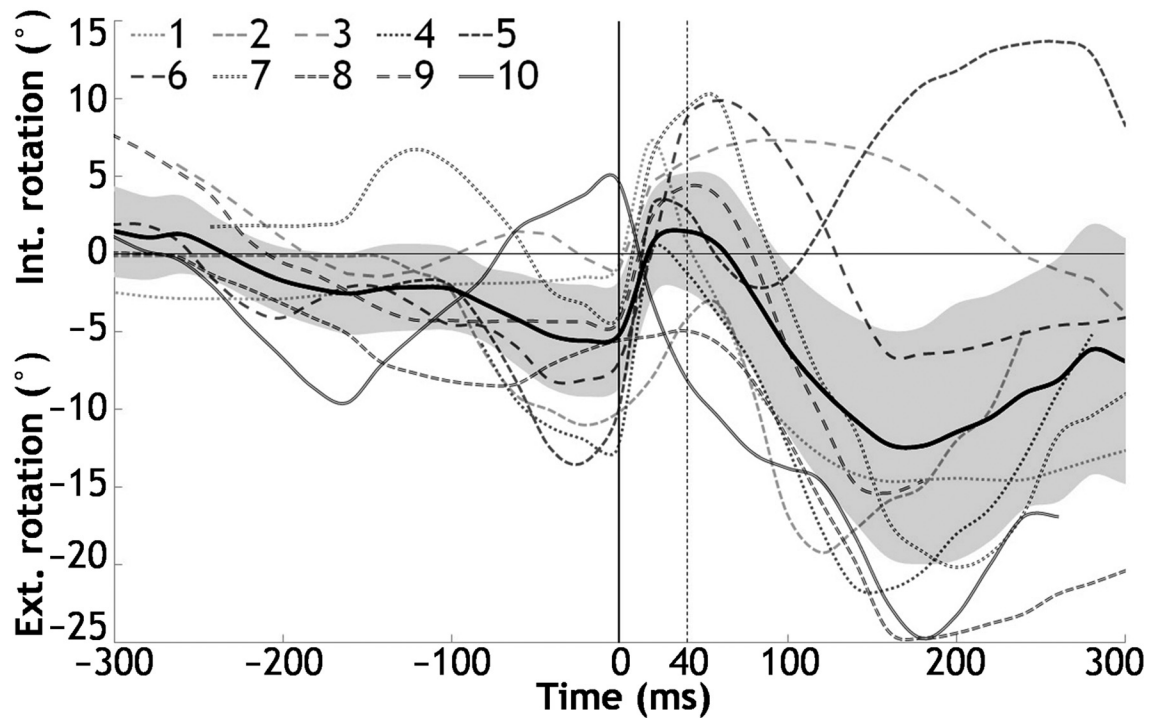


Figure 4. Time sequences of knee rotation angles (in degrees) of each of 10 cases, as well as the mean (thick black line) with 95% confidence intervals (CI) (gray area). Time 0 indicates initial contact (IC) and the dotted vertical line indicates the time point 40 milliseconds after IC. Case numbers correspond to Tables 1 through 3. Ext rotation, external rotation; int rotation, internal rotation.

TABLE 3

Estimated Peak Vertical Ground-Reaction Force (vGRF)

Case	Time, ms ^a	vGRF (\times BW) ^b
1	40	2.8
2	20	2.9
3	60	2.2
4	60	3.3
5	0	1.8
6	20	3.2
7	20	3.7
8	83	3.4
9	67	4.2
10	33	4.5

^aTime after initial contact.

^bBW, body weight.

standard television broadcasts (50 Hz) makes it difficult to capture force peaks, and the true maximal force peak likely lies some time before the estimated maximum.^{16,19}

Another limitation is that we have not included controls, that is, players who performed cutting or landing maneuver without injury. One reason is that the MBIM technique is time-consuming; matching 1 video sequence can take 1 to 2 months. However, data from an ongoing cohort study among 160 female elite handball players based on marker-based motion analysis of cutting maneuvers showed that the knee was in 21° of flexion, 3° of

valgus, and 0° internal rotation at IC, and that valgus and internal rotation increased by only 1° and 3°, respectively, within 40 milliseconds, whereas flexion increased by 23° (Kristianslund, unpublished data, 2010). These data suggest that the motions we have observed in the injury situations differ completely from what can be observed in regular cutting or landing maneuvers.

