Injury Mechanisms for Anterior Cruciate Ligament Injuries in Team Handball

A Systematic Video Analysis

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Objective: To describe the mechanisms for anterior cruciate ligament injuries in female team handball.

Study Design: Descriptive video analysis.

Methods: Twenty videotapes of anterior cruciate ligament injuries from Norwegian or international competition were collected from 12 seasons (1988-2000). Three medical doctors and 3 national team coaches systematically analyzed these videos to describe the injury mechanisms and playing situations. In addition, 32 anterior cruciate ligament–injured players in the 3 upper divisions in Norwegian team handball were interviewed during the 1998-1999 season to compare the injury characteristics between player recall and the video analysis.

Results: Two main injury mechanisms for anterior cruciate ligament injuries in team handball were identified. The most common (12 of 20 injuries), a plant-and-cut movement, occurred in every case with a forceful valgus and external or internal rotation with the knee close to full extension. The other main injury mechanism (4 of 20 injuries), a 1-legged jump shot landing, occurred with a forceful valgus and external rotation with the knee close to full extension. The results from the video analysis and questionnaire data were similar.

Conclusions: The injury mechanism for anterior cruciate ligament injuries in female team handball appeared to be a forceful valgus collapse with the knee close to full extension combined with external or internal rotation of the tibia.

Keywords: anterior cruciate ligament (ACL) injury; noncontact injury; injury mechanisms; female team handball; video analysis

The anterior cruciate ligament (ACL) is frequently ruptured in European team handball, US college and high school sports (basketball, soccer, and gymnastics), and other sports and levels.[2,3,22,28,29] Female athletes are at an increased risk for ACL injuries with an injury rate 3 to 5 times higher than men. Although a number of hypotheses have been suggested to explain this gender difference, the etiology is still unknown.[15,19,21]

Over the past 2 decades, several studies have been carried out to understand the anatomy, function, and mechanical properties of the ACL. Because of advances in surgical techniques and rehabilitation, reconstruction of the ACL has become a relatively routine procedure. However, although an understanding of the etiology of ACL injuries is essential to develop effective prevention methods, little attention has been focused on the injury mechanisms of these injuries in team sports. Injured players report that the injuries often occur in a cutting movement or landing from a jump and, apparently, without direct body contact.[7,28,29] Myklebust et al[28,29] reported on the mechanisms of ACL injury on a total of 115 injuries (male and female) in 2 studies and found that 95% and 89% of the players reported that the injuries occurred without player-to-player contact. The injured players also reported that most of the injuries occurred in a move they had done numerous times before. Boden et al[7] reported on the mechanisms of 100 ACL injuries from various sports, mainly basketball, American football, and soccer. A noncontact mechanism was reported in 72% and a contact injury in 28% of the cases. Most of the injuries were sustained at foot strike with the knee close to full extension. Noncontact mechanisms were classified as sudden deceleration prior to a change of direction or landing motion, whereas contact injuries occurred as a result of valgus collapse of the knee.

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However, because questionnaire data from these and other studies[13,26] are limited by the ability of the injured players to comprehend and recall what actually took place when they were injured, systematic analysis of videotapes from injury situations could represent an important tool to advance our understanding of the injury mechanisms for ACL tears. In fact, Boden et al[7] also reviewed videotapes of 27 separate ACL ruptures and confirmed that most noncontact injuries occurred with the knee close to extension during a sudden deceleration prior to a change in direction or during a landing maneuver. However, the methodology used to analyze these videos was not described, and they based their analysis on a mixed sample from different sports and of both genders.

Therefore, the aim of this study was to describe the injury mechanisms for ACL injuries in female athletes using a systematic approach to analyze videotapes of injury situations from team handball. In addition, questionnaire data were collected prospectively from injured athletes to validate the sample available on videotape.

MATERIALS AND METHODS

Information on injury mechanisms was collected in 2 different ways, from the analysis of video recordings of actual ACL injuries (n = 20) and through interviews with injured players (n = 32). Videotapes were collected prospectively through the 1998-1999 season (n = 5), but additional tapes were also obtained from previous (n = 7) and subsequent (n = 8) seasons. All injured players were interviewed during the 1998-1999 season to compare player recall with the video analysis. The interview data were also used to check whether the videotapes we obtained were a representative sample.

