Video analysis of the mechanisms for ACL injuries

Thesis for the PhD degree by
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March 2006

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Summary

Serious knee injuries, such as anterior cruciate ligament (ACL) injuries, are a growing cause of concern. Therefore, much attention has been given to non-contact ACL injuries in team sports. However, the mechanisms of injury are poorly understood and controversy exists on the loading patterns involved, which limits our ability to develop improved and targeted prevention programs. A complete description of the mechanisms for a particular injury type in a given sport needs to account for the events leading to the injury situation (e.g. playing situation, player and opponent behavior), as well as include a precise description of whole body and joint biomechanics at the time of injury.

The aims of this study were to develop and validate a new model-based image-matching technique for three-dimensional reconstruction of human motion from uncalibrated video sequences. This method was then used to estimate kinematic characteristics of three typical ACL injury situations from basketball, downhill skiing and European team handball. Furthermore, the accuracy and precision of kinematic estimates from video sequences of situations resembling those typically leading to ACL injuries, using simple visual inspection, was tested. We also tested if accuracy and precision could be improved by a training program. Finally, the mechanisms of ACL injury in 39 basketball cases were described.

Paper I: A new model-based image-matching technique for three-dimensional human motion reconstruction from video sequences was developed, and its accuracy was assessed using traditional motion analysis as a gold standard. This method involves manual matching of a skeleton model to the background image utilizing the commercially available 3D modeling software Poser®. A laboratory trial was conducted with one test subject performing jogging and side step cutting, while being filmed with three ordinary video cameras. This provided three single camera matchings, three double camera matchings and one triple camera matching for each of the motions. The test subject wore 33 reflective skin markers and was filmed with a seven-camera, 240Hz motion analysis system. Root Mean Square (RMS) hip and knee flexion/extension angle differences were less than 12° for all the matchings. Estimates for ad-/abduction (<15°) and internal/external rotation (<16°) were less precise. RMS velocity differences up to 0.62 m/s were found for the single camera matchings, but for the triple camera matching the RMS differences were less than 0.13 m/s for each direction. The kinematic estimates, in particular for COM velocity and acceleration, are clearly better when two or more camera views are available. This method can potentially be used to arrive at more precise

descriptions of the mechanisms of sports injuries than what has been possible without elaborate methods for 3D reconstruction from uncalibrated video sequences, e.g. for knee injuries.

Paper II: A four-camera basketball video, a three-camera European team handball video and a single-camera downhill skiing video were analyzed, using the new model-based image-matching method described in Paper I. When the match was considered satisfactory, joint angles as well as velocity and acceleration of the center of mass were calculated using Matlab®. In the basketball and handball matchings, the skeleton and surrounding models were successfully matched to the background through all frames in all camera angles. Detailed time courses for joint kinematics and ground reaction force were obtained, while less information could be acquired from the single-view skiing accident. In conclusion, the model-based image matching technique can be used to extract kinematic characteristics from video tapes of actual ACL injuries, and may provide valuable information on the mechanisms for ACL injuries in sports.

Paper III: Using a traditional surface marker based infrared, 240 Hz, 3D motion analysis system, we recorded running and cutting trials from three test subjects. Six international researchers were asked to provide estimates of kinematic variables from 27 video composites from one, two or three ordinary cameras, systematically varying viewing angles and time point of analysis. The analysts thereafter went through a training program where 35 similar composites were analyzed, and feedback on the kinematics as measured by the 3D motion analysis system was provided on a group basis. Finally, the pre-test was repeated to test for accuracy and precision. The mean error for knee flexion was -19°, indicating a consistent underestimation. Hip flexion was underestimated by 7°, but the standard deviation between the analysts was 18° on average, indicating poor precision. Substantial errors were also found in the accuracy and precision of the other estimates. Only small group effects were seen from our training program. Based on these findings, we concluded that results from studies using a simple visual inspection approach to describe joint motion should be interpreted with caution.

Paper IV: Six international experts independently analyzed 39 videos (17 male, 22 female) of ACL injury situations from high school, college and professional basketball games. Two pre-defined time points were analyzed; initial ground contact and 50 ms later. The analysts were asked to assess the playing situation, player behavior and joint kinematics. There was contact at the assumed time of injury in 11 of the 39 cases (five males, six females). Four of these cases were direct blows to the knee, all in men. Eleven of the 22 female cases collided or were pushed by an opponent *prior to* the time of injury. The estimated time of injury ranged between 17 and 50 ms after initial ground contact. The mean knee flexion angle was higher in females compared to

males, both at initial contact (15° vs. 9°, p=.034) as well as 50 ms later (27° vs. 19°, p=.042). Valgus knee collapse occurred more frequently in females compared to males (relative risk: 5.3, p=.002). Preventive programs to enhance knee control should therefore focus on avoiding valgus motion, and include distractions resembling those seen in match situations.

Acknowledgements

This project was carried out at the Oslo Sports Trauma Research Center, Norwegian School of Sport Sciences, Norway, in the period of 2001-2006. The support and working facilities provided for this project at this institution are greatly appreciated.

The project was financed by the Oslo Sports Trauma Research Center, which has been established at the Norwegian School of Sport Sciences through generous grants from the Norwegian Eastern Health Corporate, Royal Norwegian Ministry of Culture, the Norwegian Olympic Committee & Confederation of Sport, Norsk Tipping AS, and Pfizer AS.

I would like to express my sincere gratitude to everyone who has made this thesis possible.

I would especially like to thank:

Roald Bahr, MD, PhD, co-founder of the Oslo Sport Trauma Research Center, professor at the Norwegian School of Sport Sciences and my main supervisor. I greatly appreciate your precise responses on my many manuscript versions and for always being supportive. Your outstanding knowledge in sports medicine is well known, but it is remarkable how easily you are able to absorb knowledge and evaluate studies also in other research areas, such as biomechanics. Your amazing effectiveness and working capacity are well known among all your colleagues and other people in your surroundings. However, it is not only your scientific qualities that I admire, but also your personal qualities. I am convinced that I could not have had a better supervisor than you!

Lars Engebretsen, MD, PhD, professor at the Oslo Orthopedic University Clinic, co-author and co-founder of the Oslo Sports Trauma Research Center. Together with Roald you make a great team in chairing the Oslo Sports Trauma Research Center. You combine a great working capacity, high ambitions and demands made to yourself and your co-workers with a positive and relaxed approach to life. It is therefore always good to talk with you whether it concerns science, training or other important aspects of life!

Oddvar Hallingstad, PhD, professor in cybernetics and industrial mathematics. Although I have not used your skills in mathematics, robotics and estimation techniques as much as initially planned, you have always been positive and helpful whenever I was in need for your help. Thank you also for excellent teaching in Kalman filtering techniques and robotics prior to and during my PhD-period.

Ingar Holme, PhD, statistician professor at the Norwegian School of Sport Sciences, for his important statistical advices, and in particular the help of designing the generalized estimation equations in Paper III.

Andrew McIntosh, PhD, Senior Lecturer, Director of the Biomechanics and Gait Laboratory School of Safety Science, The University of New South Wales Sydney, for interesting discussions and great feedback on manuscripts and this PhD thesis. It was also fun to see your improvements in the gym during your sabbatical here in Oslo :o)

Jimmy Slauterbeck, MD, PhD for your work in Paper II, III and IV. It was great getting to know you and your family during your stay here in Oslo!

Atsuo Nakamae, MD for your work in Paper III and IV. You proved to be hard-working and smart. You also became a good friend! You also introduced me to cultural behavior previously unknown to me – I have never before had guests who refused to go through the door unless I went first ;o)

Gerald Smith, PhD, Tim Hewett, PhD, FACSM and Barry Boden, MD for your work and excellent input on Paper III and IV. Special thanks to Tim and Barry for collecting ACL injury videos. Also thank you to Gerald for valuable comments on Paper I and II.

Stein By Strømsnes, for your assistance in Paper I, and for valuable comments on the manuscript.

Thomas Moeslund, PhD, for your excellent comments on Paper I and II in relation to computer vision research.

All of the colleagues and friends at the department of sports medicine and OSTRC as well as my many friends and colleagues in other departments of the Norwegian School of Sport Sciences for your social and personal input through the project period. A special thanks goes to Sigmund Andersen for your amazing positiveness and ability to motivate the people next to you!

My good friend Svein Linge, PhD, who introduced me to the OSTRC. Your dedication to science and biomechanics has been a source of inspiration for me ever since our first cooperation during my master thesis period.

Monica Beyer and Gyda Kathrine Moan for assistance in entering data from the forms of Paper III and IV into databases.

Paal Henrik Wagner and Lasse Nettum for video editing.

The National Basketball Association and TV2 and NRK for generously providing several videotapes for this study.

All the librarians at the Norwegian University of Sport and Physical Education for their service-minded attitude.

Finally, big thanks to all my friends and my family, in particular Mamma, Pappa, Anne og Mormor for their support and belief in me.

List of papers

This dissertation is based on the following original research papers, which are referred to in the text by their Roman numerals:

I. Krosshaug T, Bahr R. A model-based image-matching technique for three-dimensional reconstruction of human motion from uncalibrated video sequences. J Biomech. 2005 38(4):919-29

II. Krosshaug T, Slauterbeck J, Engebretsen L, Bahr R. Biomechanical analysis of ACL injury mechanisms: three-dimensional motion reconstruction from video sequences. Scand J Med Sci Sports. (In press)

III. Krosshaug T, Nakamae A, Boden B, Engebretsen L, Smith G, Slauterbeck J, Hewett TE, Bahr R. Estimating human 3D kinematics from video sequences – assessing the accuracy of simple visual inspection. Gait Posture (Submitted)

IV. Krosshaug T, Nakamae A, Boden B, Engebretsen L, Smith G, Slauterbeck J, Hewett TE, Bahr R. Mechanisms of ACL injury in basketball – video analysis of 39 cases. Am J Sports Med (Submitted)

In addition, the introduction is partly based on the following review papers:

- Bahr R, Krosshaug T. Understanding the injury mechanisms – a key component to prevent injuries in sport. Br J Sports Med 2005;39(6):324-329.

- Krosshaug T, Andersen TE, Olsen OE, Myklebust G, Bahr R. Research approaches to describe the mechanisms of injuries in sports: limitations and possibilities. Br J Sports Med 2005;39(6):330-339.

Abbreviations

ACL	Anterior Cruciate Ligament
IC	Initial Contact
COM	Center Of Mass
RMS	Root Mean Square
SD	Standard Deviation
CI	Confidence Interval

Contents

Introduction

The ACL problem in ball/team sports

Serious knee injuries, such as anterior cruciate ligament (ACL) injuries, are a growing cause of concern (de Loes, 1990; Ytterstad, 1996). The highest incidence has been seen in athletes playing pivoting sports such as football, basketball and team handball, and the incidence is 3-5 times higher among women than men (Arendt & Dick, 1995; Myklebust et al., 1998; Myklebust et al., 1997). These injuries can have serious consequences for the injured athlete, not only in terms of treatment costs and time lost from sports, but also through a severely increased risk of early osteoarthrosis (Myklebust & Bahr, 2005). After ten years, approximately half of the patients display radiological signs of osteoarthrosis, and it is expected that nearly all patients will suffer from osteoarthrosis within 15-20 years, regardless of treatment choice (Myklebust & Bahr, 2005).

Recent years have seen an increased interest in sports injury prevention research, not only related to ACL injuries in pivoting sports, but at least partly spurred by the concern over ACL injuries among female athletes. In fact, recent studies show that it may be possible to reduce the incidence of knee and ankle injuries among adults (Hewett et al., 1999; Myklebust et al., 2003; Wedderkopp et al., 1999) and adolescents, (Heidt, Jr. et al., 2000; Junge et al., 2002) using various training programs. However, the prevention programs tested are multifaceted and address many aspects that could be related to the risk for injury (agility, balance, strength, awareness of vulnerable knee and ankle positions, playing technique). It is not known which program component is the key ingredient in preventing knee and ankle injuries or how they work. At least in part, our ability to target and improve current prevention programs is limited by an incomplete understanding of the causes of injuries.

The sequence of prevention

Injury prevention research has been described by van Mechelen et al. as a four-step sequence (Fig. 1) (van Mechelen et al., 1992). First, the magnitude of the problem must be identified and described in terms of the incidence and severity of sports injuries. Second, the risk factors and injury mechanisms that play a part in the occurrence of sports injuries must be identified. The third step is to introduce measures that are likely to reduce the future risk and/or severity of sports injuries. Such measures should be based on information about the risk factors and the injury mechanisms as identified in the second step. Finally, the effect of the measures must be evaluated by repeating the first step, which can be done through a time-trend analysis of injury patterns or, preferably, by means of a randomized clinical trial (Bahr et al., 2003).

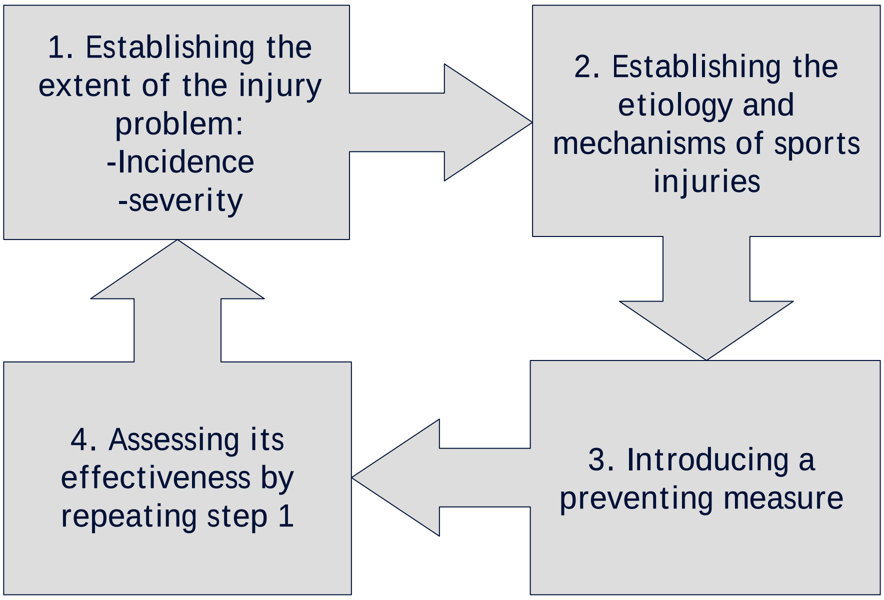

Figure 1 *The van Mechelen four-step sequence of injury prevention research (van Mechelen et al., 1992).*

A critical step in this sequence is to establish the causes. This includes information on why a particular athlete may be at risk in a given situation (i.e. risk factors) or how injuries happen (i.e. injury mechanisms). Furthermore, a complete understanding of injury causation needs to address the multifactorial nature of sports injuries (Meeuwisse, 1994). Two factors determine whether injury will occur: 1) tissue loading and 2) tissue tolerance. Injury will occur when the loading exceeds the tissue tolerance level. Therefore, a complete understanding of injury causation requires knowledge about both factors. While the injury may appear to have been caused by a single inciting event, it could result from a complex interaction between different internal and external risk factors. Internal factors like age, gender and body composition could influence the tissue strength, and thereby the risk of sustaining injuries, predisposing the athlete to injury, hence by definition being risk factors. In addition, external factors such as shoe traction and floor friction could influence the ligament loading, and thereby modify injury risk to make the athlete even more susceptible to injury. It is the presence of both internal and external risk factors that may render the athlete susceptible to injury, but the mere presence of these risk factors is not sufficient to produce injury. The sum of these risk factors and the interaction between them "prepares" the athlete for an injury to occur in a given situation. Meeuwisse describes the inciting event as the final link in the chain that causes an injury, and such events are regarded as necessary causes. He also states that such an inciting event is usually directly associated with the onset of injury.