It has not been possible to determine the exact timing of ACL injury from video analysis based on simple visual inspection.^{4,18,30} However, this may be possible by using the MBIM technique, by assessing abnormal joint configurations, sudden changes in joint angular motion, and timing of ground-reaction forces. Because of the limited precision of the kinematic estimates, it is difficult to determine the exact moment of injury in each case, but given the consistency of all cases, it seems likely that the injury occurs within 40 milliseconds for the majority of these cases. These 10 cases showed that sudden valgus angle increase reached 12° and internal rotation angle abruptly increased by 8° within the first 40 milliseconds after IC. These periods also correspond to the average peak vertical ground-reaction force in the 10 cases. These results correspond well with previous studies showing that the ACL was strained shortly (approximately 40 milliseconds) after IC in simulated landing.^{34,37}

There is an ongoing debate in the literature regarding the mechanisms for noncontact ACL injury, whether sagittal or nonsagittal factors dominate. DeMorat et al⁸ proposed that aggressive quadriceps loading was responsible, based

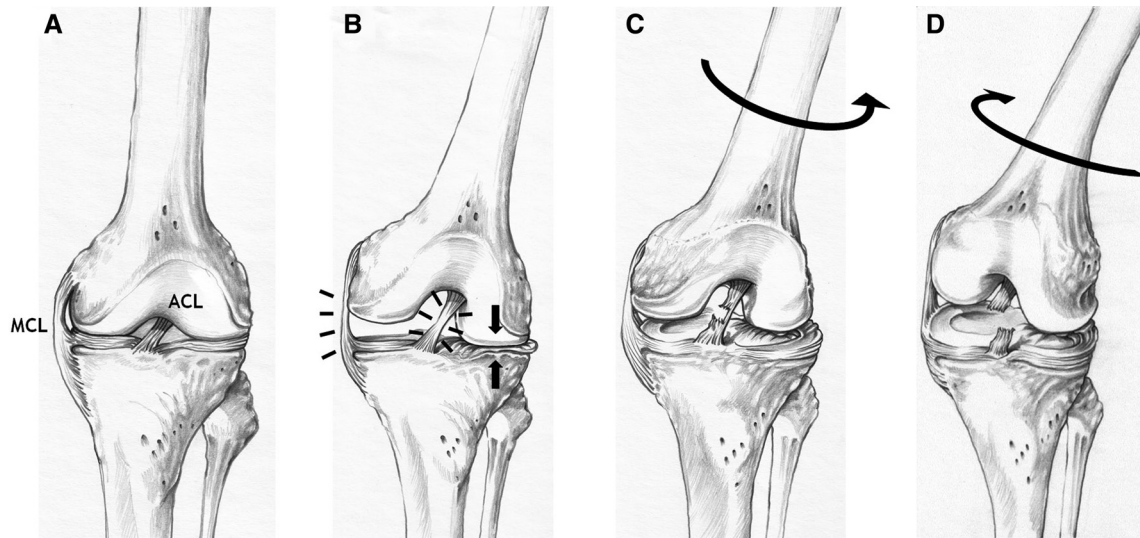


Figure 5. Our hypothesis for noncontact anterior cruciate ligament (ACL) injury mechanism. A, an unloaded knee. B, when valgus loading is applied, the medial collateral ligament becomes taut and lateral compression occurs. C, this compressive load, as well as the anterior force vector caused by quadriceps contraction, causes a displacement of the femur relative to the tibia where the lateral femoral condyle shifts posteriorly and the tibia translates anteriorly and rotates internally, resulting in ACL rupture. D, after the ACL is torn, the primary restraint to anterior translation of the tibia is gone. This causes the medial femoral condyle to also be displaced posteriorly, resulting in external rotation of the tibia.