Prospective Survey

A prospective cohort study of ACL injuries in the 3 upper divisions for women in Norwegian team handball was carried out during the 1998-1999 season. A total of 60 teams from the elite division (12 teams), first division (12 teams), and second division (36 teams) agreed to take part in the study. The players on these teams were either semiprofessional or amateurs. The teams were followed for 12 months (June-May). Information about players with suspected ACL injuries (ie, knee injuries that caused more than 1 week of missed participation in training or match) was obtained from team coaches, physical therapists, and team physicians based on monthly reports (in most cases, injuries were reported as soon as they happened). Injury records were checked with the insurance company for the Norwegian Handball Federation, where all players were insured through their mandatory player licenses. Each case of a suspected ACL injury was either referred by us or self-referred for examination by an orthopedic surgeon, in most cases including an arthroscopic examination and MRI, and their medical records were obtained to confirm the diagnosis (after written informed consent had been obtained from the player). Only total ruptures of the ACL were included in the study. An ACL injury was recorded if it occurred during organized handball training or games among players registered on the team roster by their coaches. All the players who were reported injured consented to participate in a personal or telephone interview. Three trained physiotherapists, who were not involved in any of the teams, conducted the interviews based on a standardized questionnaire (Table 1). Among the information requested in each case were personal data, as well as data on the playing situation and mechanisms of injury. The study was approved by the data inspectorate and the regional committee for medical research ethics.

TABLE 1
Data Collected in the Standardized Questionnaire

1	Age
2	Gender
3	Team name
4	Division
5	Date of injury
6	Whether the injury occurred during practice or game
7	Type of match
8	Which type of floor the injury occurred on (wooden, artificial)
9	How the injury occurred
10	Field position when the injury occurred
11	If there was any contact with an opponent when the injury occurred (this includes all types of contact, direct contact with the lower extremity as well as contact with other body parts)
12	If surgery had been completed or was scheduled; when and where
13	Permission to obtain the medical hospital record

Video Analysis

Videotapes of ACL injury situations were collected prospectively during the 1998-1999 season (n = 5). In addition, 7 tapes from previous and 8 from subsequent seasons were collected through a search of Norwegian TV station archives and through coaches and players. Eleven of the videotapes were collected from the TV station archives on BETA SP (good or excellent quality, ie, the player's body position, including foot, knee, and hip position, could be seen with good [high-resolution tape] or excellent [high-resolution tape, including close-up camera view(s)] picture quality) and 9 through handball contacts on VHS (moderate or good quality, ie, the player's body position, including foot, knee, and hip position, could be seen with moderate [moderate-resolution tape] or good [moderate-resolution tape but including close-up camera view(s)] picture quality). Eleven tapes captured the incident from 1 camera position and 9 from 2 or 3 camera positions.

The videos were digitized and enhanced by creating still, slow motion, and enlarged picture sequences to clearly show the incident. A video editing program (Media 100 5.5 XS, 1999, Media 100 Inc, Marlboro, Mass) was used to digitize the original videotapes and transfer them to a master videotape that was used in the video analysis. Three knee injury experts (MDs with clinical and research experience

TABLE 2
Variables and Categories Used in the Video Analysis for the 3 Handball Coaches

Variable	Category
1. Player position (ie, static positions of player on the floor based on playing formations)	Back player, wing player, line player, goalkeeper
2. Playing phase	Attack: a team is in possession (ie, with ball control on the opponent's court half); breakdowns: attacks that start by winning the ball in play and maintaining and/or increasing imbalance in opponent defense throughout the attack; return: returning back in defense after losing the ball in play and maintaining and/or increasing imbalance in own team defense throughout the opposing team attack; defense: the opposing team is in possession (ie, with ball control on own team's court half)
3. Activity	Plant and cut: a high-speed evasive technique in which the player tries to get past an opponent by changing direction sideways; landing after a jump shot: a landing on 1 or both legs after the player has jumped up to shoot the ball; turning: the player turns around to run back in the opposite direction; running forward: the player runs straight forward; other, describe: for example, deceleration, collision
4. Push-off knee (ie, the leg used to change direction in the plant-and-cut movement)	Right; left
5. Take-off leg (ie, the leg used to take off in a jump shot)	Right; left; both legs
6. Landing leg (ie, the leg used to land on after a jump shot)	Right; left; both legs
7. Ball handling	In possession; has shot; has passed; no
8. Contact with another player	Direct: a direct blow to the lower extremity of the injured player (thigh, knee, or lower leg); indirect: contact (through being hit, pushed, or held) to the body other than the lower extremity; noncontact: no contact with other players
9. Disturbed by another player (ie, in a way that could influence the movement)	Yes: if yes, describe type of disturbance; no
10. Balance (ie, is the player in balance)	Yes; no
11. Attention (ie, who is the player focusing on)	The goal; primary dualist; pass player; recipient player; other, describe
12. Speed (ie, the player's movement intensity)	Very high intensity: sprinting; high intensity: high-intensity running below sprinting; moderate intensity: moderate-intensity running; low intensity: jogging, walking, and standing
13. Unusual (ie, is there something unusual in the playing situation or in the player's movement)	Yes: if yes, describe; no