Defining "injury mechanisms"

A precise description of the inciting event is a key component to understand the causes of any particular injury type in sports (Bahr & Krosshaug, 2005). The term "injury mechanism" is widely used in medical literature to describe the inciting event in biomechanical terms, but its meaning is not well defined.

If we were to describe a situation where a basketball player sustained an ACL injury, one report might be that the injury was caused by "an attacker planting and cutting to set up for a shot". This description includes aspects of the playing situation and skill performed when injured. Additionally, the explanation could add that "the incident occurred to a powerful attacker, who was pushed just as she was trying to pass the opponent in a maximal effort", which includes aspects of athlete characteristics and behavior, as well as opponent behavior. Another description, with more emphasis to the biomechanical causes of the injury, might be that "the injury occurred as a result of a rapid sideways translation on a high-friction surface, rotating while his foot remained firmly planted on the floor." A more detailed biomechanical description could be that "the injury occurred as a result of large external valgus moment and external rotation moment in combination with a translatory shift of the tibia relative to the femur." In other words, the description could include information ranging from the playing situation, player and opponent behavior, to a more or less detailed biomechanical description of joint motion and loads.

An examination of the literature on sports injuries to see how the term "injury mechanism" is used to understand the mechanisms for ACL injuries shows that biomechanically oriented descriptions dominate, although with different levels of detail. Some studies only provide simple characteristics such as "contact/non-contact injuries" (Arendt & Dick, 1995) or "jumping/non-jumping injuries" (Paul et al., 2003). Others use terms like "side-step cutting maneuvers", "tackle" or "long shot", (Strand et al., 1990), "spiking" or "blocking", (Ferretti et al., 1992) ”phantom foot-mechanism" (Ettlinger et al., 1995) – descriptions that are related to a specific sport (European team handball, volleyball and alpine skiing, respectively). However, most of the more detailed studies use different biomechanical descriptors to depict the mechanism of injury. The level of detail varies here as well, e.g. "deceleration injury" (describes whole body acceleration), (Boden et al., 2000) "valgus torque" (describes knee kinetics), (McLean et al., 2004a) "anterior drawer" (describes the relative translation between femur and tibia), (Geyer & Wirth, 1991) "quadriceps drawer" (describes the relative translation between femur and tibia due to quadriceps activation) (DeMorat et al., 2004) and "intercondylar lift-off" (kinematical description of the result from e.g. a valgus or varus load) (Hewett et al., 1996).

In response, Bahr & Krosshaug (2005) introduced a new model (Figure 2) where the inciting event or injury mechanism described a) vital aspects of the playing (sports) situation (i.e. the situation description described from a sports specific point of view), b) athlete and opponent behavior (i.e. a qualitative description of the athlete's action and interaction with the opponent), c) gross biomechanical characteristics (i.e. a description of whole body biomechanics) and d) detailed biomechanical characteristics (i.e. a description of joint/tissue biomechanics).

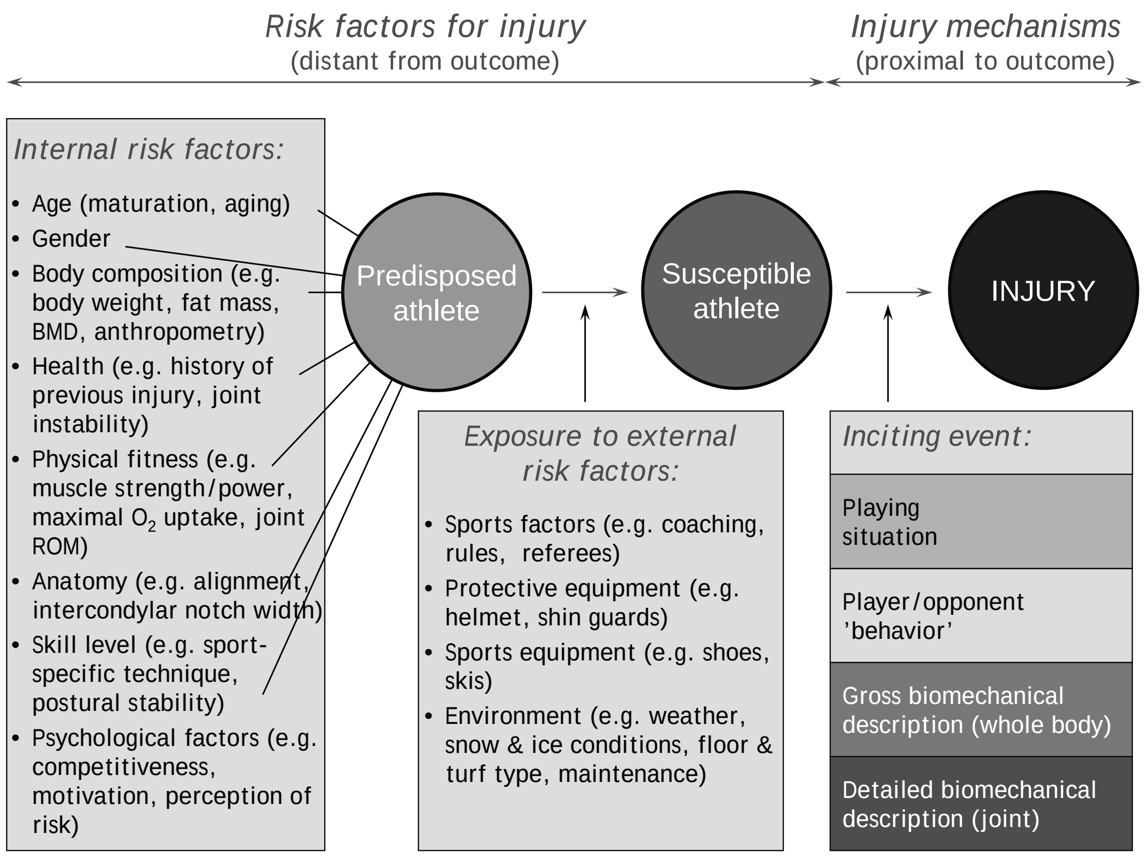

Figure 2 *A comprehensive injury causation model developed based on the epidemiological model of Meeuwisse (1994) and the biomechanical model of McIntosh (2005).*

Hypotheses on non-contact injury mechanisms in ball/team sports

As early as in 1938 Palmer (1938) suggested that a pathologic relationship existed between the ACL and the intercondylar notch in patients with ACL injuries. He noted that the ACL was in a vulnerable position in these patients because the ACL was being stretched over the medial margin of the lateral femoral condyle with the knee in flexion and the patient supine.

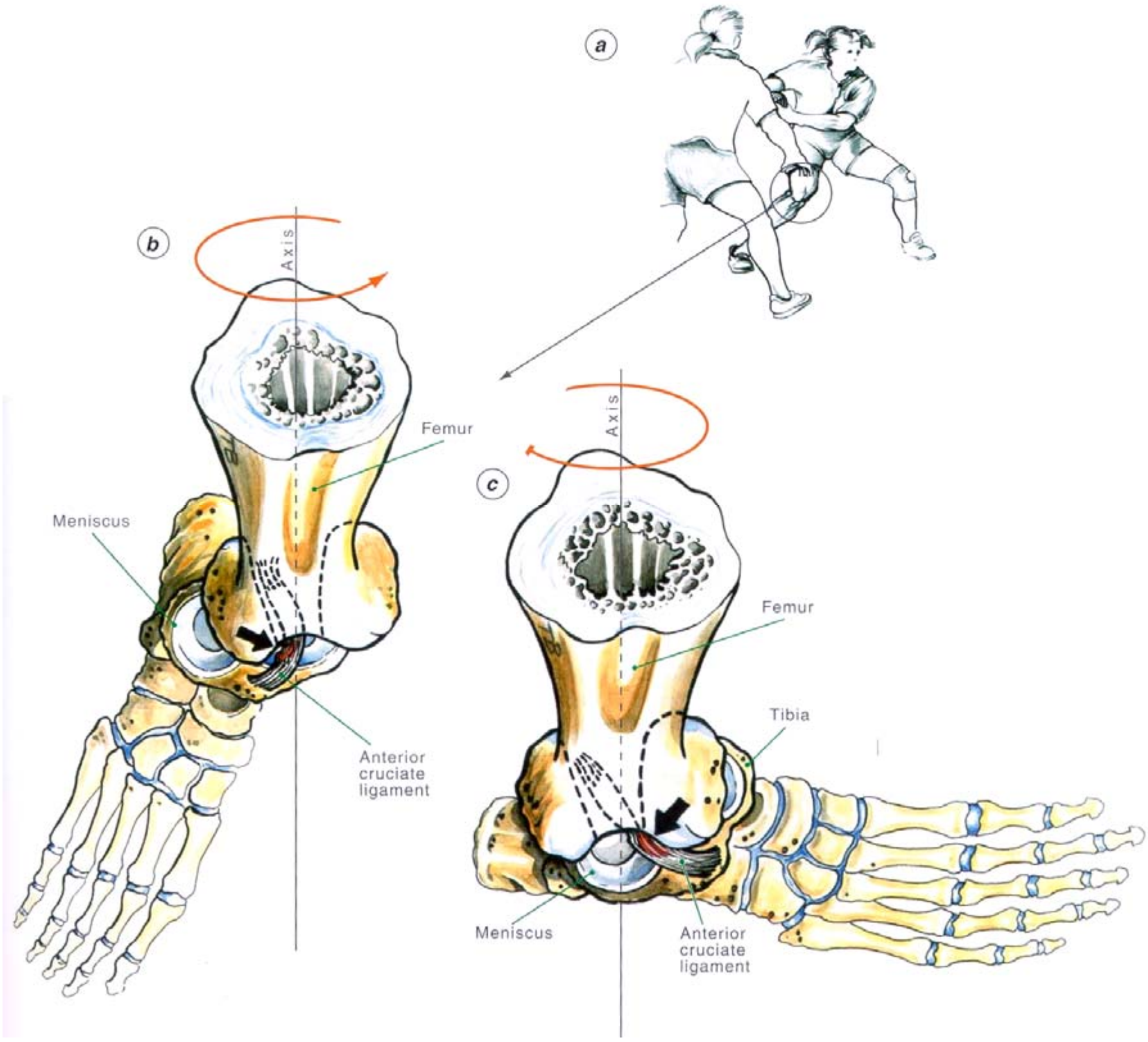

Figure 3 *From Bahr & Mæhlum (Bahr & Mæhlum, 2004). A sidestep cutting maneuver a) can lead to two scenarios: b) Valgus and external tibial rotation, and c) Valgus and external tibial rotation. In both scenarios, the solid arrow indicates a possible impingement of the ACL against the intercondylar notch.*

In 1974, Kennedy et al. (1974) in a cadaver study, showed that external rotation and abduction in a partially flexed knee initiated ACL tension over the medial border of the lateral femoral condyle. Norwood & Cross (1977) demonstrated in cadavers that the ACL impinges on the anterior intercondylar notch with the knee in full extension. The impingement theory has later been suggested based on video analysis of non-contact ACL injuries in team handball sports

(Ebstrup & Bojsen-Moller, 2000; Olsen et al., 2004) (Figure 3 and Figure 4b). In the study of Olsen et al.(2004), seven of 19 situations were reported to involve valgus and external knee rotation, whereas Ebstrup and Bojsen-Moller (2000) reported this joint motion patters to be "typical" in their 15 videos.

Ebstrup & Bojsen-Møller (2000) also suggested an additional scenario based on their findings from video analysis; a combination of varus and internal tibial rotation (Figure 4a).

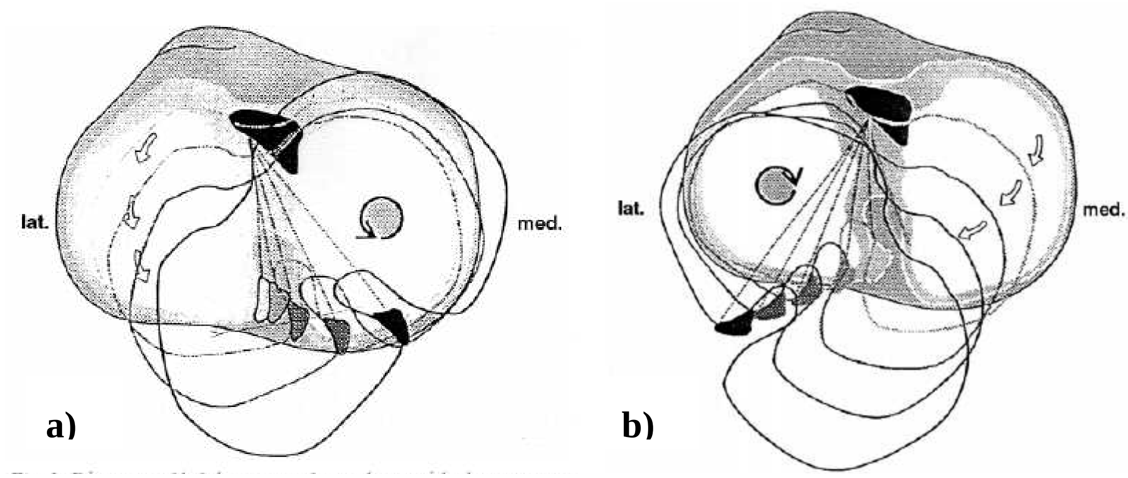

Figure 4 *a) Diagram of left knee seen from above with the contours of the femoral condyle marked in four positions of external rotation (internal tibial rotation). With varus load, the pivot is maintained in the medial joint compartment and the ACL becomes taut by the shown rotation. b) Diagram of left knee seen from above with the contours of the femoral condyle marked in four positions of internal rotation (external tibial rotation). With valgus load, the pivot is shifted to the lateral joint compartment and the ACL becomes taut by the shown rotation.*

Based on interviews of 361 patients, Arnold et al. (1979) suggested that the most frequent mechanism of ACL injury is internal tibial rotation on a relatively straight leg (also termed "twisting" or "pivoting" injury by many) (Chong & Tan, 2004; Feagin, Jr. & Curl, 1976; Gray et al., 1985; Harner et al., 1994; Nakajima et al., 1979; Wirtz, 1982) (see Figure 5). The rationale behind this hypothesis was also supported by cadaver studies showing that internal rotation generated high ACL tension (Cabaud, 1983; Markolf et al., 1995).

Based on MRI findings, and the rationale that the ACL serves as a primary restraint to anterior tibial translation and as a secondary restraint to internal rotation , Remer et al. (1992) claimed that valgus in combination with internal rotation was the most common injury mechanism in 205 patients with arthroscopic correlation. They also stated that hyperextension was the second most common mechanism of injury of the knee. According to Remer et al. (1992), the least common mechanism of injury was varus motion in combination with external rotation.