on a cadaver study that demonstrated that aggressive quadriceps loading (4500 N) could take the ACL to failure.⁴¹ In contrast, McLean et al,^{25,26} using a mathematical simulation model, argued that sagittal plane loading alone could not produce such injuries. A prospective cohort study among female athletes showing that increased dynamic valgus and high valgus loads increased injury risk led Hewett et al^{14,32} to suggest valgus loading as an important component. Some video analyses also showed that valgus collapse seemed to be the main mechanism among female athletes.^{18,30} However, cadaver studies and mathematical simulation have shown that pure valgus motion would not produce ACL injuries without tearing the medial collateral ligament first.^{3,24,33}

Nevertheless, other simulation studies have suggested that valgus loading would substantially increase ACL force in situations where anterior tibial shear force is applied, for instance through quadriceps contraction.^{37,38} Furthermore, it has been shown that valgus loading induces a coupled motion of valgus and internal tibial rotation, similar to what was observed in the present study.^{22,23} The MRI findings in the current cases were not available, but Speer et al³⁵ reported that bone bruises of the lateral femoral condyle or posterolateral portion of the tibial plateau occurred in more than 80% of acute ACL noncontact injuries. They concluded that valgus in combination with internal rotation and/or anterior tibial translation occurred at the time of ACL injuries,³⁵ consistent with the current observations.

Although both cadaver studies and MRI studies have suggested that internal rotation is present in ACL injury situations, video analyses have suggested that valgus in

combination with external rotation is the most frequent motion pattern.^{10,30} However, the abrupt internal rotation observed using the MBIM analysis technique in the present study is likely not easily detected from visual inspection alone. The external rotation that occurs afterward is more pronounced and therefore easier to observe. The internal-to-external rotation sequence has also been reported previously.²⁸ In a recent cadaver study, the application of pure compressive loads led to anterior tibial translation and internal tibial rotation of up to 8° followed by a sudden external rotation of 12°. The internal tibial rotation is probably caused by the joint surface geometry. The concave geometry of the medial tibia facet combined with the slightly convex lateral tibia facet may cause the lateral femoral condyle to slip back.²⁸ This may also explain why ACL-injured patients tend to have greater posterior lateral tibial plateau slopes than uninjured controls.^{5,36}

Combining the present study with previous findings, we propose the following hypothesis for the mechanism of non-contact ACL injury (Figure 5). (1) When valgus loading is applied, the medial collateral ligament becomes taut and lateral compression occurs. (2) This compressive load, as well as the anterior force vector caused by quadriceps contraction, causes a displacement of the femur relative to the tibia where the lateral femoral condyle shifts posteriorly and the tibia translates anteriorly and rotates internally, resulting in ACL rupture. (3) After the ACL is torn, the primary restraint to anterior translation of the tibia is gone. This causes the medial femoral condyle to also be displaced posteriorly, resulting in external rotation of the tibia. This external rotation may be exacerbated by the typical

movement pattern when athletes plant and cut, where the foot typically rotates externally relative to the trunk.

The knee kinematics of the 10 cases were remarkably consistent, regardless of type of maneuver (Table 2). The exception was case number 10, where we observed no internal rotation of the tibia (Figure 4), indicating that internal rotation is not necessarily a requirement for ACL injury. One can speculate that anterior tibial translation originating from compressive forces and quadriceps drawer, combined with valgus loading, was responsible for the injury in that case.

In conclusion, remarkably consistent descriptions of knee joint kinematics were found from the 10 ACL injury situations. Valgus motion coupled with internal tibial rotation appear to be important components of the injury mechanism. The low flexion angles suggest that quadriceps drawer may contribute as well. Therefore, prevention training programs should focus on acquiring a cutting and landing technique with adequate knee flexion and avoiding knee valgus. Hamstring strength training should also be tested, as cocontraction of the hamstrings may potentially reduce the quadriceps drawer effect.

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