on ACL injuries) and 3 handball experts (present or former national team coaches) systematically analyzed the videos independently to describe the injury mechanisms and playing situations. The information was recorded on 2 standardized forms (Tables 2 and 3). The observers watched the injury tapes on their own TV monitors using a video player that allowed them to view the sequences as many times as needed—picture by picture, at normal speed, at slow speed, or as still pictures. The physicians were asked to analyze the injury mechanisms with particular attention to knee position, whereas the coaches were asked to analyze the playing situations that led to the injury. Among the information requested from the coaches was player position, playing phase, player movement, whether the player was with or without the ball, balance, attention, speed, whether there was player-to-player contact, and if there was something unusual in the situation (Table 2). The physician form contained questions concerning knee position, and they were specifically asked to estimate knee flexion, internal/external rotation, and valgus/varus position at the time when the ACL ruptured (Table 3). They were also asked about the foot position,

TABLE 3
Variables and Categories Used in the Video Analysis for the 3 Physicians

Variable	Category
1. Foot position at foot strike	Knee over toe: the foot is positioned neutral (below) to the femur-knee joint axis Inside the knee: the foot is positioned medial to the femur-knee joint axis Outside the knee: the foot is positioned lateral to the femur-knee joint axis
2. Knee position at foot strike	Flexion/extension: determine whether the knee is in flexion or extension and estimate the angle Tibia rotation: determine whether the knee is in internal or external rotation of the tibia and estimate the angle Valgus/varus: determine whether the knee is in valgus or varus and estimate the angle
3. Injury time (ie, determine the time of the ACL rupture)	Did the ACL injury occur at foot strike: Yes; no: if no, when does the ACL rupture take place, and what is the knee position at the time of the injury
4. Movement direction at the time of injury	Medial side of the knee axis: the player is moving medially to the injured weightbearing leg Lateral side of the knee axis: the player is moving laterally to the injured weightbearing leg Straight forward: the player is moving straight forward to the injured weightbearing leg Standing still: the player is standing still (not moving)
5. Weight distribution (ie, estimate the degree of weightbearing on the injured leg)	0%-100%

movement direction, and the degree of weightbearing on the injured leg at the time the foot was planted on the floor (Table 3).

Statistical Methods

For categorical variables (eg, player position, playing phase, contact vs noncontact), we report the results in which at least 2 of the 3 observers agreed in their assessments. For continuous variables (eg, knee position, weight distribution), we report the mean values reported by the 3 physicians. A κ test was used to compare interobserver agreement for categorical data—strength of agreement: poor (κ value: < 0.20), fair (0.21-0.40), moderate (0.41-0.60), good (0.61-0.80), and very good (0.81-1.00).[1] The method error was used to report the reproducibility for continuous data. The method error is reported for each paired comparison between observers (1 vs 2, 2 vs 3, and 1 vs 3).[32] A chi-square test was used to compare the results from the questionnaire and video analysis. A Fisher exact test was used to calculate the P value, and an alpha level of .05 was considered as statistically significant. Results are presented as the mean ± SD and/or the range, unless otherwise noted.

RESULTS

Video Analysis

A total of 20 videotapes of ACL injuries from the Norwegian league or international matches involving Norwegian teams was collected. Of these, 5 were from the 1998-1999 season, 8 from the 1999-2000 season, and 7 from previous seasons (1988-1998). Nine of the injuries on videotapes occurred in the elite division, 2 in the first division, 2 in the second division, and 7 in international matches. Ten players injured their right knees and 10 their left knees. Fifteen of the injuries occurred on artificial floors (synthetic floor covering) and 5 on wooden parquet floors. All of the injuries occurred during competition, 19 in the attacking phase and 1 in the defensive phase. The defensive injury resulted from a collision, a direct contact blow to the anterior aspect of the leg by an opponent while the injured player was standing still.

Of the 19 injuries occurring in the attacking phase, 6 took place during a fast break. All the injuries occurred by back or wing players in different back positions (right, middle, or left). All the players were handling the ball when injured, and they had taken 0 to 3 steps with the ball prior to being injured. Their attention was directed toward an opponent or the goal. Six of the players were in indirect contact with an opponent, all of them to the torso being pushed or held. Seven players were judged by the coaches to have been out of balance, and in 12 cases some form of perturbation (ie, being out of balance, being pushed or held by an opponent, or trying to evade a collision with an opponent) occurred that may have influenced their coordination or movement.

The injury situations could be classified into 2 main groups (Table 4). The plant-and-cut mechanism was the most common with 12 cases, 4 were 2-foot and 8 were 1-foot pushoffs. The second most common mechanism was a 1-leg landing from a jump shot with 4 cases. The other 3 attacking injuries occurred when the players were running forward or decelerating without change of direction (all when landing on 1 foot). Detailed information on each of the cases is shown in Table 4. The injury mechanisms from 2 typical cases—1 plant-and-cut injury and 1 landing injury—are shown in Figures 1 and 2.