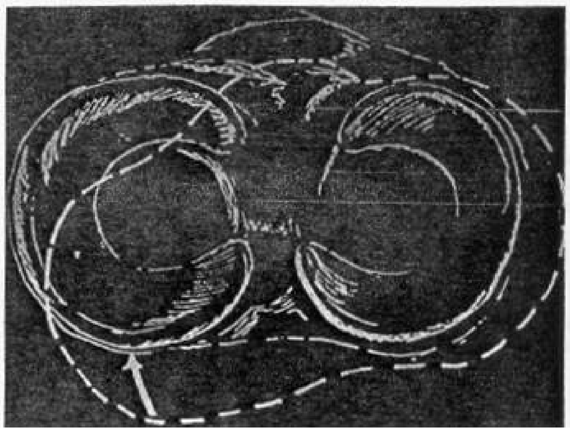

Figure 5 *From Arnold et al. (1979). A) Patient reproduction of exact mechanism of injury often disclosed the extended knee, internal rotation of the tibia on the femur, and a loud pop, and a sensation of something "giving way" in the knee. B) Anterior displacement of the lateral tibial plateau with the left knee in extension, tibia internally rotated, and subsequent forward subluxation of the tibial plateau causing frequent impingement of the posterior horn of the lateral meniscus*

The same year, Speer et al. (1992) reported bone bruise findings from MRI in 54 non-skiing patients. They found an 83% prevalence of osseous contusion directly over the lateral femur condyle terminal sulcus and posterolateral joint injury of the tibia or soft tissue, and therefore stated that valgus motion must have been a part of the injury mechanism. However, Speer et al. (1992) reported that it was not clear where the reciprocal site on the lateral tibial plateau was located. Speer et al. (1992) therefore proposed three different models to explain their findings (see Figure 6):

A) Pivot shift injury of the posterolateral tibial rim and meniscus

B) Hyperextension injury of the anterolateral tibial rim and meniscus

C) Reduction following pivot shift event of the anterolateral tibial rim and meniscus

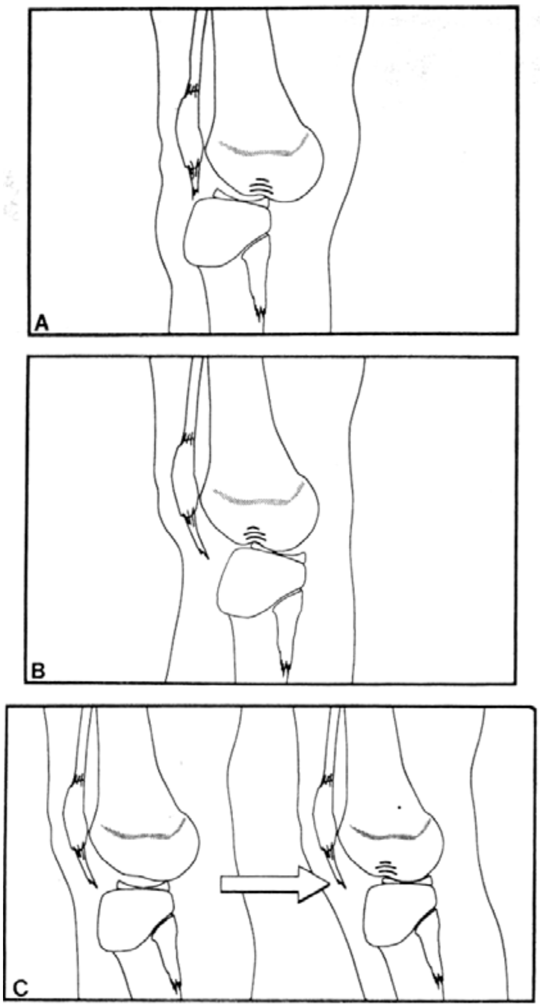

Figure 6 *From Speer et al. (1992) Possible mechanisms for terminal sulcus injury. A. pivot shift injury of the posterolateral tibial rim and meniscus. B. hyperextension injury of the anterolateral tibial rim and meniscus. C. reduction following pivot shift event of the anterolateral tibial rim and meniscus.*

Also based on MRI findings, Murphy et al. (1992) proposed anterolateral subluxation (i.e. internal rotation) as a possible injury mechanism (Figure 7). Furthermore, they hypothesized that the rotation occurs about the MCL, and stated that with additional valgus stress or axial loading, femoral and tibial bone impaction might occur.

Spindler et al. (1993) studied a patient population (N=54) consisting mainly of athletes (N=52), with football (24%), skiing (22%) and basketball (20%) as the largest sports groups. Seventy percent of the injuries did not involve contact. They agreed with Speer et al. (1992) that anterior subluxation of the tibia with impaction on the anterior aspect of the femur and the posterior aspect of the tibia was the mechanism of injury.

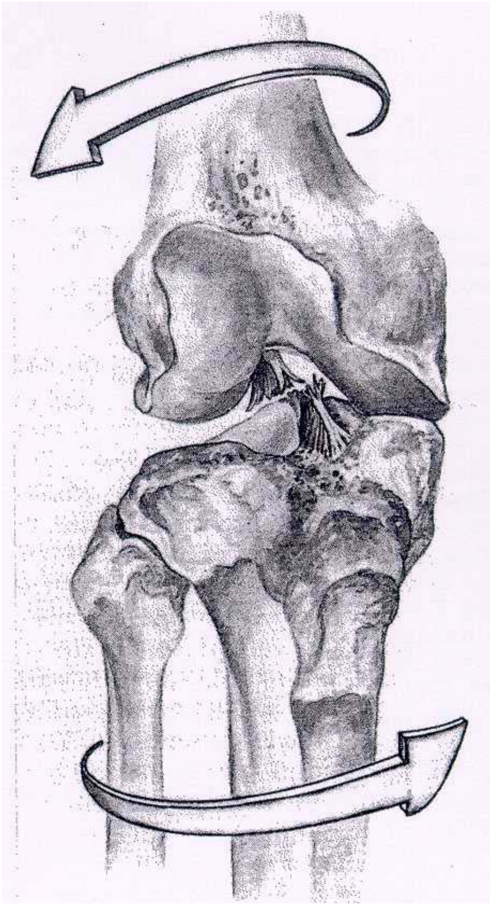

Figure 7 *From Murphy et al. (1992). Anterolateral subluxation of the knee in a complete ACL tear. The axis of rotation in this instability is the medial collateral ligament, which allows anterior subluxation of the lateral tibial plateau with respect to the lateral femoral condyle.*

Recently, there has been a debate in the scientific community on the potential scenarios for how non-contact ACL injuries in team/ball sports occur, in particular the quadriceps-induced anterior tibial drawer hypothesis (Chaudhari & Andriacchi, 2006; DeMorat et al., 2004; Kirkendall & Garrett, Jr., 2000; McLean et al., 2005a; Van Den Bogert & McLean, 2006). In this theory, the quadriceps generates forces ($F_{Q,x}$) that act as an anterior drawer on the tibia due to the patella tendon angle (α) (Figure 8). This loading mechanism was also found in several cadaver studies (Draganich & Vahey, 1990; Hirokawa et al., 1992; Renstrom et al., 1986)

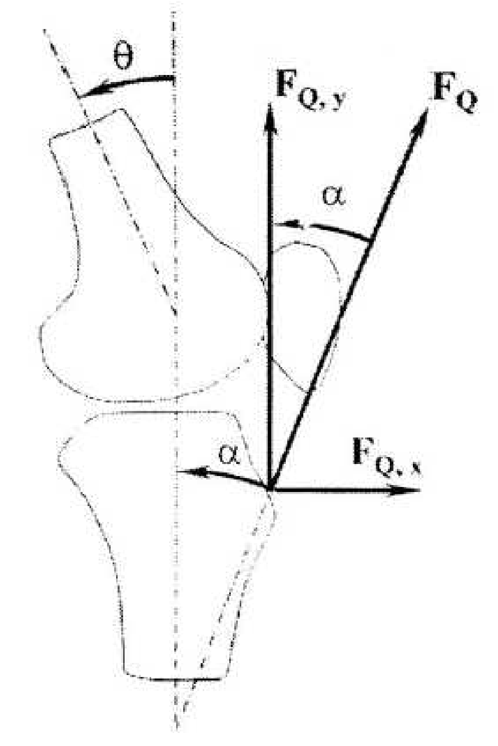

Figure 8 *From DeMorat et al. (2004) Definition of patella tendon tibial shaft angle (θ), knee flexion angle (α), and the anterior shear force vector ($F_{Q,x}$) is the total quadriceps muscle force applied to the patella tendon.*

Research approaches to describe the mechanisms of injuries

As indicated in the previous chapter, a number of different methodological approaches have been used to describe the inciting event (Krosshaug et al., 2005). These include interviews of injured athletes, analysis of video recordings of actual injuries, clinical studies (where the clinical joint damage findings are studied to understand the injury mechanism, mainly through plain radiography, MRI, arthroscopy, or CT scans), in vivo studies (measuring ligament strain or forces to understand ligament loading patterns), cadaver studies, mathematical modeling and simulation of injury situations, or measurements/estimation from "close to injury" situations. In rare cases, injuries have even occurred during biomechanical experiments (Barone et al., 1999; Zernicke et al., 1977).

Important insight can be gained from studying the events *preceding* (e.g. the velocity at impact, the playing situation), *at* (e.g. the loads) or *following* (e.g. the associated joint damage to the knee) the point of injury. In addition, we can learn from similar situations that did not lead to injury (e.g. by studying the loading patterns in a side-step cutting maneuver in the lab or in a match situation). Laboratory studies generally have better potential for accurate measurements, but it is difficult to predict to what extent the results are valid for actual injury situations. It is also necessary to expand the traditional biomechanical approach to describing the inciting event, if the objective is to prevent injuries (Bahr & Krosshaug, 2005) A complete description of the mechanisms for a particular injury type in a given sport needs to account for the events leading to the injury situation (playing situation, player and opponent behavior), as well as include a description of whole body and joint biomechanics at the time of injury (Bahr & Krosshaug, 2005)

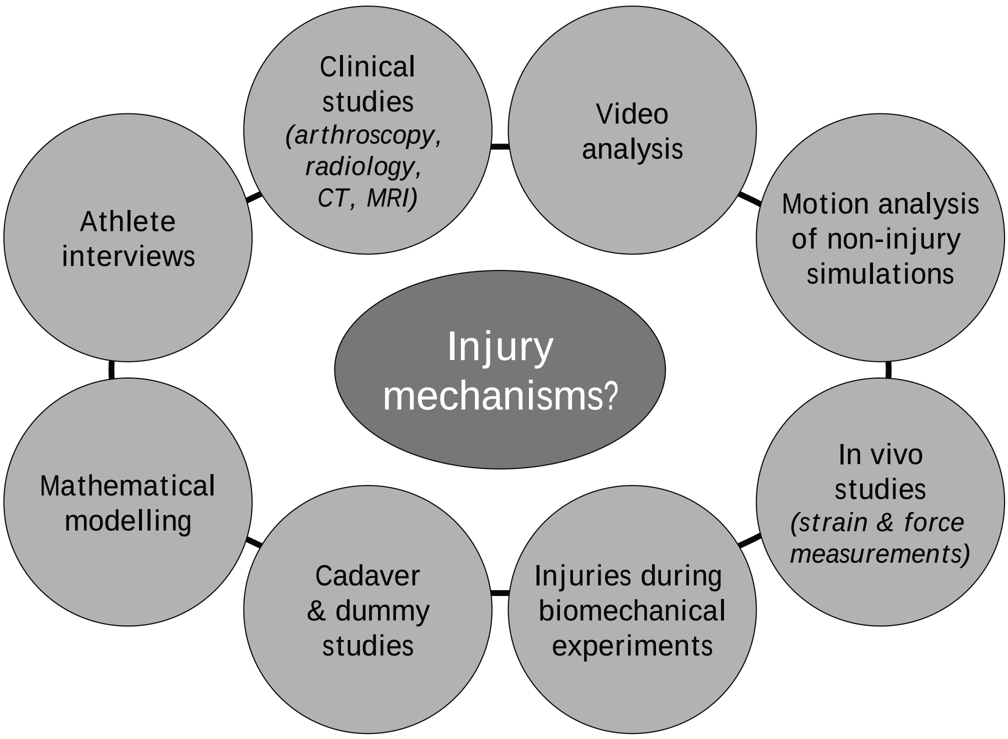

Figure 9 *Research approaches to describe the mechanisms of injuries in sports.*

No single method exists that can provide a complete description of the injury mechanisms in sport. Consider, as an example, a popular hypothesis for non-contact ACL injuries in ball/team sports – the quadriceps drawer hypothesis (Kirkendall & Garrett, Jr., 2000) According to this, the patellar tendon force acts as an anterior drawer that may rupture the ACL. This hypothesis is built on several underlying premises:

1. force is transmitted through the patella tendon as the ACL ruptures
2. the patellar tendon angle to the long axis of the tibia results in an anterior force on the tibia when the tendon is loaded
3. the patellar shear force must be larger than the ultimate ACL strength plus other forces acting as agonists with the ACL
4. the loading rate must be such that the ligament rather than bone fails (Lee & Hyman, 2002)

These premises can be studied with different approaches. For instance, through cadaver experiments (Markolf et al., 1995) and in-vivo studies (Fleming et al., 1993) we know that knee flexion must be approximately 30° or less to generate significant anterior shear forces through the patella tendon from a quadriceps contraction. Although the precision may limit the usefulness of athlete interviews or video analysis, it is possible to obtain important information regarding key factors, e.g. flexion angle estimates (Boden et al., 2000; Olsen et al., 2004; Teitz, 2001). To achieve better accuracy, laboratory studies can be utilized to measure joint angles (Decker et al., 2003; Fagenbaum & Darling, 2003; Pollard et al., 2004), muscle activation patterns (Colby et al., 2000; Cowling et al., 2003) and joint loading (Besier et al., 2003; Decker et al., 2003; McLean et al., 2004b; Pollard et al., 2004; Salci et al., 2004). However, since it is not known how well such experiments correspond to the actual injury situations, at what point an injury would occur, or even how ACL loading relates to the estimated net joint kinetics, the external validity of evidence from such studies can be questioned. Cadaver studies, on the other hand, can study directly how the ACL is influenced by the quadriceps force, as demonstrated by e.g. DeMorat et al. (2004) However, the relevance of this approach to study the actual non-contact ACL injuries was questioned, since a mathematical modeling approach showed that the experimental set-up did not replicate the dynamics involved in a sporting situation (McLean et al., 2004a). Mathematical models can potentially test all the implicated premises. But, again their relevance can be questioned, since such methods rest on data obtained in the laboratory as input for the simulations. If this is the case, the simulations may also be substantially different from what is actually occurring in a real injury situation. Mathematical models must also be extensively validated before their results are of value, which can be done using one or more of the approaches: cadaver studies, motion analysis studies or in-vivo studies.

This example is used to illustrate why, in many cases, it may be necessary to combine different approaches to provide results that are both valid and accurate. Combining evidence from separate studies using different approaches is valuable, but differences in the experimental set-up or study design may prevent the findings from one study to be compared to the other.

The video analysis approach

With the exception of rare accidents during biomechanical research experiments, the only approach that has the potential to record the kinematics of a real injury situation is analysis of injury videos. Estimates of kinematics from real injury situations are essential for several reasons: In addition to the information obtained directly from such studies, estimates of joint kinematics from actual injury situations are necessary for studies using other approaches to simulate injury situations (cadaver studies, mathematical simulation studies, motion analysis studies, in-vivo ACL force/strain studies, etc.). Such simulations must display similar kinematics as seen in real injury situations in order to be valid. Otherwise, false solutions may be the result, or at least solutions that are not commonly seen. Secondly, video analysis can reveal important aspects of the inciting event, not only the biomechanics, but also related to the playing situation and player/opponent behavior. This information can possibly be used to design improved preventive strategies. Video analysis has therefore been utilized within different sports for different injury types. For example, Andersen et al. (Andersen et al., 2003; Andersen et al., 2004a; Andersen et al., 2004b) have adapted the analytical methods used to describe football performance to analyze ankle and head injury situations from match videos, with the main focus on playing situation and player/opponent behavior. Ettlinger et al. (1995) used kinematic information collected from videotapes of recreational skiers and described the "phantom foot" injury mechanism as the typical movement pattern resulting in injury. McIntosh et al. (2000) used video analysis to quantify the head impact velocity in Australian Rules Football. However, these studies have not attempted to quantify joint kinematics. For ACL injury situations, research is so far limited to four studies (Table 1).

Table 1 Studies reporting injury mechanism data from video analysis.

Reference	Total (N)	Non-contact analyzed (N)	Methods
Boden et al., 2000	27 (23)	15	Videos obtained from professional and collegiate teams - football (56%), basketball (30%), soccer (9%) and volleyball (4%). Seven females and 16 males.
Ebstrup et al., 2000	15	3	Prospective collection of videos from Danish indoor ball games. Two representative handball injuries and one basketball injury were analyzed. All females.
Teitz, 2001	54	14	Retrospective multi center video analysis - 20 basketball, 18 football and 9 soccer injuries. Only basketball injuries were analyzed. Three males and 11 females.
Olsen et al., 2004	20	19	Retrospective and prospective video collection. Women's Norwegian or international handball competition.

