Research approaches to describe the mechanisms of injuries in sport: limitations and possibilities

T Krosshaug, T E Andersen, O-E O Olsen, G Myklebust and R Bahr

Br. J. Sports Med. 2005;39;330-339
doi:10.1136/bjsm.2005.018358

REVIEW

Research approaches to describe the mechanisms of injuries in sport: limitations and possibilities

T Krosshaug, T E Andersen, O-E O Olsen, G Myklebust, R Bahr

Br J Sports Med 2005;**39**:330–339. doi: 10.1136/bjsm.2005.018358

A number of different methodological approaches have been used to describe the inciting event for sports injuries. These include interviews of injured athletes, analysis of video recordings of actual injuries, clinical studies (clinical findings of joint damage are studied to understand the injury mechanism, mainly through plain radiography, magnetic resonance imaging, arthroscopy, and computed tomography scans), in vivo studies (ligament strain or forces are measured to understand ligament loading patterns), cadaver studies, mathematical modelling and simulation of injury situations, and measurement/estimation from ''close to injury'' situations. In rare cases, injuries have even occurred during biomechanical experiments. This review describes each research approach and assesses its strengths and weaknesses in contributing to the understanding and prevention of sports injuries.

See end of article for authors' affiliations

Correspondence to: Professor Bahr, Oslo Sports Trauma Research Center, Norwegian University of Sport and Physical Education, Oslo, Norway; roald@nih.no

Accepted 27 February 2005

Research on injury prevention has been described by van Mechelen *et al*[1] as a step by step process, in which information on the causes of injury is systematically collected and used to develop potentially effective intervention methods. One important goal is to map the different extrinsic and intrinsic risk factors that contribute to the susceptibility of an athlete to injury, as described by Meeuwisse.[2] However, to develop specific injury prevention methods for a particular injury type in a given sport, it is important to describe the inciting event or mechanism of injury, as outlined by Bahr and Krosshaug.[3] The latter conclude that a precise description of the inciting event is a key component to understanding the causes of any particular injury type in a given sport and emphasise the need to expand the traditional biomechanical approach to describing the inciting event. Although it may be important to have an exact and detailed biomechanical description of the injury, this is not always sufficient to develop effective prevention methods. According to Bahr and Krosshaug,[3] 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 behaviour), as well as to include a description of whole body and joint biomechanics at the time of injury. Furthermore, to address the potential for prevention, the information on injury mechanism must be considered in a model that also considers how internal and external risk factors can modify injury risk.

The different components of the inciting event are not completely independent. Characteristics of the sports situation and athlete/opponent behaviour will of course influence whole body biomechanics as well as the joint or tissue specific loading. However, they represent different areas at which preventive measures can be introduced to reduce the risk of injury. If, for instance, freestyle skiers are injured in the landing after a specific trick, it would be possible to change the rules—for example, prohibit the specific trick—or to change the course profile—for example, remove the mogul in which they land. Alternatively, it could be possible to develop improved boot-binding release systems, but this would require a detailed biomechanical description of the injury mechanism.

A number of different methodological approaches have been used to describe the inciting event (fig 1). These include interviews of injured athletes, analysis of video recordings of actual injuries, clinical studies (in which the clinical findings on joint damage are studied to understand the injury mechanism, mainly through plain radiography, magnetic resonance imaging (MRI), arthroscopy, or computed tomography (CT) scans), in vivo studies (ligament strain or forces are measured to understand ligament loading patterns), cadaver studies, mathematical modelling and simulation of injury situations, or measurement/estimation from ''close to injury'' situations. In rare cases, injuries have even occurred during biomechanical experiments. The purpose of this review is therefore to describe and assess strengths and weaknesses of each of these research approaches to address how each of the methods can provide knowledge on the mechanisms of injury in sport that can be used to develop methods for prevention.

ATHLETE INTERVIEWS

One of the most commonly used approaches in studying injury mechanisms is the description of the injury as reported by the athlete, coach, medical personnel, or others who witnessed the accident.[4] We will term this approach ''athlete interviews,'' even if it is not always the athlete who is actually interviewed.[4–14] The advantage of using this approach is that it is relatively easy to obtain data—for example, through a personal

Abbreviations: BIAD, boot induced anterior drawer; ACL, anterior cruciate ligament; CT, computed tomography; MRI, magnetic resonance imaging

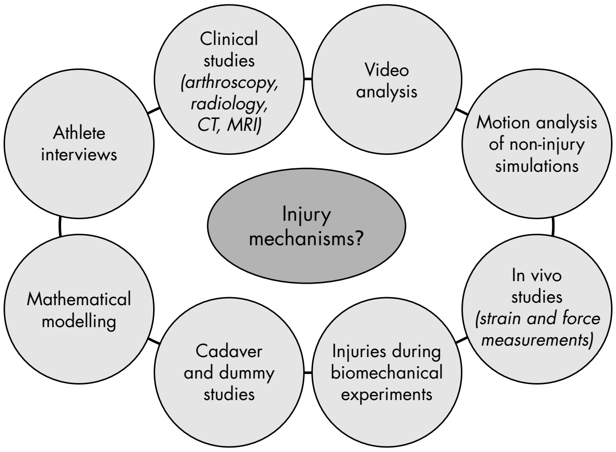

Figure 1 Research approaches to describe the mechanisms of injuries in sports.