TABLE 4
Information on Each Case Based on Analysis of the Videotapes (n = 20)

Activity	Speed	Knee Position (degrees): Flexion	Knee Position (degrees): Tibia Rotation[a]	Knee Position (degrees): Valgus	Weight Distribution: Percentage on Injured Leg	Contact[b]
Plant-and-cut	High	5	5	5	100	No
	Moderate	5	–10	10	100	Indirect
	High	15	–10	20	80	No
	High	15	–5	15	65	No
	High	10	–5	15	100	Indirect
	High	15	–10	15	100	No
	Moderate	15	–10	15	90	No
	High	10	10	20	80	No
	High	10	10	10	100	No
	High	20	–15	15	100	No
	High	20	10	15	100	No
	Moderate	20	10	15	100	Indirect
One-leg landing	High	20	10	10	100	Indirect
	Very high	15	10	15	100	No
	Very high	25	15	15	100	No
	Very high	15	5	10	100	No
Deceleration[c]	Moderate	25	10	10	100	No
	High	20	10	10	100	Indirect
Running	High	20	10	10	100	Indirect
Collision						Direct

[a]Internal rotation of the tibia, negative number; external rotation, positive number.
[b]Direct, a direct blow to the lower extremity of the injured player (thigh, knee, or lower leg); indirect, contact (through being hit, pushed, or held) to the body other than the lower extremity; no, no contact with other players.
[c]Without change of direction.

All the 12 plant-and-cut injuries occurred to the push-off knee. The injuries occurred when the foot was planted and firmly fixed to the floor, and in all cases the foot was outside the knee. The knee was nearly straight and in valgus, combined with either internal or external rotation of tibia (see Table 4). All but 1 of the players were pushing off to change direction toward the medial side of the knee axis.

The 4 injuries resulting from landing after a jump shot occurred to the take-off and landing leg (taking off and landing on the same leg). The injuries occurred when the foot was planted and firmly fixed to the floor, and the foot was externally rotated in all cases. The knee was in slight flexion and valgus, combined with external rotation of the tibia.

Questionnaire: Video Analysis Comparison

A total of 32 ACL injuries was recorded during the 1998-1999 season—14 in the elite division, 5 in the first division, and 13 in the second division. Seventeen players injured their right knees and 15 their left knees. The age of the injured players was 21 ± 4 (SD) years (16-33).

A comparison of some results from video analysis with questionnaire data is shown in Figure 3. The results from the video analysis and questionnaire data were similar, except for the proportion of match versus training injuries (P = .017, Fisher exact test). Most of the injuries occurred during competition, in the attacking phase by back or wing players when they were handling the ball (Figure 3). The players were either in close proximity to an opponent or in contact with an opponent at the time of the injury (Figure 3). As described above and in Table 4, the video analysis showed that 7 of the 20 videotaped injuries included some sort of contact with an opponent (1 case with direct contact with the lower extremity and 6 with indirect contact with the upper body). In comparison, 12 of the 32 injured players reported in the questionnaire that there was contact (the questionnaire did not distinguish between direct and indirect contact). The majority of the injuries occurred on an artificial surface (Figure 3).

A total of 15 of the 20 injured players captured on videos had completed the questionnaire, either in the prospective study during the 1998-1999 season (n = 5) or in other studies using the same questionnaire (n = 10).[27-29] The average age of the 15 interviewed players was 25 ± 4 years (18-33). The 5 players who were not interviewed were players on international teams who were injured in competition in which a Norwegian club or national teams participated.

Reliability of the Method

The agreement of the primary variables related to the playing situations for the 3 handball coaches is shown in

Figure 1. The sequence of events leading to a right-sided ACL injury to a back player (in red). A, pushing off to prepare for a plant-and-cut movement. She has taken 2 steps with the ball and is moving at a high speed. B, airborne just prior to landing. C, touchdown preparing for right-left fake. D, the ACL injury is believed to have occurred at the time the foot is planted to push off with the right knee. The foot is firmly fixed to the floor (externally rotated), and she has a wide stance. The knee is in slight flexion (15°), internal rotation of the tibia (10°) and valgus (20°). Approximately 80% of her body weight is on the injured leg. E, the moment just after the injury, with an increasing valgus angle. F, the injured knee collapses, and she continues to fall to the floor.