All the studies listed in Table 1 were based on simple visual inspection, where the joint configuration and other kinematic variables were estimated simply from watching videotapes of ACL ruptures, without employing any measurement tools. Unfortunately, this method cannot produce continuous estimates of joint angles and positions, which are necessary for detailed biomechanical analyses of the injury mechanisms, e.g. joint angle time histories, velocities and accelerations. Furthermore, it is inherently difficult to interpret segment attitudes and, based on this, to calculate joint angles in three planes simply through visual inspection. However, other options may exist. A few methods for markerless three-dimensional reconstruction from video sequences have been described in the biomechanical literature (Halvorsen, 2002; Trewartha et al., 2001) However, due to their use of edge or color tracking, these methods are only applicable under special conditions. Literature from the field of computer vision reveals that to track and reconstruct three-dimensional motion from video sequences with one or more camera views, several approaches are possible. However, these have limitations related to the movement (no camera motion, only one person in camera view at a time, subject facing camera at all times, movement parallel to camera plane, no occlusion, slow continuous movements, moving on flat ground, etc.), the appearance of the environment (constant light, static/uniform background, known camera parameters, etc.), or the appearance of the subject (known starting pose, known subject, markers, special clothing, etc.) (Gavrila, 1999; Moeslund & Granum, 2001) Also, in most cases, the ability to automate tracking and three-dimensional reconstruction is considered more important than optimal accuracy. For these reasons, none of the methods published so far seem to be suited for use in more demanding conditions with uncalibrated video sequences from one or more cameras that may simultaneously be rotating, translating and zooming. In addition, since motion patterns often are complex and the color and contrast properties of the person of interest can blend with the background, new approaches must be sought. The purpose of Paper I was therefore to develop and validate a new model-based image-matching technique for three-dimensional reconstruction of human motion from uncalibrated video sequences.

The next logical step was to assess the feasibility of the method when using real injury video sequences as input. For obvious ethical reasons, laboratory measurements of injury situations cannot be done. Comparing motion estimates to lab trials may even have limited value, since injury situations most likely differ from non-injury situations. The purpose of Paper II was to investigate if this technique could successfully be applied to estimate kinematic characteristics of ACL injury situations from video tapes typical for basketball, downhill skiing and European team handball.

The video analysis studies on non-contact injuries in ball/team sports agree that the knee is relatively straight at the assumed point of injury. However, in contrast to questionnaires from the athletes, none of the videotaped injuries revealed sharp pivoting motion around a planted leg, varus collapse or hyperextension (Boden et al., 2000). This finding agrees with the results of

Olsen et al. (2004). In contrast, Ebstrup & Bojsen-Møller (2000), reported varus/internal knee rotation as a typical injury situation.

Unfortunately, the variables reported in these studies are non-standardized, making it somewhat difficult to compare. For example, only Olsen et al. (2004) attempted to quantify knee joint kinematics, although they failed to report hip joint motion. Many believe this to play a major role in the non-contact ACL injuries (McClay Davis & Ireland, 2001). The remaining studies described different aspects of "typical situations" without quantifying joint motion. Nevertheless, all the studies agreed that knee valgus was frequently seen. Boden et al. (2000) stated that the amount of internal/external rotation at the time of rupture was minimal. This agrees well with the findings of Olsen et al. (2004), where the amount of internal/external knee rotation was estimated to be 10° or less in 90% of the cases. Two of the studies stated that most of the injuries occurred in high-speed situations. This implies that the forces involved were relatively high. This is also further emphasized by the estimated weight distribution in the study of Olsen et al. (2004), where all except one injured athlete had at least 80% of the weight distribution on the injured leg.

Even though the findings in all these studies were similar (i.e. the injury typically occurred early after initial contact (IC) in landings or cutting maneuvers with the knee near full extension and often resulted in a "valgus collapse"), the interpretation of the findings varied considerably. Olsen et al. (2004) stated that valgus loading in combination with external or internal knee rotation caused the injury, and proposed notch impingement as a plausible cause of the excessive ACL loading. Boden et al. (2000), on the other hand, hypothesizes that a vigorous, eccentric quadriceps contraction is the main cause. Teitz (2001) proposed the center of gravity being posterior to the knee when running across the basketball floor may trigger the rectus femoris to fire, thereby creating a quadriceps drawer.

Apart from the study of Olsen et al. (2004) on injured team handball players, previous video analyses have only investigated a limited number of cases from mixed sports. A large sample may provide an opportunity to group injury mechanisms in different categories. Furthermore, the accuracy in kinematical estimates based on ordinary TV recordings, where temporal and spatial resolution is limited, can not be expected to be optimal. It is therefore necessary to study a large sample to improve the precision of the estimates, provided that the mechanisms are consistent. We had therefore collected 39 videos of ACL injury situations in basketball. However, the model-based image-matching technique was found to be too time-consuming to apply on a large number of injury videotapes. Simple visual assessment of joint kinematics was therefore considered as an alternative. Hence, the purpose of Paper IV was to describe the mechanisms of

ACL injury in basketball in terms of the playing situation, player behavior and joint kinematics based on 39 videotapes of real injury situations, using the visual assessment approach.

However, the accuracy and precision of such analyses were unknown. Olsen et al. (2004) performed interobserver tests in their study, showing that the reliability was relatively good, i.e. the average difference between the analysts was 10° or less for all knee joint angle estimates. Nevertheless, this finding does not guarantee the accuracy. For example, the analysts may have over- or underestimated joint angles systematically. The purpose of Paper III was therefore to test the accuracy and precision of researchers to estimate kinematics from video sequences of situations resembling those typically leading to ACL injuries. We also tested if accuracy and precision could be improved by a training program.

Aims of the thesis

The aims of the thesis were:

1. To develop and validate a new model-based image-matching technique for three-dimensional reconstruction of human motion from uncalibrated video sequences. (Paper I).

2. To investigate the application of this technique to estimate kinematic characteristics of three typical ACL injury situations from basketball, downhill skiing and European team handball (Paper II).

3. To test the accuracy and precision of kinematic estimates from video sequences of situations resembling those typically leading to ACL injuries, using simple visual inspection (Paper III).

4. To describe the mechanisms of ACL injury in basketball in terms of the playing situation, player behavior and joint kinematics based on videotapes of real injury situations (Paper IV).

Methods

The model-based image-matching technique

In Paper I, a new model-based image-matching technique was developed. This method was based on the commercially available three-dimensional modeling software Poser® 4 and the Poser® Pro Pack (Curious Labs, Inc., Santa Cruz, California, USA). This software package features several pre-built models as well as background video import, split camera view (up to four views), camera models containing six translational and rotational degrees of freedom, as well as variable focal length. A skeleton model within Poser (Zygote Media Group Inc., Provo, Utah, USA) was used in the first stage of the matching. This model was customized to match the anthropometry of the person in the video.

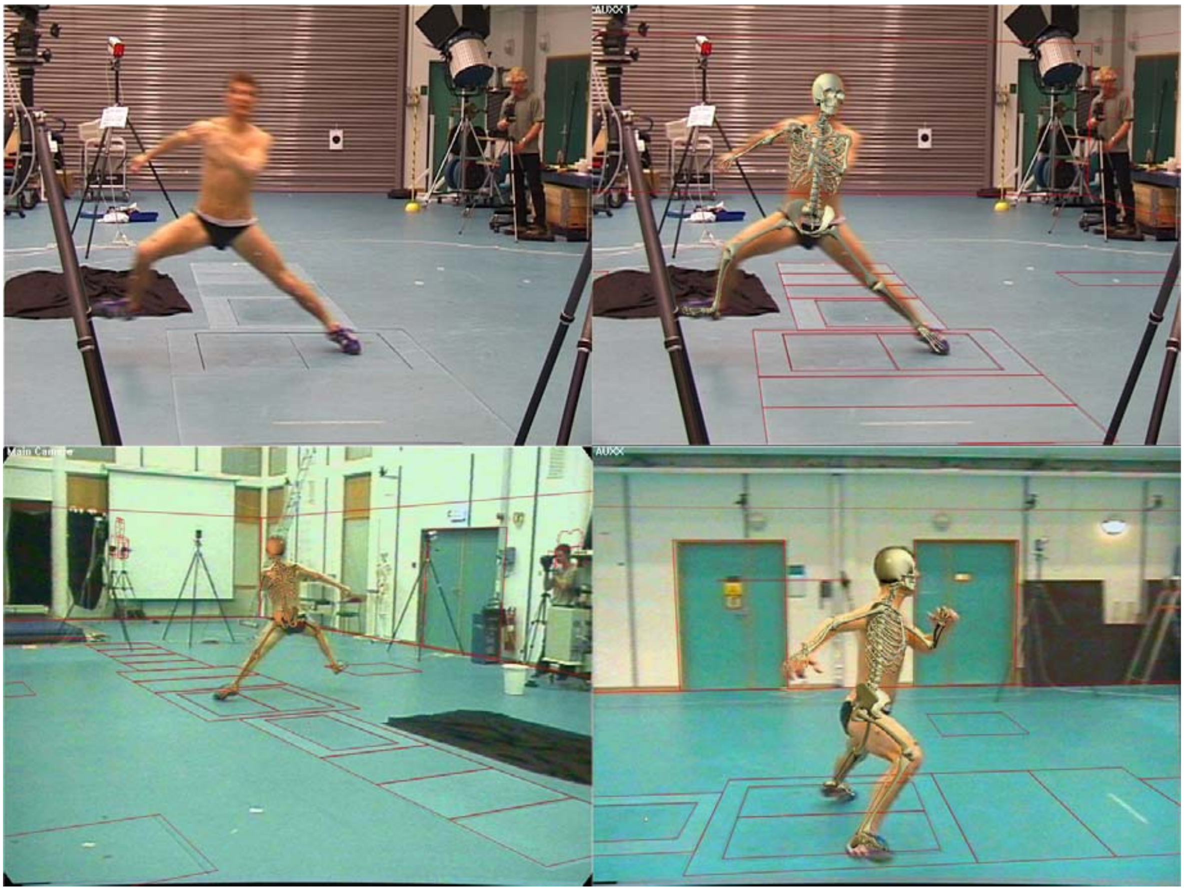

Figure 10 *Triple camera matching at toe-off. The top left panel (a) shows the original video image from the front camera. In the top right panel (b) the customized skeleton model and the laboratory model is super-imposed and matched with the same video image. In the lower left (c) and lower right (d) panels, the model is matched in the rear and side view, respectively. The Poser cameras can be seen as wire-frame models in the top right panel (one camera) and in the bottom left panel (two cameras).*

The model, as we used it, had 21 segments (fore foot, rear foot, lower leg, thigh, pelvis, abdomen, chest, neck, head, collar, upper arm, forearm and hand) and 57 degrees of freedom. All joints had three rotational degrees of freedom, except for the sternoclavicular, elbow and wrist joints that had two. In addition, there were three translational degrees of freedom for the pelvis.

The videos were de-interlaced to obtain an effective frame rate of 50 Hz. Then we corrected for lens distortions by using the Andromeda LensDoc filter (version 1.1, Andromedia Software, Thousand Oaks, California, USA). In the cases where we used more than one camera recording, a manual synchronization was performed, by determining the time for initial contact of the left foot in each camera view.

We then manually matched the surroundings and the skeleton model to the background video footage (Figure 10). The frame-by-frame matching of the surroundings enabled us to reconstruct camera motion for video footages shot from translating, rotating and zooming cameras. We started out with key frames, and used the cubic spline interpolation feature in Poser for the intermediate frames. The skeleton matching started with the pelvis segment. We then worked distally by matching the thighs, then the lower legs, and so on. When the skeleton matching was completed, we replaced it with the "nude man" model in Poser. This way we could use the surface anatomy to better determine the rotation around the longitudinal axis of each segment. When it was not possible to reliably determine the shank orientation, we simply distributed the rotation evenly between the knee and ankle joints.

Validation of the model-based image-matching technique

One test subject, a 25 yr old team handball player, performed trials of jogging and side step cutting maneuvers. We recorded the trials with three ordinary cameras, two S-VHS (Blaupunkt CC695, Hildesheim, Germany) and one miniDV camera (Sony TRV900E, Tokyo, Japan) (Figure 11). A total of seven matchings were performed for each of the two recorded motions. Independently, two clinicians gave their opinion on the goodness of the fit twice during the process, to minimize bias resulting from single-operator judgment. The matchings were then adjusted accordingly until finally an accepted motion pattern was found. When a sequence was satisfactory, the translation and joint angle time histories were read into Matlab with a customized script for further processing.

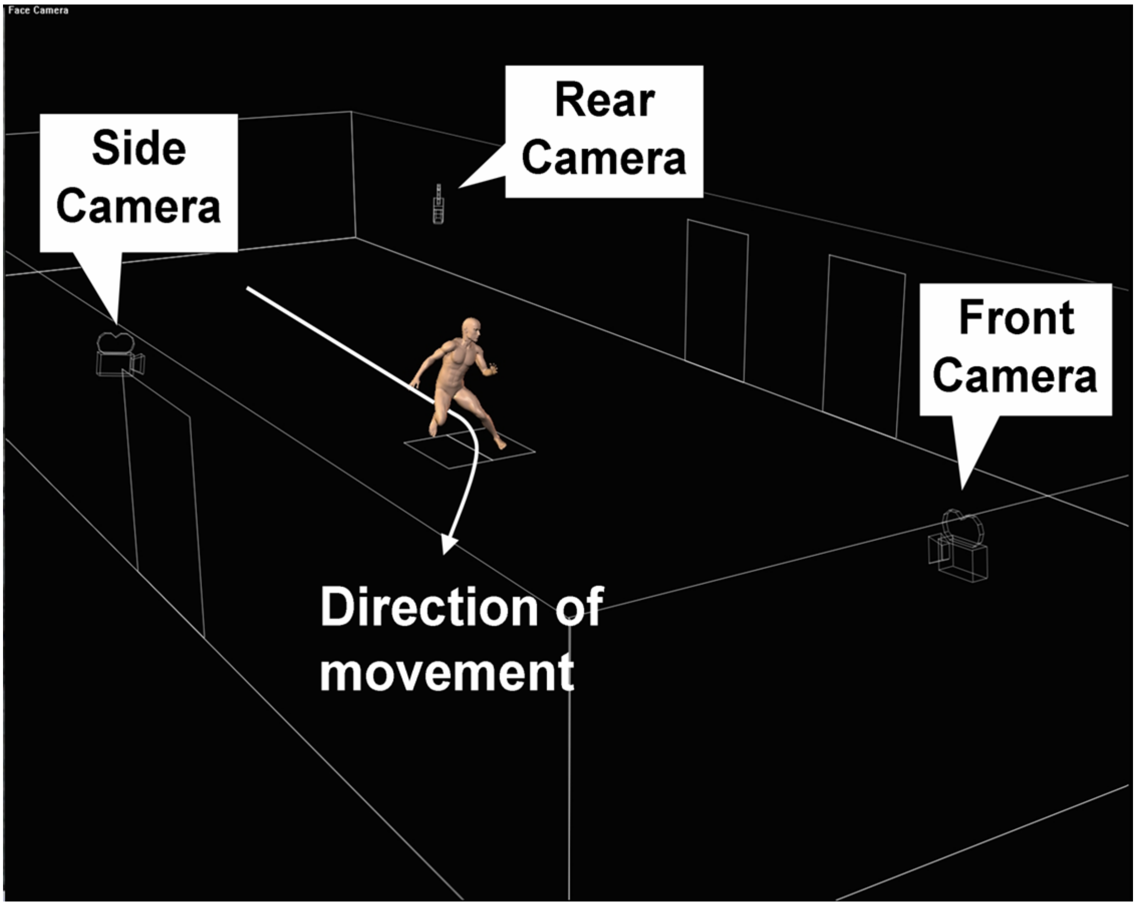

Figure 11 *Overview of the video camera placement in relation to the test subject.*

In addition to the three ordinary video camcorders, a seven-camera infrared, motion analysis system (ProReflex, Qualisys Inc., Gothenburg, Sweden.), and two force platforms (AMTI LG6-4-1, Watertown, MA 02472, USA) simultaneously recorded the motion at 240 and 960 Hz, respectively. Thirty-three reflective markers allowed for a three-dimensional description of the lower extremities, trunk and upper arm. The head was simply assumed to be rigidly connected to the trunk. The elbow joint was modeled with one degree of freedom, and the hand was assumed to be rigidly connected with the forearm. The method of Söderquist & Wedin (1993) was utilized to obtain the segment embedded reference frame for the thigh and shank. A static calibration recording of the athlete in the anatomical position was performed to determine the anatomical axes of the three-dimensional modeled segments in the lower extremity.