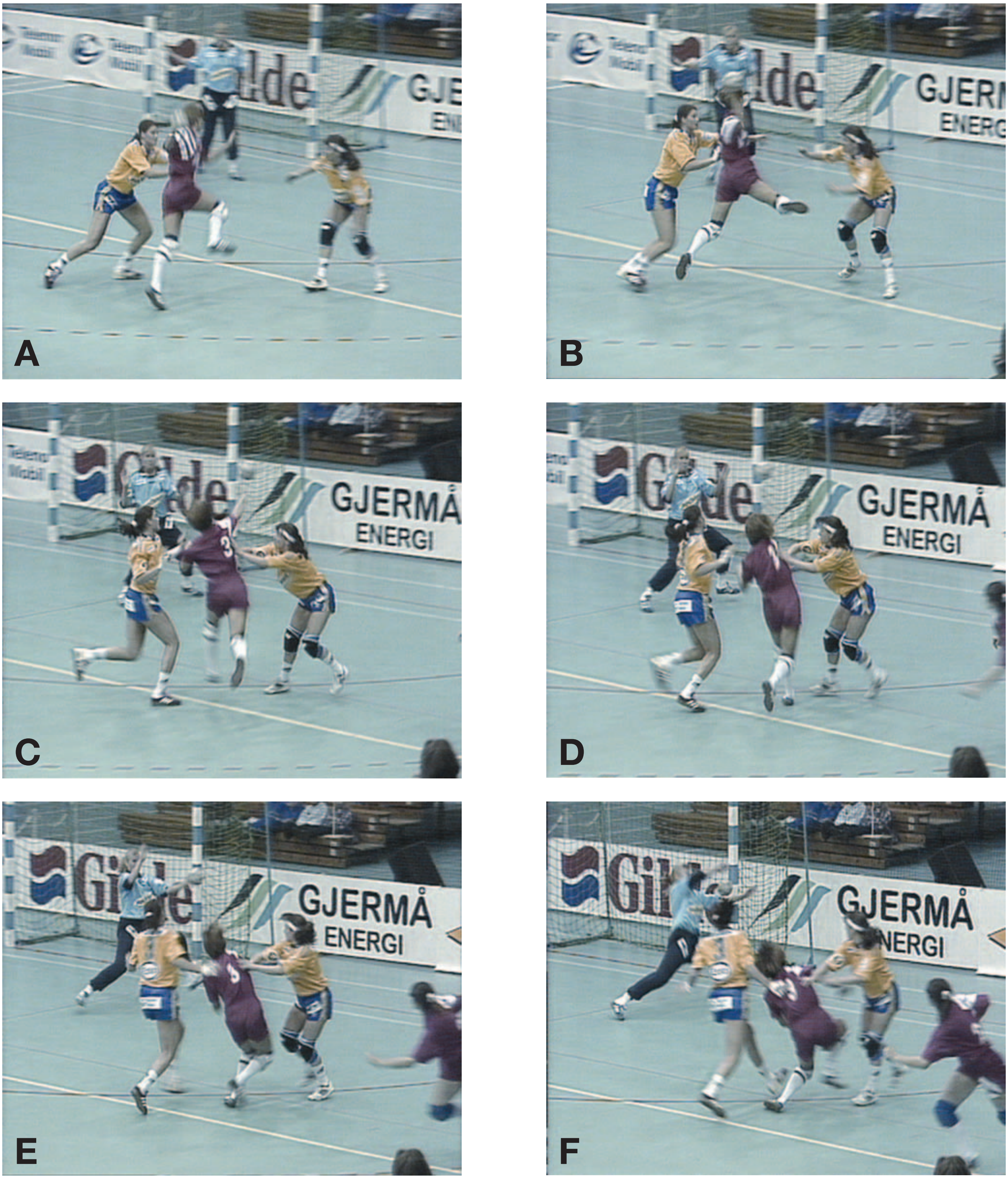

Figure 2. The sequence of events leading to a left-sided ACL injury to a back player (in red). A, taking off on her left leg for a jump shot from the right-back position. She has taken 2 steps with the ball and is moving at high speed. B, the injured player is pushed slightly off-balance disturbed by the opponent before the landing. C, off balance in the air, preparing to land with her body weight on the left leg. D, the ACL in her left knee is believed to have been injured immediately after foot strike. The foot is firmly fixed to the floor and externally rotated. The knee is in slight flexion (20°), external rotation of the tibia (10°) and valgus (10°). E, the moment just after the injury, with increasing knee valgus and flexion. F, the injured knee collapses, and she continues to fall to the floor.