To allow direct comparisons between the ProReflex measurements and the estimates from the Poser model, the local axes of the segments were defined so that the vertical axes of the thigh and shank (X3) pass through the joint centers. The antero-posterior axis (X1) of the local axis system was defined perpendicular to the X3 axis with no medio-lateral component. The third axis was the right hand side cross product of the vertical and antero-posterior axis (X2 = X3 x X1).

The joint centers of the ankle and knee were determined by the method of Davis *et al.* (1991) but the ankle joint center location was defined 1 cm distal to the lateral malleolus, as proposed by Eng & Winter (1995). The hip joint centers were estimated by the method of Bell *et al.* (1990). The shoulder centers were determined by the method of de Leva (1996). The elbow centers were located midway between the lateral and medial epicondyles. To estimate the inertia parameters, we used a modified version of Yeadon's stadium solid method (Yeadon, 1990). For both the Poser model's center of mass (COM) translation and the marker trajectories, smoothing and interpolation were performed by the generalized cross validation package of Woltring (1986) using a 12 Hz cut-off frequency for the marker trajectories and a 7Hz cut-off for the Poser model's COM translation. The joint angles were calculated using the helical angular convention of Woltring (1994).

Matching of three ACL injury videos

In Paper II, three non-contact ACL injuries in basketball, handball and downhill skiing were analyzed, using the model-based image-matching technique. The basketball video showed a situation where a male player suffered an ACL injury to the right knee in a one-leg landing, filmed with 4 cameras (Figure 12).

In this matching, based on four ordinary 60 Hz (deinterlaced) video sequences, we found that two of the camera views were shifted in time by approximately 1/120 s compared to the two other camera views. We therefore generated artificial images between frames in order to achieve a full set of images at each time step, resulting in an effective frame rate of 120Hz for all four camera views using the software Morpheus (version 1.85, Morpheus Software, LLC, USA). The dimensions of the basketball court, as well as the basket and backboard, were modeled based on NBA standards. No anthropometrical measurements were available, except for the subject's height and body mass. The segment dimensions were therefore iteratively adjusted during the matching process until finally, a fixed set of scaling parameters was determined. The COM for the segments was then determined by the method of de Leva (1996) Because the shank axial rotation was difficult to assess precisely, we distributed the rotation evenly between the ankle and knee joint, using foot orientation as guidance.

Figure 12 *Matching of the four-camera basketball injury situation 50 ms after initial ground contact. The four panels show the customized skeleton model and the basketball court model superimposed on and matched with the background video image from cameras 1 through 4. One Poser phantom camera (camera 1) can be seen as a wire-frame model in the bottom left panel as an exact fit.*

The team handball video showed an ACL injury to the right knee in a female player during a one-leg cutting movement from right to left, filmed with 3 cameras (Figure 13).

Measurements of the line markings on the handball court and goal posts were used for calibration when modeling the surroundings. Anthropometrical measurements were obtained from the athlete, and body segment parameters were calculated, using a modified version (Paper I) of Yeadon's inertia model (Yeadon, 1990). In addition to the modifications described in Paper I, the chest was separated into one extra solid to fit the female anatomy better. The skeleton model segment dimensions were set based on these measurements. Again, the axial rotation was evenly distributed between the ankle and knee joint.

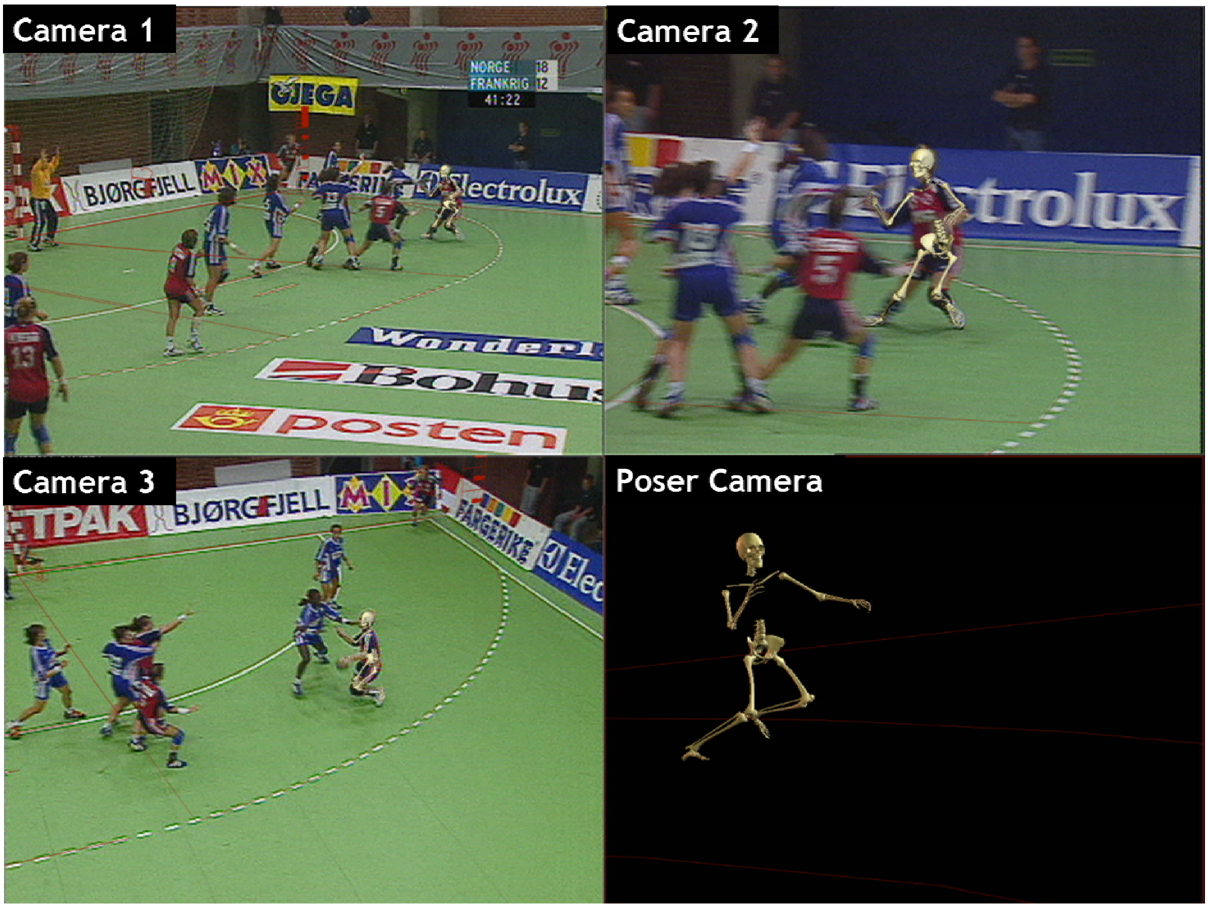

Figure 13 *Matching of the three-camera team handball injury situation 140 ms after initial ground contact. Three panels show the customized skeleton model and the handball court model superimposed on and matched with the background video image from cameras 1 through 3. The bottom right panel shows the skeleton model from an alternative view created in Poser.*

The alpine skiing video showed a downhill skier suffering an ACL injury to the left knee filmed from one camera view only (Figure 14).

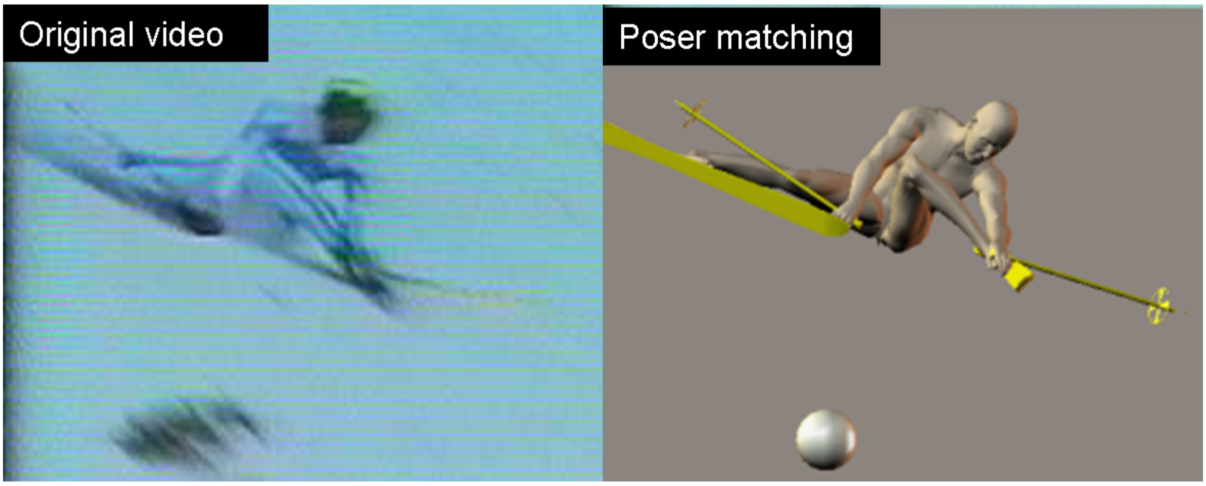

Figure 14 *Example of matching of the single-camera alpine skiing injury situation. The left panel shows the skier in the original video sequence. The right panel shows the resulting matching visualized with a nude model.*

The skis were assumed to be rigidly connected to the feet. The ski suit had markings that were used to assess body configuration. However, as can be seen in Figure 14, it was difficult to assess thigh rotation. Only a few surrounding landmarks were visible, and since the coordinates for these landmarks were not known, it was not possible to determine position and velocity reliably. Anthropometrical measurements were obtained from the injured athlete, and body segment parameters were calculated, using a modified version (Paper I) of Yeadon's inertia model (Yeadon, 1990), and the skeleton model segment dimensions were set accordingly.

Validation of the visual inspection technique

The video analysis

In Paper III, six international experts were asked to analyze 27 video sequences of running and side step cutting maneuvers performed in the laboratory. Three test subjects, 25, 23 and 22 yrs old, performed trials of running and side step cutting maneuvers in the laboratory. We recorded the trials with three ordinary video cameras placed on tripods or fixed to the wall, similar to the set-up described in Paper I (Figure 11). The 27 video sequences were generated from 12 different laboratory trials of test subjects 1 and 2, where different cameras views were systematically combined: front only, side only, rear only, front/side, front/rear, side/rear, and front/side/rear. We also systematically changed the test subject and cutting direction. In each video, a key frame was marked at pre-defined time points, either initial contact (IC), 100 ms after IC or 200 ms after IC. The time point was also systematically changed between each of the cases. The videos were composed in two versions, one in real time and one in de-interlaced slow motion that could easily be played back and forth frame-by-frame using the keyboard arrows. Each of the analysts did the analysis independently blinded to the results of the other analysts. The analysts were asked to provide estimates for the pre-defined frames marked in each of the videos by assessing knee flexion/extension, knee varus/valgus, knee internal/external rotation, hip flexion/extension, hip adduction/abduction, hip internal/external rotation, approach velocity, vertical velocity, cutting angle, and internal/external rotation of the foot relative to the pelvis using a standard form. In addition, they were asked to assess the direction of motion for the knee and hip joint angles at the pre-defined time points (e.g. whether the knee joint was neutral or moving towards flexion or extension).

The marker based motion analysis

As the gold standard, we again used a seven-camera infra-red, motion analysis system (ProReflex, Qualisys Inc., Gothenburg, Sweden.), and two force platforms (AMTI LG6-4-1, Watertown, MA, USA) were used simultaneously to record the motion at 240 and 960 Hz, respectively. We used the same methods as in Paper I, with exception from the joint angle calculations, where we used the Grood & Suntay (1983) convention. We also calculated the frontal plane projected valgus angle ("2D valgus"), as described by McLean et al. (2005c). 2D valgus was calculated as the angle between the hip-knee and knee-ankle vectors projected in the pelvic frontal plane. Foot-pelvis rotation was calculated as the angle between the foot antero-posterior axis and the pelvis antero-posterior axis, projected into the global transverse plane (the floor).

To determine the tendency of joint movement we chose an 80 ms period, corresponding to two video frames prior to and two frames after each of the pre-defined time points in the videos (see below).

Training session and post-training assessment

Thirty-five videos from 5 cases were produced for the training session, systematically varying different camera view combinations, test subjects and cutting directions in the same way as for the test videos. The training session started by first using the single camera videos, then multiple camera view composites were analyzed. All three time points were analyzed and the correct answers (i.e. the results from marker-based motion analysis) were provided at regular intervals with group discussions. After the training session had been completed, the analysts reanalyzed the same 27 cases as described previously to establish whether the training had any effect on accuracy.

Data reporting and statistical methods

For Paper I and II, the original pelvis translation and joint angle time histories were read into Matlab® with a customized script for further processing.

In Paper I, we reported joint angles, and COM velocity and acceleration. To evaluate the error originating from each of the matched segments, we also calculated the segment orientation, expressed in helical angles relative to the global system. The estimated velocities from the matchings were compared with the velocities derived from the skin marker measurements. The accelerations were compared with those derived from the force plate measurements. The results are presented as the root mean square (RMS) and maximal differences.

In Paper II, we reported joint angles and COM velocity and acceleration, in addition to the qualitative visual assessment of the quality of the matching.

In Paper III and IV, the analysts' forms were entered into a custom-made database using Microsoft Access (version 2003, Microsoft Corporation, Redmond, WA, USA). Descriptive statistics were calculated using SPSS (version 13, SPSS Inc., Chicago, IL, USA).

In Paper III, we calculated the difference between each of the analysts' estimates and the marker-based measurements as the gold standard for each variable in the pre-test. The accuracy of the estimates was reported as the mean difference from the gold standard. The precision of the estimates was reported as the standard deviation (SD) between the analysts, averaged over cases, of this difference (with range). A paired t-test was used to see if the training led to significant improvements in the means (accuracy) and standard deviations (precision) for the differences between the estimates and the gold standard. Furthermore, we reported the mean difference between the pre- and post-test with 95% confidence intervals (95% CI). Using generalized estimating equation, we tested whether the following factors had a significant influence on the observed mean differences from the gold standard: The true angle/velocity, time point (IC, 100 ms, 200 ms), number of cameras (single or multiple), inclusion of a side camera (yes, no), inclusion of a front camera (yes, no), analyzed leg on same side as the side camera (yes, no), movement type (jogging, cutting), and subject (1, 2). The analyses were done with the software package STATA8 (StataCorp LP, Natrick, Texas, USA), using an unstructured correlation matrix. For the categorical variables (joint motion), a kappa-test was used to compare the agreement between the estimates and the gold standard. The strength of agreement can be classified as follows: poor (value: <.20), fair (.21-.40), moderate (.41-.60), good (.61-.80), and very good (.81-1.00) (Altman, 1991).

In Paper IV, we calculated the mean value between analysts for each case, for all the continuous variables, except time of injury. For the time of injury, we used the median instead of the mean, since one analyst in several cases estimated the injury to occur much later than the rest of the group. Results are reported as the means with standard deviations (SD) and ranges across cases. Finally, the SD across analysts were reported as a measure of inter-tester reliability for each variable. To obtain a consensus on each of the categorical variables, at least three of the analysts had to agree on the category. If less than three analysts agreed on a category, or if the analysts' opinion were split in two groups of three, the decision was "no consensus". We used an independent samples t-test to see if there were differences between genders. An independent samples t-test was also used to see if there were differences in vertical speed between cutting maneuvers and landings. Pearson's chi-square test was used to test if there was a difference in relative risk for sustaining a valgus collapse between genders.

For all analyses, an alpha level of <0.05 was used to denote statistical significance.

Results and discussion

Laboratory validation of the model-based image matching method

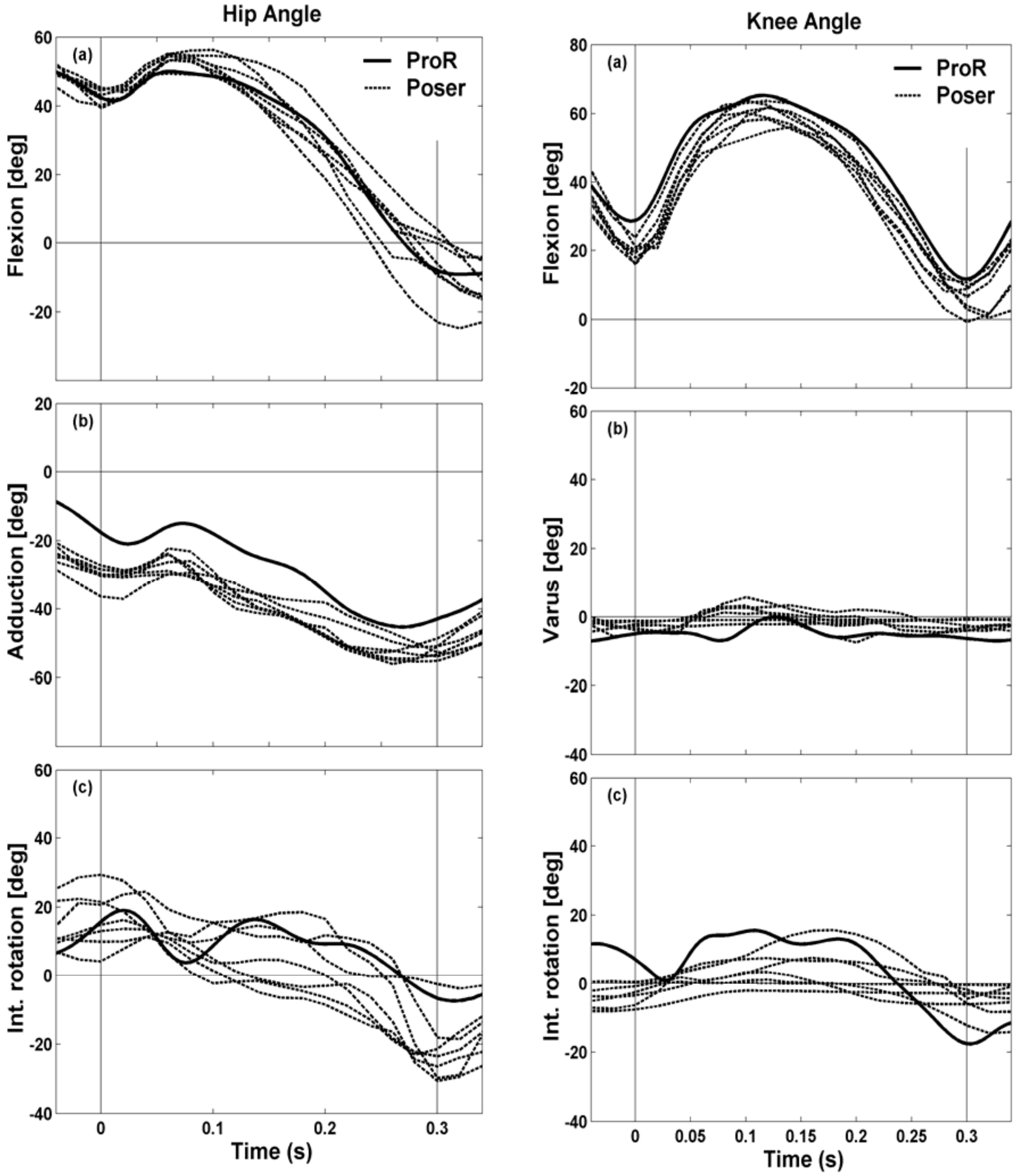

Figure 15 *Hip and knee joint angles (°) of the support leg, calculated with the Pro Reflex system (solid lines) and the model-matching technique for each of the seven side-step cutting matchings (dotted lines). The vertical lines indicate initial ground contact of the support leg and toe-off.*

We found that three-dimensional motion could be successfully reconstructed with the new method, providing kinematic estimates which until now have not been available from uncalibrated videos. We did not find any substantial differences between the quality of matchings between the complex cutting motion and the more simple jogging motion. The joint angles for the cutting motion agreed well for flexion/extension for all the matchings (Figure 15), although the ProReflex knee flexion was higher than in all the model-based estimates. Hip ab-/adduction was shifted approximately 15° for all the matchings, but the patterns were similar. Internal/external rotation clearly varied most, but due to the skin motion artifacts present in our golden standard (as observed from video tapes) it is difficult to tell how accurate our gold standard was for the transverse plane rotation measurements.

Analyses of the individual segments showed that error in the hip joint angles mainly originated from the pelvis matching (Figure 16). This is not surprising, since the shape of the pelvis makes interpretation of its attitude difficult. The matching of the shank was, on the other hand, very good, which implies the knee joint center will probably be estimated more accurately than the hip joint center.

Figure 16 *Example comparing the ProReflex-generated skeleton motion (left) and the triple camera model-matching skeleton (right). Note how the pelvis rotation differs.*

The best COM velocity estimates were obtained with the side/front and rear/side/front cameras (Table 2). This is probably due to the fact that the nearly perpendicular positions provided complimentary information, as well as the relatively higher resolution of the test subject in the front and side views.

Table 2 Root mean square and maximal difference in velocity (m/s) for the center of mass between the Pro Reflex recordings and the estimates from our model-based matching-technique for each of the seven matchings of the plant and cut motion. The maximal differences are shown in parentheses.

Camera views	Antero-posterior velocity (m/s)	Medio-lateral velocity (m/s)	Vertical velocity (m/s)
Rear	0.38 (0.70)	0.34 (0.69)	0.10 (0.22)
Side	0.17 (0.39)	0.62 (1.06)	0.19 (0.44)
Front	0.31 (0.78)	0.15 (0.26)	0.14 (0.33)
Rear/side	0.10 (0.18)	0.19 (0.32)	0.13 (0.36)
Rear/front	0.31 (0.78)	0.12 (0.22)	0.15 (0.33)
Side/front	0.11 (0.28)	0.10 (0.22)	0.14 (0.36)
Rear/side/front	0.09 (0.19)	0.11 (0.22)	0.13 (0.39)

Although the acceleration estimate from the triple camera matching was reasonably good, we were not able to capture the high frequency dynamics of the impact. We found, by down-sampling the original Pro Reflex recording from 240 to 50 Hz, that the acceleration error increased considerably, resulting in an estimate very similar to what was produced with the model-matching technique.

The ability to incorporate one, two or even more cameras for the motion reconstruction makes the proposed method versatile. In addition, the ability to reconstruct camera motion parameters (rotation, translation, and focal length) for every frame makes it possible to handle most videos from television broadcasts or amateur film. A drawback is that the technique involves manual frame-by-frame matching by the operator, which means that the method is time-consuming, and possibly biased by the operator's subjective judgment. The advantage, on the other hand, is that manual assessment allows us simultaneously to utilize edge, surface, color, contrast, segment shape, texture and size as well as point landmark properties, to provide optimal motion estimates without the need to implement these complex criteria mathematically.

We concluded that the model-based image-matching procedure is adequate for some research purposes, e.g. to describe body velocity and knee angle patterns in situations where traditional motion analysis is not possible, provided that at least two camera views are present, and that the video quality is good. However, joint translations and high-frequent acceleration peaks can not be estimated realistically. The limitation is the video frame rate and resolution standards.

Application to ACL injury videos

The matching of the skeleton to the video image of the athlete appeared to be excellent for the basketball and handball situations, achieving a good fit with the skeleton model joints in all frames. Even so, it is likely that axial rotations of the thigh and shank were less accurate than hip and knee flexion and abduction angles, since matching rotational orientation is more difficult due to the shape of the segments, lack of visible landmarks as well as skin motion that occurs relative to the underlying bones. The athlete's clothing further limited our ability to precisely assess pelvis and thigh orientation.

Of the three injury situations studied, the basketball video sequences represent the best input that can be expected from real injury situations, with one front, two side and one rear view and excellent picture quality. The mix of overview and close-up views was beneficial for the camera calibration and thereby positioning of the athlete in space, as well as for assessing axial rotations. An indication that the positioning estimates are reasonably good is that the calculated ground reaction forces are close to zero in all directions prior to initial ground contact (Figure 17).

For the skiing video, snow spray and relatively poorer video quality made it more difficult to interpret the segment poses for individual frames. However, after several iterations assessing the skier in different views, a satisfactory result was produced, which was consistent throughout the matching.

When examining the time course for knee joint angles in the basketball and team handball cases, the valgus angle increased abruptly, going from 4° to 15° within 30 ms and from 3° to 16° within 40 ms, respectively. These results indicate that valgus loading on a relatively straight leg (from about 15° to 40°) may be a key causative factor. This interpretation supports previous theories from video studies, and also agrees with recent findings by Hewett et al. (2005), who showed that female athletes who tended to land with increased dynamic valgus and high abduction loads are at increased risk of ACL injuries. However, analyses of a larger sample of cases and comparisons of injury vs. non-injury situations are necessary to evaluate if this is indeed a general trend or merely a result of estimate errors.

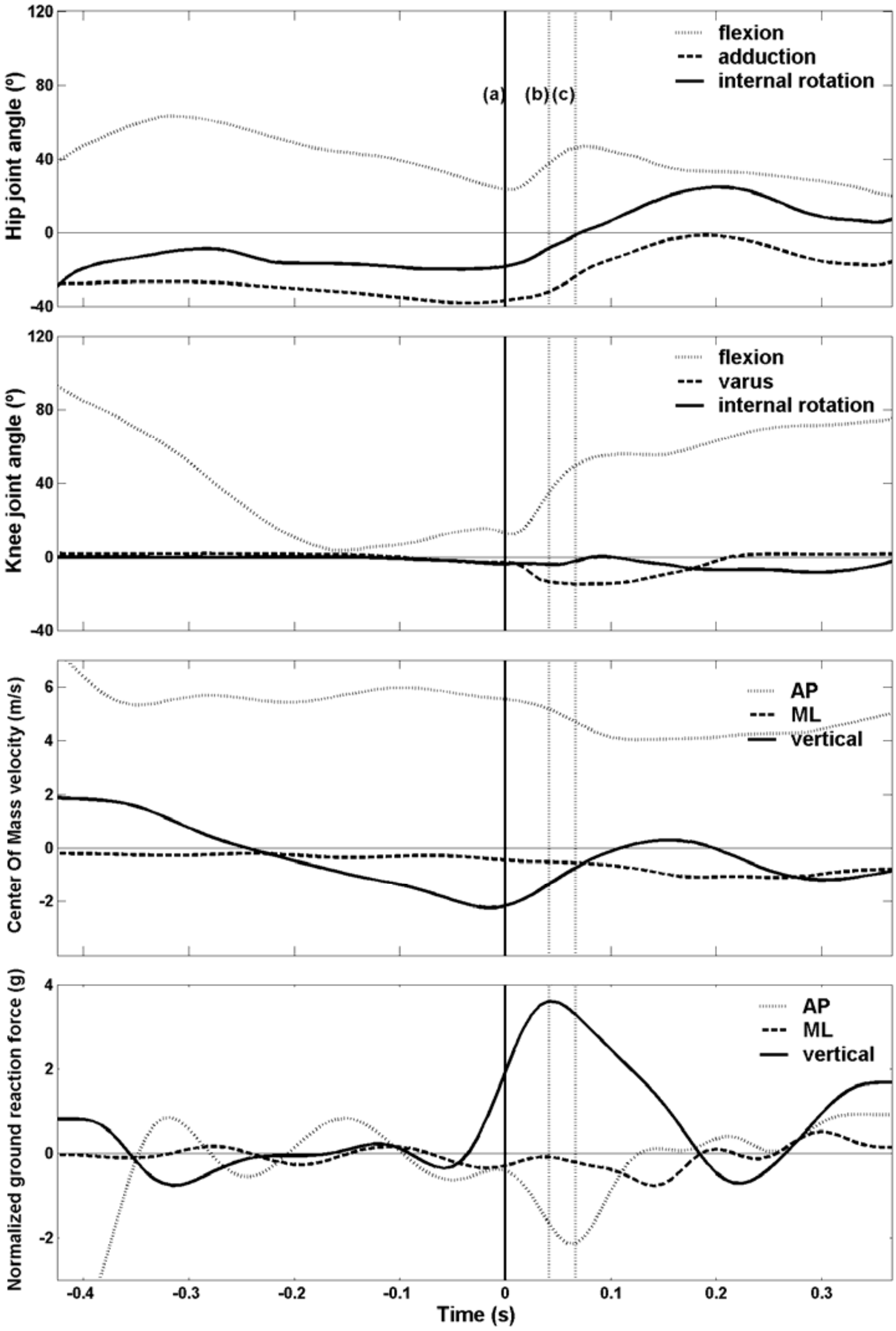

Figure 17 *Time sequence of hip joint angle (º), knee joint angle (º), center of mass velocity (m/s) and normalized ground reaction force (g) of the injured right leg for the basketball injury situation. The solid vertical line (a) indicates initial ground contact. The two dotted vertical lines indicate the time points 30 ms (b) and 60 ms (c) after initial contact, respectively, corresponding to the peak vertical and horizontal force.*

For the alpine skiing injury, the visual match also looked good. Because of the relatively poor video quality, the lack of known landmarks in the surroundings and the fact that only one camera view was available, it was somewhat difficult to assess if the matching was done correctly at all frames (e.g. the right foot in Figure 14) Due to the possible errors in such low-quality, single-camera situations, the accuracy needed for the specific research question should therefore be carefully assessed before considered for analysis.

It was concluded that frame-by-frame 3D reconstructions of three ACL injury video sequences could be produced successfully. From the high-quality handball and basketball videos, which included multiple views, a detailed time course for joint kinematics and ground reaction force was obtained, while less information could be provided from the single view skiing accident.

Laboratory validation of the visual inspection technique

In Paper III, substantial errors were found for the visual inspection technique, as shown by the mean difference from the gold standard (Table 3). The true knee flexion angle was generally twice as high as the estimate (Figure 18). When the analysts estimated 30° knee flexion, the true angle was 50-60°. The present assumptions regarding the knee flexion angle at the time of rupture (i.e. that the knee is relatively straight with less than 30° knee flexion) (Boden et al., 2000; Ebstrup & Bojsen-Moller, 2000; Olsen et al., 2004; Teitz, 2001) may therefore not hold true.