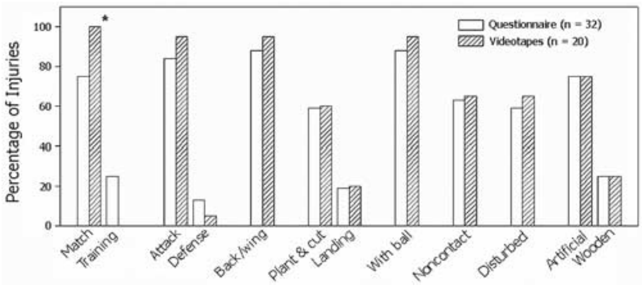

Figure 3. Comparison of injury characteristics between the questionnaire (open bars) and the videotapes (hatched bars). *P = .017 (Fisher exact test).

TABLE 5
Primary Variables Used in the Video Analysis of ACL Injuries in Team Handball (n = 20)[a]

	Coaches		
Variable	1 vs 2	1 vs 3	2 vs 3
Player position	0.85 ± 0.15	0.85 ± 0.13	0.70 ± 0.15
Playing phase	0.65 ± 0.15	0.89 ± 0.10	0.59 ± 0.19
Activity	1.00	1.00	1.00
With ball	0.88 ± 0.15	0.88 ± 0.12	1.00
Contact before injury	0.80 ± 0.13	0.89 ± 0.10	0.70 ± 0.15
Contact at injury	0.60 ± 0.18	0.67 ± 0.17	0.50 ± 0.17

[a]Results from interobserver κ analysis for the 3 handball coaches.

TABLE 6
Number of Responses With Agreement, Nonagreement, and Not Completed for Different Variables From the Questionnaire and the Video Analysis (n = 15)

	Player Position	Playing Phase	Activity	With Ball	Contact With Opponent	Disturbed by Opponent[a]
Agree	12	13	12	14	10	5
Not agree	2		3		5	2
No reply	1	2		1		5

[a]Three injuries were from earlier questionnaire studies in which this question was not included.

Table 5. There was good to very good agreement between the 3 coaches for most variables. The agreement of the variables related to the knee position for the 3 physicians was good. The method error for knee flexion was 8° when comparing observer 1 versus observer 2, 7° for observer 1 versus observer 3, and 8° for observer 2 versus observer 3. The corresponding results were 6°, 6°, and 5° for varus-valgus angle and 10°, 8°, and 9° for tibia rotation, respectively.

The agreement between the data related to playing situation from the video analysis and player recall is shown in Table 6. For a total of 66 of 78 responses there was agreement; 7 of the 12 nonagreements were related to contact with an opponent or the player being disturbed by an opponent at the time of the injury. The 5 other nonagreements were related to player position and activity at the time of injury.

DISCUSSION

The main observation of this study was that ACL injuries in female team handball mainly occurred in 2 situations, a plant-and-cut faking movement (to change direction to pass an opponent) or a 1-leg landing from a jump shot. In both cases, the injury mechanism appeared to be the same. A consistent pattern with a forceful valgus collapse from a position with the knee close to full extension combined with slight rotation of the tibia (external or internal) was observed. The foot was firmly planted on the floor and, in nearly all cases, was outside the knee.

Methodological Considerations

When interpreting the results from the present study, there are some limitations that must be kept in mind. First, the number of videotaped injuries is low. Before the start of the 1998-1999 season, we set out to interview all injured players and collect videotapes of these injuries to ensure a representative sample. We obtained injury interview data on a total of 32 ACL injuries from this season but only 5 videotapes from the same period. The reason for this is that only some games were televised, and practices are rarely videotaped. Most of these videos were from the highest level, where more games are taped. Because a larger sample was needed, we also included 8 injuries from the subsequent and 7 from previous seasons. Nevertheless, even then we had only 4 injuries caused by a 1-leg landing after a jump shot available for analysis. However, as shown in Figure 3, there is a close correspondence between the results from video analysis and those of the questionnaire data. The results related to the playing situation leading to injury and the injury mechanisms are also very similar to previous questionnaire studies from Norwegian team handball.[28,29,34] We collected the questionnaire data using a prospective study design in close contact with team coaches and medical staff throughout the study period, and they were requested to report ACL injuries as soon as they occurred. Also, all insurance claims were examined for additional ACL injuries. Even so, there is always a possibility that an injury may have been overlooked. However, an ACL injury usually causes pain, swelling, and disability, and it is unlikely that a player may have developed an injury without the need for medical follow-up. All the ACL injuries, both from questionnaire and on video, were verified arthroscopically, and in most of the cases reconstructive surgery was performed. It is therefore highly unlikely that there were "false positive" or overlooked ACL injuries during the prospective study period. Also, if injuries were lost, it does not seem likely that there would be a bias for either playing situation or injury mechanism.

Second, from the video analysis it is not possible to determine the exact moment at which the ACL injury occurs. All the observers concluded, based on their long clinical and research experience on ACL injuries, that the ACL tear occurred at or shortly after foot strike. Moreover, we make no claim that it is possible to exactly determine knee position at time of injury from a single-angle 2-dimensional TV image. Even so, the interobserver agreement was good for all 3 main knee position variables (7°-8° for knee flexion, 5°-6° for varus-valgus angle, and 8°-10° for tibia rotation). Approximately half of the videos were TV-quality tapes, and additional digital enhancement techniques were used to enlarge and improve picture quality to aid the observers. We therefore believe that we have a reasonably good measure of the knee position at the time of injury.

Mechanisms for ACL Injury

In contrast to skiing-related ACL injuries[12] and despite the fact that specific training programs have been introduced to prevent ACL injuries,[9,18,23,27] little attention has been focused on the mechanism of noncontact ACL injuries in team sports. Except for 3 case reports,[11] only 1 study has attempted to describe the mechanisms of ACL injuries based on videotapes.[7] However, it should be noted that the methodology was poorly described in the latter study, and the videos represented a mixed sample, which included men and women from widely different sports. Nevertheless, in concurrence with the present findings, they also found that most noncontact ACL injuries occurred with the knee close to extension during a sharp deceleration or landing maneuver.

Previous studies (using videotapes or questionnaires) have not differentiated between direct blows to the lower extremity (as a direct cause of injury) and contact with the rest of the body (which may put the player off balance and indirectly contribute to the injury). Also, studies have not distinguished between contact prior to injury and contact at the time of injury. In the present study, we found that although the injury may appear to be noncontact because there was no direct contact with the injured extremity, a closer scrutiny showed that in 6 cases there was contact with the body other than the lower extremity. In addition, by comparing video analysis with player recall in the 15 cases in which questionnaires were available, the players overreported contact with an opponent at the time of the injury.

The function of the ACL is to stabilize the knee joint, prevent abnormal movements, and steer the movement of the knee.[30] The ACL prevents forward translation of the tibia relative to the femur, and cadaver studies have shown that at 30° of knee flexion the ACL represents 85% of the total capsular and ligamentous resistance.[8] In addition, sectioning studies have shown that the ACL prevents hyperextension and stabilizes the knee against tibia rotation.[14,25,35] These studies also show that sectioning results in significant valgus and varus instability between 20° and 40° of knee flexion.

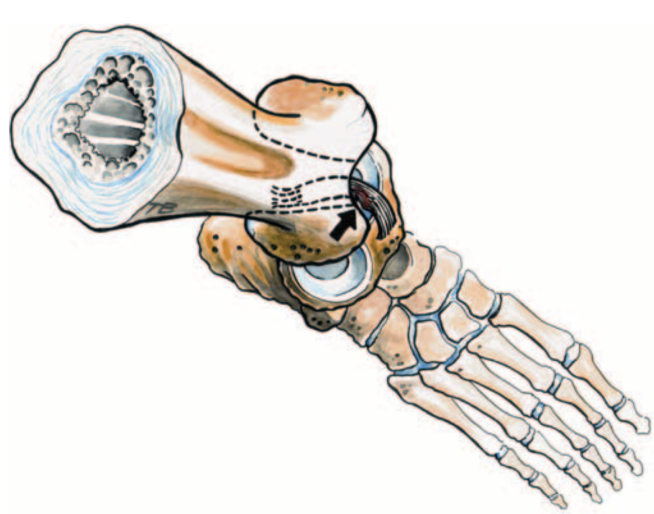

Figure 4. Possible mechanism of ACL rupture. The addition of tibia rotation to forceful quadriceps contraction in a valgus position may cause impingement of the ACL on the femoral condyle. Illustration by Tommy Bolic (reproduced with permission from Bahr R, Mæhlum S, eds. *Idrettsskader.* Oslo, Norway: Gazette Bok).

In the present study, we found that the knee was close to full extension and in a valgus position for both the plant-and-cut and landing mechanisms and that there was some rotation of the tibia at the assumed time of injury. Therefore, it could be hypothesized that a valgus movement may play an important role in the disruption of the ACL. In this model, the knee can be perceived as a buckling column that simply results from the athlete contacting the floor with the foot placed outside the knee. However, whether the consistent valgus collapse observed in the videos was actually the cause of injury or simply a result of the ACL being torn is open for discussion.

It has been reported that the quadriceps is capable of loading the ACL throughout the full motion of the knee[16] and can be seen as an antagonist of the ACL.[36] Investigators have also found that knee flexion between 0° and 30° increases the ACL strain.[4-6,16,17] In addition, Beynnon et al,[5,6] using an in vivo strain gauge technique, have shown that contraction of the quadriceps increases ACL strain between 15° and 30° of knee flexion. In fact, they show that the highest strain is seen at 15° of knee flexion, which corresponds closely with the estimated knee position at the time of injury in the present study. They also found the same results with simultaneous quadriceps and hamstrings co-contraction, whereas hamstrings contraction alone had no effect on ACL strain. Therefore, contraction of the quadriceps may result in significant anterior shear forces on the proximal tibia in this knee position. Moreover, the addition of tibia rotation to forceful quadriceps contraction in a valgus position may cause impingement of the ACL on the femoral condyle, as suggested by Ebstrup and Bojsen-Moller[11] (Figure 4).