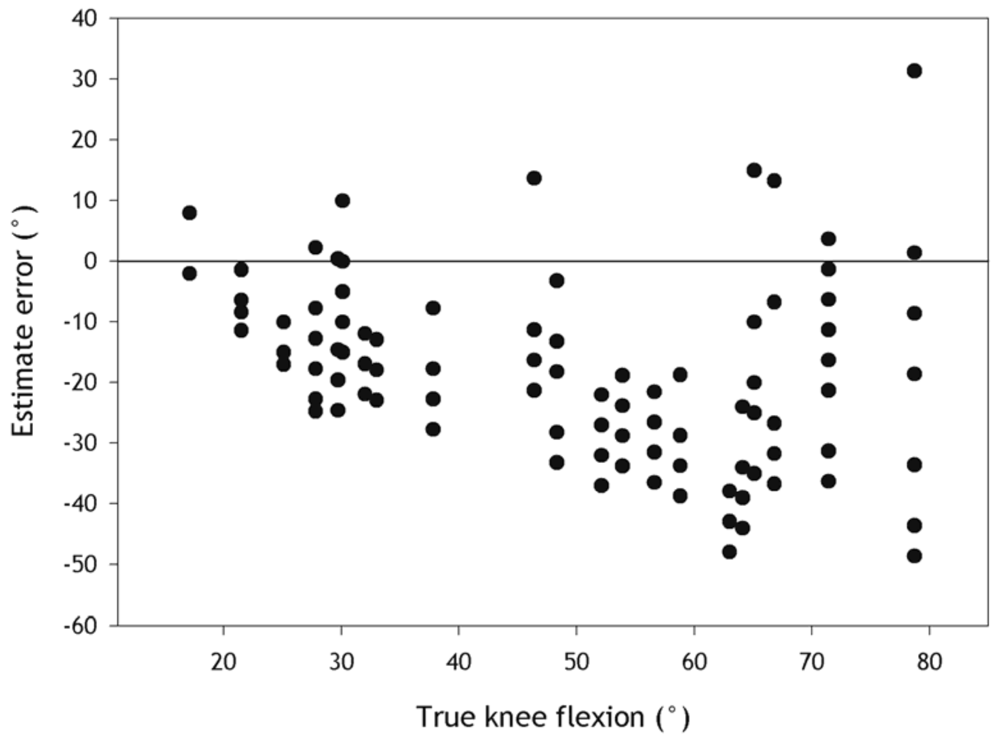

Figure 18 *Error in knee flexion angle estimates as a function of the true knee flexion angle.*

However, from the multivariate regression analysis, we found that the knee flexion estimate errors were significantly less (-6° vs. -37°) when a side camera was present ($p=0.02$), when the right leg (i.e. closest to the side camera) was analyzed ($p<0.001$) and when the flexion angle was lower than 30° ($p<0.001$), indicating that several factors may influence the estimate. Hip flexion angles were also underestimated systematically by an average of 7°.

Table 3 Mean error (°, m/s or %) and standard deviations for the mean error (SD) with range for the pre- and post-tests. The mean difference between the pre- and post-test is also shown, with the corresponding 95% confidence interval (95% CI). P-values are reported for pre- to post-test changes in the mean error (p mean) and the standard deviation of the mean error (p SD). The numbers of observations ranged between 123 and 162.

	Pre-test	Post-test	Pre- to post-difference	p mean	p SD
Knee flexion (°)	-19±14 [-49,31]	-18±15 [-54,21]	1 [-1 to 3]	0.47	0.30
2D valgus (°)	4±9 [-12,35]	5±10 [-15,35]	1 [0 to 2]	0.005	0.12
3D valgus (°)	-2±6 [-19,16]	-5±6 [-19,11]	-3 [-4 to -2]	0.000	0.01
Knee internal rotation (°)	-12±11 [-46,11]	-9±8 [-29,8]	3 [2 to 5]	0.000	0.000
Hip flexion (°)	-7±18 [-50,48]	-7±19 [-50,43]	0 [-2 to 2]	0.93	0.40
Hip abduction (°)	4±10 [-27,34]	2±13 [-35,37]	-2 [-4 to 0]	0.046	0.53
Hip internal rotation (°)	-10±16 [-57,17]	-10±14 [-37,13]	0 [-2 to 2]	0.85	0.16
Approach speed (m/s)	0.1±1.1 [-3.1,2.6]	0.3±0.9 [-2.1,3.4]	-0.2 [-0.4 to 0.0]	0.02	0.053
Vertical speed (m/s)	-0.5±1.0 [-2.4,4.1]	-0.5±1.0 [-2.7,2.4]	0.0 [-0.2 to 0.2]	0.8	0.58
Cutting angle (°)	2±19 [-41,47]	2±19 [-51,39]	1 [-1 to 3]	0.36	0.07
Foot-pelvis rotation (°)	1±11 [-31,28]	0±14 [-33,43]	-1 [-2 to 0]	0.095	0.002

Even if the evaluation of the accuracy could be affected by a sub-optimal gold standard (Benoit et al., 2005; Reinschmidt et al., 1997), the large between-analyst standard deviations clearly demonstrate that the ability to estimate joint kinematics using simple visual inspection is limited.

Overall agreement was also poor between estimated and actual tendency of the joint motion. The relative match was best for knee flexion/extension, where a kappa value of 0.40 indicated a fair agreement.

The fact that our structured feedback program did not improve estimates could either indicate that the training was inadequate, or simply that the task of segment orientation perception and joint angle calculation is inherently difficult.

In conclusion, the accuracy and precision of the estimates across analysts and trials was generally poor, and only small changes were seen as a result of the training session. Results from studies using a simple visual inspection approach to describe joint motion should therefore be interpreted with caution.

Visual inspection analysis of ACL basketball injuries

In Paper IV, the majority of the 39 injury situations from basketball were classified as "landings" (Table 4).

Table 4 Player action at the time of injury (N=39).

	Males	Females
One-legged landing	6	4
Two-legged landing	4	9
Cutting	2	2
No consensus	1	2
Direct blow to the knee	4	0
Impossible to judge	0	5

Although the results showed that 72% of the injuries did not involve contact with other players at the assumed time of injury, opponents were in close proximity to the injured athlete in nearly all of the injury situations and as many as half of the injured female players were pushed or collided *prior to* the time of injury. Experimental studies show that the introduction of a static defender in cutting maneuvers (McLean et al., 2004b) or using an overhead goal (Ford et al., 2005a) in vertical jumps alters the knee biomechanics significantly. Thus, it seems reasonable to suggest that preventive programs (Hewett et al., 1999; Myklebust et al., 2003) should include similar perturbations, resembling those seen in match situations, to enhance knee control.

The time point of injury was estimated to take place between 17 and 50 ms after IC. Although it is not possible to verify the exact moment when the ACL injury occurred with the visual inspection approach, the relatively consistent overall judgment from the group does strengthens the hypothesis. Also previous video analysis studies have come to the same conclusions (Boden et al., 2000; Olsen et al., 2004; Teitz, 2001).

On average, the analysts' knee flexion estimates, calculated through linear interpolation between the estimates at IC and 50/33 ms after IC, corresponded to 18º in males and 24º in females at the assumed time of injury. However, the results from Paper III indicated that the true knee flexion angles may have been twice as high as the visual estimates.

Table 5 Mean knee and hip flexion (°) and standard deviations with range. (N=27) The three cases of no consensus in player action are not included in the table.

	Knee flexion				Hip flexion			
	Males (N=12)		Females (N=15)		Males (N=12)		Females (N=15)	
	IC	50/33 ms after IC	IC	50/33 ms after IC	IC	50/33 ms after IC	IC	50/33 ms after IC
One-legged landing (N=10)	8±6 [3,16]	18±6 [10,28]	10±4 [5,14]	18±4 [13,23]	16±8 [5,27]	22±7 [17,31]	20±10 [5,27]	20±7 [14,30]
Two-legged landing (N=13)	9±7 [3,19]	17±6 [11,23]	15±4 [10,22]	27±7 [18,40]	18±4 [13,22]	18±5 [14,26]	25±8 [17,44]	32±11 [21,54]
Cutting (N=4)	12±2 [11,13]	23±7 [18,28]	14±11 [7,22]	27±4 [24,29]	29±6 [25,33]	22±1 [21,22]	37±7 [32,42]	45±6 [41,49]

Numerous studies have investigated if the gender difference in ACL injury incidence might be caused by differences in knee and hip flexion in landings. However, although several laboratory studies support this theory, (Decker et al., 2003; James et al., 2004; Malinzak et al., 2001; McLean et al., 2004b; Salci et al., 2004), some studies also report no differences (Ford et al., 2005b; McLean et al., 1999; Pollard et al., 2004), and several studies even report larger flexion angles in females (Fagenbaum & Darling, 2003; Ford et al., 2003; Hewett et al., 1996). In the present study, females were found to have significantly higher knee and hip flexion angles at IC, at 50/33 ms after IC and at the assumed point of injury. These results suggest that females are likely *not* more prone to the quadriceps drawer mechanism than males. However, caution must be taken since e.g. hamstrings co-activation could be different.

Despite this, the question still remains if the quadriceps drawer mechanism is a possible cause of injury in the situations studied here, considering that the knee flexion angles at the time of injury may be higher than have been assumed previously. However, the relationship between flexion angle and ACL strain induced by quadriceps contraction is not clear. Although it has been demonstrated that isolated ACL rupture from the quadriceps mechanism is possible (DeMorat et al., 2004), this was only done with a 20° flexion angle. While Aune et al. (1997) concluded that quadriceps muscle contractions actually protected the ACL from externally applied anterior drawer force, Withrow et al. (2006) found that ACL strain induced by quadriceps was maximal at approximately 30°. However, neither of these studies compared their results at 30° with set-ups at lower or higher flexion angles. In light of these findings, it is difficult to interpret the flexion angle results from the present study.

Table 6 Valgus knee collapse (N=30)

	Yes	No	No consensus	Impossible to judge
Male	2	10	0	1
Female	9	2	2	4

Table 6 indicates that valgus loading must have been present prior to the rupture in approximately half of the cases. A possible implication of the higher proportion of valgus collapses in females (relative risk: 5.3, p=.002) is that the knee loading patterns in non-contact ACL injuries may be different between males and females. This hypothesis is supported by laboratory motion analysis studies, where males demonstrate internal rotation combined with varus motion, whereas females demonstrate the combination of valgus/external rotation, (Chappell et al., 2005; McLean et al., 2004b) possibly due to insufficient lumbopelvic strength or lack of neuromuscular control (Leetun et al., 2004; McClay Davis & Ireland, 2001; McLean et al., 2004b; McLean et al., 2005b; Myklebust et al., 2003). An alternative explanation could be that the loading patterns are *not* different between genders, but that valgus collapses are more apparent *after* injury in females because of e.g. reduced joint stiffness (Granata et al., 2002; Hsu et al., 2006; Rozzi et al., 1999; Wojtys et al., 2002; Wojtys et al., 2003). In support of this theory, some degree of valgus was estimated in all cases in the present study. However, the relatively poor accuracy and precision of these estimates as shown in study III does not allow firm conclusions to be made.

Injury mechanism considerations and the role of video analysis

Injury mechanism considerations

Much attention has been given recently to the non-contact ACL injury problem in team/ball sports. The focus has mostly been directed towards single factors like e.g. gender differences in knee flexion angles. Fewer studies have investigated the actual injury mechanism, even if this information may be more important to develop specific preventive measures (Bahr & Krosshaug, 2005). This may partly be attributed to the inherent difficulty in investigating sports injury mechanisms. For obvious ethical reasons, these cannot be studied experimentally the same way as e.g. sports performance. Even though new research investigating the mechanisms of non-contact ACL injuries in ball/team sports is beginning to blossom (DeMorat et al., 2004; Fung & Zhang, 2003; McLean et al., 2004a; Meyer & Haut, 2005; Pflum et al., 2004; Withrow et al., 2006), we are still far from a full understanding of the biomechanics involved in such injuries. A complete description should quantify whole body and knee kinematics as well as loading directions, magnitudes and rates of external and internal forces. Our current understanding of non-contact ACL injury mechanisms is to a large degree based on the findings from athlete interviews and video analysis, even if other approaches has been utilized, as discussed below. Unfortunately, athlete interviews may be unreliable and prone to recall bias (Krosshaug et al., 2005). Even if video analysis has the potential to provide more objective and detailed descriptions of the injury biomechanics, Paper III clearly demonstrated that the accuracy of the kinematical descriptions in previous studies using a simple visual analysis approach may be poor. A systematic underestimation of knee flexion angles will likely influence our interpretation of the injury mechanism. Another possible implication is that injury simulations may be based on false assumptions.

Hewett et al. (2005) showed that a landing pattern with valgus loading predicted ACL injury in a prospective study, indicating that valgus loading is likely an important element in the non-contact ACL mechanism. As discussed previously, the large number of valgus collapses seen in Paper IV adds support to the hypothesis that valgus loading is an important part of the non-contact ACL injury mechanism, at least in females. Moreover, based on the findings of McLean et al. (McLean et al., 2005b), the larger hip flexion angles at IC for females suggests that their maximal normalized valgus moments were likely higher compared with males. The three cases in Paper III also displayed a substantial valgus angle increase early, similar to what was shown in the study of McLean et al. (McLean et al., 2004b). However, more situations obviously need to be analyzed using the model-based image-matching technique before any conclusions can be drawn.

Furthermore, mathematical simulation studies (McLean et al., 2004a), as well as clinical studies (Speer et al., 1992), conclude that valgus loading is a likely contributor. Several studies also report that MCL injuries of various grades are frequently seen in connection with non-contact ACL injuries, indicating that valgus loading has been present. Laboratory motion analysis studies have demonstrated that females to a larger degree than males display a combination of valgus/external rotation (Chappell et al., 2005; McLean et al., 2004b), suggesting that knee valgus motion may be a reason for the relatively larger proportion of ACL injuries seen in females. Finally, cadaver studies have also demonstrated that valgus loading induce ACL strain (Kanamori et al., 2000; Markolf et al., 1995) All in all, this evidence strongly suggests that valgus loading plays an important role in many of the non-contact injury situations, at least in females. However, it is presently not known what other loads that may contribute to the injury. In fact, it is not even known if there are more than one typical loading pattern that may lead to these injuries, or if the typical injury mechanisms are different between genders. Even if Paper IV, as well as motion analysis studies, indicate that such differences may exist, it is unknown if the large gender difference seen in the proportion of "valgus collapses" is a result of differences in loading patterns or simply is caused by the lesser joint stiffness in females (Granata et al., 2002; Wojtys et al., 2002; Wojtys et al., 2003). Additionally, the likelihood of the different hypotheses proposed by Speer et al. (Figure 6) to explain the typical tibial impaction patterns still remains an open question, almost 15 years later. However, hyperextension can be ruled out as a common non-contact mechanism, considering that such injuries have not been reported in any of the video analysis studies.

Although valgus loading may be a part of the injury mechanism, other loads may also be present . It has been shown that pure valgus loading will likely rupture the MCL before the ACL is ruptured (Mazzocca et al., 2003). A significant number of MCL ruptures are found in conjunction with non-contact injury ACL injuries (Cross et al., 1993; Ferretti et al., 1992; Friden et al., 1995; Speer et al., 1992). This suggests that other loading components than pure valgus are likely involved. Fung et al. (2003) modeled ACL impingement against the intercondylar notch. In their model, 8° valgus and 5° external rotation initiated impingement. However, this model did not investigate loading levels that lead to ACL failure. Unfortunately, no studies have yet investigated combined loads that will take the ACL to failure, and it therefore remains unknown if e.g. valgus combined with external rotation loads can produce ACL injuries without rupturing the MCL. However, other hypotheses than the ones already proposed in the literature also emerge from the data available. If an athlete is used to performing landing and cutting maneuvers in a way that involves repeated valgus loading, their MCL may become stretched. This may increase the relative load distribution onto the ACL from valgus loading (van den Bogert, 2006 – personal communication).