As we have acknowledged, using experts to determine knee position visually at the presumed time of injury has some limitations. To get a more complete and dynamic understanding of the injury mechanism, more precise methods are necessary to track knee motion throughout the injury situation. This can possibly be achieved through markerless 3-dimensional reconstruction from video sequences. We are currently developing a model-based frame-by-frame image-matching technique for reconstruction of human motion from uncalibrated video sequences. If this method can be used to obtain an exact time sequence of joint motion, it might provide clues as to the exact timing of ACL rupture and even be used as input for inverse dynamics models to estimate the forces involved, if adequate precision can be achieved.

High-speed activities such as cutting or landing maneuvers require eccentric muscle action of the quadriceps to resist further knee flexion. Under these conditions, the quadriceps can exert more forces than concentric contractions.[10,33] EMG data have revealed a high level of quadriceps activation at heel strike, consistent with deceleration and landing activities.[24] Simonsen et al[33] also found that even with maximal contraction of hamstrings, the muscles were not able to reduce the forces on the ACL during cutting movements in young, well-trained team handball players. Colby et al[10] found the same results during deceleration in young, healthy college athletes. Although we have not been able to accurately assess muscle action from the videotapes, in a landing or stopping move with increasing knee flexion, quadriceps muscle action was probably eccentric. Thus, it may be hypothesized that vigorous, eccentric quadriceps muscle action may play an important role in disruption of the ACL. Although this normally may be insufficient to tear the ACL, it may be that the addition of a valgus knee position, which could cause additional strain in the ligament, or rotation, which could cause impingement on the femoral condyle, could trigger an ACL rupture.

One important question, which is often posed by injured athletes and scientists alike, is why the ACL tears in situations and maneuvers that appear very similar to tasks the athletes have performed innumerable times before without injury.[28,29] To address this question, we specifically asked 3 experienced coaches to examine the videos for unusual features, such as subtle player contact prior to injury, differences in skill execution, and so forth. The coaches were chosen from the national team staff because they had watched the injured players perform the same playing actions numerous times before. Although all but one of the injuries were noncontact in the sense that there was no direct contact with the lower extremity, a perturbation was reported to have occurred in a significant number of situations. Among the factors reported were being out of balance, being pushed or held by an opponent, trying to evade a collision with an opponent, and having an unusually wide foot position. Thus, it appears that with scrutiny several aspects of the injury situations are, in fact, not normal. It is therefore possible that perturbations occur that may contribute to the injury by causing the athlete to plant the foot unpreparedly, with an unfavorable lower extremity alignment or with inadequate muscle protection and poor neuromuscular control.

ACL Injury Prevention

Because the long-term consequences for an ACL injury may be serious, and basketball, soccer, and team handball are high-risk sports, specific training programs to prevent ACL injuries have been tested.[9,18,23,27] The exercises used have been designed to improve balance, awareness, and knee control during standing, running, cutting, jumping, or landing. In addition, some included sports-specific exercises focusing on the “knee-over-toe” position and on 2-feet landing after jump shots.[18,23,27] In view of the present findings, these approaches seem reasonable. In fact, Hewett et al[20] have shown that neuromuscular training reduces dangerous valgus torques at the knee and increases the hamstrings torques. Both factors are believed to be related to reducing impact forces. The studies did not collect data to detect any change in technique after the intervention because they only measured the effect on injury rates. However, data from the present study and the 2 other studies using video analyses of ACL injuries[7,11] indicate that athletes could benefit from not letting their knees sag medially during cutting movements or when suddenly changing speed.

Because the injuries in every situation occurred when the foot was planted and firmly fixed to the floor, it can be assumed that the friction between shoe and the floor surface was high. We have prospectively collected data on 53 ACL injuries in team handball,[31] and the results indicate that the risk of ACL injury for women is higher on artificial floors (generally having higher friction) than on wooden floors (parquet, generally having lower friction). Hence, shoe and surface designs that result in a safer environment with as low shoe-surface traction as possible, yet provide sufficient friction to allow optimal performance, must be sought.

CONCLUSIONS

ACL injuries in team handball mainly occurred in 2 situations—a plant-and-cut faking movement or a 1-leg landing from a jump shot. In both cases, the injury mechanism appeared to be the same, a forceful valgus collapse from a position in which the knee is close to full extension combined with some rotation of the tibia (external or internal).

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