The quadriceps drawer hypothesis has been cited in review papers (Kirkendall & Garrett, Jr., 2000), video analysis studies (Boden et al., 2000) and numerous motion analysis studies looking specifically at knee flexion angles in males compared to females (Decker et al., 2003; Fagenbaum & Darling, 2003; Ford et al., 2003; Ford et al., 2005b; Hewett et al., 1996; Huston et al., 2001; James et al., 2004; Malinzak et al., 2001; McLean et al., 1999; McLean et al., 2004b; Pollard et al., 2004; Salci et al., 2004). However, as discussed in detail in Paper IV, the results from the motion analysis studies do not show a consistent difference in landing flexion angles between males and females. Several cadaver studies have shown that quadriceps loading will strain the ACL at low flexion angles (Aune et al., 1997; DeMorat et al., 2004; Draganich & Vahey, 1990; Hirokawa et al., 1992; Markolf et al., 2004; Renstrom et al., 1986; Withrow et al., 2006). Although the study of DeMorat et al. (2004) demonstrated that this mechanism is capable of producing ACL rupture in a cadaver experiment, this approach was criticized for not including ground reaction forces, which will act posteriorly, and thus prevent anterior tibial translation (McLean et al., 2005a). Three mathematical model simulation/estimation studies (McLean et al., 2004a; Pflum et al., 2004; Simonsen et al., 2000), which included the effect of hamstrings activation, all conclude that anterior shear forces can not generate sufficient force to rupture the ACL, even in extreme cases where hamstrings forces are non-existent (McLean et al., 2004a). In contrast, in the more recent study of Withrow et al. (2006), the effect of ground contact forces were simulated by applying a vertical impact load that was directed 4 cm posterior to the knee joint center at 25° flexion, in a model that included quadriceps and hamstrings forces. The experiment demonstrated that anterior tibial translation and ACL strain approximately proportional to the quadriceps force were generated. It is not known how the recorded relative strain of approximately 2-4% (max 4.7%) corresponds to ACL force. However, compared with previous reported in-vivo strain of 5.47% in a sub-maximal one legged jump landing onto a force plate, as well as previously reported critical strains of 20% (Zavatsky & Wright, 2001), this figure seems to be far from dangerous levels. Since this study only investigated sub-maximal loads (i.e. less than 1/3 of the quadriceps loading used by DeMorat et al. (2004)), it is not possible to make firm conclusions regarding the quadriceps drawer mechanism from this study.

The potentially conflicting results between the mathematical simulation studies and cadaver simulation studies may have other explanations. The model of McLean et al. (McLean et al., 2003; McLean et al., 2004a) and Simonsen et al. (2000), is based on input from sidestepping maneuvers rather than vertical landings. This will likely generate a larger posterior ground reaction force compared to vertical landings, and thus reduce the net anterior force applied to the tibia. It is therefore possible that the quadriceps drawer mechanism contributes more to injury in vertical landings compared to impacts involving forward velocity. Furthermore, these models did not include the effect of tibial slope, which has been found to generate significant anterior tibial translation, depending on the slope angle and the actual knee flexion angle (Meyer & Haut, 2005; Pflum et al., 2004). In the soft-style landing model of Pflum et al. (2004), the tibial slope was included, but the knee flexion angles were approximately 40° at the maximal predicted ACL force, which may explain why only low ACL forces were obtained in this study. Paper IV showed that, in actual injury situations, females were found to have significantly higher knee and hip flexion angles at IC, at 50/33 ms after IC and at the assumed point of injury. This finding is important because it suggests that landing on straighter knees may not be an important reason for the observed gender difference in ACL injury frequency. Still, more investigations are needed, e.g. to see if similar gender differences are seen in other sports, as well. Differences in hamstrings activation, laxity and strength could possibly influence the anterior quadriceps drawer mechanism, and should therefore be studied. In conclusion, further investigations are required to delineate the role of quadriceps drawer in the ACL injury mechanism. As a first step, we need to develop valid models that can estimate the effect of pure quadriceps drawer on ACL forces at different flexion angles, while taking ground reaction forces and joint properties into consideration. Moreover, it is necessary to investigate the effect of quadriceps forces under combined loading, for example if quadriceps drawer forces could place the knee joint in a vulnerable position when valgus or internal rotation moments are applied.

There are several factors suggesting that internal rotation on a relatively straight knee could be a potential mechanism of non-contact ACL injuries. First, the ACL is known to be loaded from internal rotation (Markolf et al., 1995). Internal rotation is reported to be an injury mechanism in athlete interview studies (Arnold et al., 1979; McNair et al., 1990; Myklebust et al., 1998), in video analysis (Ebstrup & Bojsen-Moller, 2000; Olsen et al., 2004), as well as suggested from the associated clinical findings (Murphy et al., 1992; Remer et al., 1992). The hypothesis of Speer et al. (1992) to explain the MRI findings, i.e. pivot shift injury of the posterolateral tibial rim and meniscus, is consistent with an internal rotation about the medial compartment as shown in Figure 7. In motion analysis studies, it is also commonly found that the knee is internally rotated in the stance phase. However, males are reported to exhibit this pattern to a larger degree than females (Chappell et al., 2005; McLean et al., 1999). Unfortunately, knee internal/external rotation motion and moments cannot reliably be quantified with surface markers (Reinschmidt et al., 1997). Our study (Paper IV) also indicated that some situations were likely to involve internal rotation. However, due to the limitations in video analysis as reported in Paper III, and also in athlete interviews and clinical studies (Krosshaug et al., 2005), it is not possible to make firm conclusions from the current scientific evidence.

In conclusion, there is an obvious need to develop better research methods to investigate non-contact ACL injury mechanisms. Mathematical simulation models have the potential to include all important aspects, like e.g. ground reaction forces and neuromuscular stimulation patterns in a computer environment, thus avoiding any hazard to athletes. Nevertheless, major challenges are present. New studies indicate that it is necessary to consider the complex interactions of the muscles and joints in the whole lower extremity (Ferber et al., 2003; McLean et al., 2004b; McLean et al., 2005b; Zeller et al., 2003) and possibly also upper body actions (Cowling & Steele, 2001). Due to the complexity in anatomy and neuromuscular control, a sophisticated mathematical simulation model will necessarily have to rely on assumptions and simplifications to deal with the inherent undeterministic nature of the equations describing the dynamics. Because of this, a more complex model may be able to reproduce the measured kinematics more precisely, but the ability to predict new (e.g. injury-producing) situations may possibly suffer (McLean et al., 2004a). The fact that a mathematical injury model nearly always needs to be validated in a non-injury situation or in vitro, clearly adds a degree of uncertainty to its use. An alternative could be to develop physical simulation models using cadaver knees. For example, the model of Withrow et al. (2006) could be expanded by including valgus moments, e.g. by adding sideways inclination (simulating hip abduction). An even more sophisticated approach would be to use a robotic/UFS testing system to study the effect of combined loading, or to measure forces from specified knee kinematics (Darcy et al., 2005; Moore et al., 2005; Woo et al., 1999). However, this approach must be expanded with muscle activation before it can be considered adequate for ACL injury simulation. Finally, it is absolutely necessary to verify that the simulated injury pattern actually resembles what is experienced in real life. Thus, such models should be backed up by video analysis as well as clinical studies, cadaver testing and in-vivo studies.

The role of video analysis – limitations and possibilities

With the exception of rare accidents during biomechanical research experiments, the only approach that has the potential to record the kinematics of a real injury situation is analysis of injury videos. The simple visual inspection technique is the only one to have been used in research of ACL injury mechanisms so far. Our three-case study (Paper II), demonstrated that far more sophisticated and accurate methods are feasible, but very time-consuming due to the manual matching process. As previously discussed, we are still far from reaching a general solution for automatic tracking and 3D reconstruction (Moeslund, 2003; Moeslund & Granum, 2001). Reaching adequate accuracy for biomechanical purposes, or simply estimating axial rotations of the segments seems to be difficult using automated (Cheung et al., 2005; Sminchisescu & Triggs, 2005) or even semi-automated systems (Barron & Kakadiaris, 2005; Zheng et al., 2000). Although one might consider utilizing features like e.g. learning algorithms for segment motion, joint range of motion limitations etc. to improve the matching accuracy, it is difficult to justify this due to the possibly different nature of the injury situations compared to non-injury situations. It therefore seems likely that video analyses that require a high degree of accuracy must incorporate manual assessment to a certain degree. Nevertheless, Paper I showed that the accuracy of manual matchings will still be limited. For example, the pelvic rotation and tilt, as well as femur rotation were difficult to assess due to clothing and segment shape. It is likely that training may improve such assessments, but the final outcome will remain limited by spatial and temporal resolution, picture quality, camera views as well as the available surrounding landmark information in the video sequence(s). The accuracy of video analyses can therefore not achieve the same level as e.g. fluoroscopy (Stagni et al., 2005) or motion analysis based on bone-pins (Benoit et al., 2005; Reinschmidt et al., 1997). Nevertheless, kinematical estimates are still valuable, as demonstrated in Paper IV. Moreover, descriptions of playing situation and player/opponent behavior may provide information that can easily be utilized to develop preventive measures.

Although Paper II demonstrated the feasibility of using more sophisticated methods to analyze injury videos, we need to analyze a larger number of videos to draw conclusions with regards to injury mechanisms. Importantly, we should compare injury vs. non-injury situations to investigate if, or at what point, it is possible to distinguish between the situations; to study the specificity and sensitivity of these assessments.

Finally, laboratory studies have shown that the introduction of static defenders (McLean et al., 2004b), use of an overhead goal (Ford et al., 2005a) or performing unanticipated cutting motions (Besier et al., 2001; Ford et al., 2005b) will significantly alter the recorded biomechanics. A final major application for video analysis studies is therefore to investigate how well laboratory situations compare with actual match situations; this will assist in establishing the external validity of laboratory based studies.

Implications for injury prevention

Several studies have shown positive effect of programs aiming to reduce the number of non-contact ACL injuries in team/ball sports (Hewett et al., 1996; Mandelbaum et al., 2005; Myklebust et al., 2003; Olsen et al., 2005). Such programs are mostly based on modifying dynamic loading through neuromuscular training (Myer et al., 2004). However, despite the fact that these programs were successful in reducing injury rates, it is possible that even better results could have been produced if accurate descriptions of playing situation, player/opponent behavior and the involved biomechanics were available. Such preventive measures could include simple guidelines, like attempting to distribute the ground contact forces on both legs (i.e. avoid one-legged landings) (Myklebust et al., 2003). Rule regulations or stricter rule enforcing may also be considered if fault play is detected, e.g. pushing prior to or in a landing or cutting maneuver, such as seen in many of the basketball injury situations. Modification of shoe/floor friction may be a solution if e.g. pivot on a straight leg causes the injuries. Also existing neuromuscular training aiming to improve dynamic stability may be optimized to be even more effective if the joint loading patterns of non-contact ACL injuries are known. For example, several studies point to lack of quadriceps activation as a possible factor for excessive valgus motion (Besier et al., 2003; Pope et al., 1979; Wojtys et al., 2002; Wojtys et al., 2003) . On the other hand, high quadriceps activation may also lead to anterior tibial drawer (DeMorat et al., 2004; Withrow et al., 2006). Hence, it may be difficult to propose the optimal motion pattern in neuromuscular training programs. Nevertheless, our findings (Study IV) suggest that such programs should include "disturbing elements", resembling those seen in match situations, to enhance knee control.

However, even if the neuromuscular prevention programs have proved to be effective, a major problem is to motivate athletes to continue to do the exercises. Myklebust et al. (2002) concluded that the intervention teams and players only to a small degree continued to follow the program one year after, even if the injury incidence was reduced by approximately 50%. Because of this, it seems necessary to limit the time that is spent on such programs. A better understanding of the loading patterns involved in ACL injuries may help in the process to develop a program that includes the best exercises, while keeping the spent time to a minimum.

Also in other sports, such as e.g. alpine skiing, kinematical estimates can potentially be utilized to prevent injuries, e.g. by technique changes, equipment changes, or designing more "intelligent" binding release criteria and systems (Bahr & Krosshaug, 2005; Krosshaug et al., 2005). Preventive measures have previously been applied with promising results in recreational skiing, as was demonstrated in the study of Ettlinger et al. (1995) using injury awareness training. However, if we are to prevent ACL injuries, a systematic approach to collect and analyze more injury videos is needed.

Conclusions

1. A new model-based image-matching technique has been developed, which can produce temporal joint angle histories, velocities and accelerations from uncalibrated video recordings. The kinematic estimates, in particular COM velocity and acceleration, were clearly better when two or more camera views are available.

2. Frame-by-frame 3D reconstructions of three ACL injury video sequences were produced successfully, using the new model-based image-matching technique. From the high-quality handball and basketball videos, which included multiple views, a detailed time course for joint kinematics and ground reaction force was obtained, while less information could be provided from the single view skiing accident. As long as the quality of the video input is good, the method may give valuable information on the mechanisms for ACL injuries in sports.

3. The accuracy of the simple visual inspection approach was poor, with considerable systematic as well as random errors. Minimal group effects were seen from our training program aiming at improving accuracy. Based on these findings, results from studies using a simple visual inspection approach to describe joint motion must be interpreted with caution.

4. The knee flexion angles at the assumed point of injury were higher in males than in females, and females had a 5.3 times higher relative risk of sustaining a valgus collapse compared to males. Although the majority of the injuries did not involve contact at the assumed point of injury, the movement patterns were likely perturbed by an opponent, e.g. by pushing prior to the injury.

Future studies

Several questions have arisen, which should lead to new studies related to ACL injury mechanism research:

1. Validation of the model-based image-matching technique against a better gold standard, e.g. motion capture using bone-pin markers rather than surface markers. The method might also be improved by implementing automatic calibration procedures, and Kalman-filtering techniques for optimizing COM trajectory during the airborne phase. This could reduce the matching time, and furthermore improve approach velocity estimates.

2. Prospective collection and analysis of videos of ACL injuries in various sports, using the model-based image-matching method. If possible, similar situations – not leading to injuries – should also be analyzed to investigate if, or at what point, it is possible to predict injury. In such a study, one should preferably collect information of clinical findings (CT, MRI or arthroscopy), as well as obtain anthropometrical measurements and test the athlete's shoe/surface friction. Such a study could also include a pre-season screening of the athletes, including a description of three-dimensional kinetics and kinematics in landings and cutting maneuvers.

3. Studies should be conducted, comparing the kinematics of laboratory trials with game situations, to investigate the validity of laboratory trials.

4. Cadaver studies have inherent limitations, but are still valuable in determining ACL loading patterns. Unfortunately, there are no studies on combined loads in loading conditions close to injury, or in ligament failure. One particularly interesting combination would be, as suggested by several (Fung & Zhang, 2003; McLean et al., 2004a; Olsen et al., 2004), to study the combination of external rotation and valgus. Using a robotic/UFS method (Darcy et al., 2005; Moore et al., 2005; Woo et al., 1999), it may e.g. be possible to replicate joint kinematics obtained from video analyses to investigate the development of ligament forces. However, the effect of muscle forces must be incorporated in such models.

5. Another interesting study would be to measure ACL loading in cadaver knees for a longer period in a large number of combined external loading states. From such measurements a multivariate regression model could be developed (van den Bogert, 2002 – personal communication) that may predict the limits of joint motions beyond which ACL injury

occurs. Such information may help to determine joint loading and time of rupture from our video-extracted joint kinematics. Unfortunately, in this approach the external forces would have to be limited so that permanent damage to the ligaments is avoided during the testing. Therefore, an approach that also included taking some specimens to failure would be necessary, to ensure that the loading relationships remain the same during high external loading.|

6. Furthermore, new, improved measurement techniques are needed for most of the research approaches for ACL injury research, e.g. improved in-vivo measurement techniques of bone motion and ACL force.
7. Ultimately, we need to develop realistic (e.g. that incorporates a detailed knee model with an adequate full body model) mathematical simulation models that can replicate the injury kinematics seen in video analysis studies. Such models must be validated extensively using e.g. motion analysis, EMG, in-vivo force measurements and cadaver knee comparisons.

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Papers I-IV

Paper I

Paper II

Paper III

Paper IV