interview or a questionnaire. Information on injury mechanisms is therefore often collected as part of routine injury surveillance systems, by which it is possible to gather data on a large number of injured athletes. Such systems have been established in various sports, such as the National College Athletic Association (NCAA) Injury Surveillance System for US collegiate sports[5] and similar systems in professional Australian rules football[6] and professional football at the national team level (FIFA),[7] international club level (UEFA),[8] and national club level in various countries.[9 15 16] Furthermore, a number of the injury surveillance systems established in alpine skiing resorts also routinely collect information on injury mechanisms.[10 17 18]

To use anterior cruciate ligament (ACL) injuries as an example, one important question is whether these occur without opponent contact or result from opponent contact. There are a number of examples of epidemiological studies that attempt to answer this question. For example, Arendt and Dick[5] performed a five year evaluation of ACL injuries in collegiate men's and women's football (soccer) and basketball programmes using the NCAA Injury Surveillance System. They concluded on the basis of 367 cases that non-contact mechanisms were the primary cause of ACL injury for both sexes, but that the non-contact to contact ratio was higher in women than men (4:1 *v* 2:1 in basketball and 1.7:1 *v* 1:1 in football respectively). In two prospective cohort studies from Norwegian team handball with a total of 112 cases, Myklebust *et al*[13 14] reported a non-contact to contact ratio of 16:1, and Strand *et al*[19] reported a 2:1 ratio in a retrospective case series of 144 team handball players undergoing surgery for a suspected ACL injury.

The studies mentioned here and their widely differing results illustrate one of the limitations of the athlete interview approach—that is, the lack of precise definitions of the categories used when reporting data. Although it may seem intuitively easy to distinguish between contact and non-contact mechanisms, there is no universally accepted definition for these terms. Direct contact with the knee—for example, a hit to the lateral side of the knee—clearly falls into the contact category. Conversely, injuries without any form of opponent contact must be classified as non-contact. However, it is not clear how the question would be interpreted by a player who was pushed in the back or held by his shirt just before or at the time of injury. In fact, the papers mentioned did not report the definitions used. Olsen *et al*[20] later suggested discrimination between injuries with direct contact (direct blow to the lower extremity of the injured player; thigh, knee, or lower leg), indirect contact (where the injured player is held, hit, or pushed in a body region other than the lower extremity), and non-contact (where there is no contact with other players). Depending on the results, the distinction between indirect and direct contact mechanisms could have important implications for prevention. This example illustrates the need to clearly explain to the athlete (or other person) completing the injury form the definitions used, and to detail the definitions used when reporting the results of the study.

Furthermore, the categorisation of injury mechanisms into predefined descriptions may result in incomplete or even erroneous interpretation—for example, if the categories are created to fit with a specific theory on the injury mechanism. Interestingly, in one study[21] on ACL injuries in which the description of the injury mechanism was written down as stated by the patients, 17 different injury mechanisms were reported, whereas normally the number of categories is much fewer. Unfortunately, injury mechanism descriptions based on the athlete interview approach commonly use widely different terminology; categories and definitions are rarely provided and sometimes it seems somewhat arbitrary which variables are reported. There are examples of papers on ACL injury mechanisms that report on the sporting situation[11 13 14 19 22] and others even report on detailed joint kinematics.[23–25]

Such detailed descriptions should be interpreted with caution if based on athlete interviews alone. One important limitation of the athlete interview approach is the ability of injured players to comprehend and recall what actually took place when they were injured. Injuries usually happen quickly and often involve several players, opponents, and teammates. It is therefore difficult to determine to what extent the injured athlete or the witnesses are able to assess the playing situation and, perhaps even more difficult, the biomechanical aspects of the injury mechanism. The description given may not even be the athlete's own interpretation of the event, but be influenced by what he was told by others witnessing the event, his coach, parents, or teammates. It may be argued that a major injury is a landmark event in the life of an athlete. Even so, our recollection of a situation often changes with time, and recall bias is another possible source of error.[26] In addition, the description may be "filtered" by the person completing the injury form, and the record may reflect his interpretation of the description—for instance, in the case of an athletic trainer or doctor taking notes for the medical record.

In other words, there are significant methodological limitations that must be borne in mind when interpreting the results from studies based on questionnaire data. It could even be argued that it is not possible to collect accurate and detailed information on injury mechanisms using this approach, thus limiting the ability to develop preventive measures.

However, for some injury types and sports where playing actions and injury mechanisms are easily categorised and the injury mechanisms are consistent, questionnaire data may provide an accurate description of the mechanisms, at least for the playing (sports) situation and athlete/opponent behaviour. For example, questionnaire studies from volleyball have clearly documented the mechanisms for ankle sprains. These mainly occur at the net as the result of landing on the foot of an opponent or a teammate after blocking or attacking.[27] About half of all ankle sprains occur when a blocker lands on the opposing attacker's foot, and about one quarter result from a player landing on his/her teammate's foot when landing from a two or three man block. This information on the injury mechanisms was successfully used as the basis for an intervention study focusing on exercises to teach correct approach, take off, and landing technique when blocking or attacking.[28] This example shows that data from athlete interviews can be important for developing prevention methods.

CLINICAL STUDIES

Another approach to understanding the mechanism of injury is to analyse the pathology of the injury and associated damage. For instance, MRI or CT scans of the head can diagnose the location of brain and skull damage accurately, and thereby form the basis for an estimate of the location and direction of the forces causing the observed damage. In the case of an ACL injury, the use of radiography,[29] MRI,[29 30] CT,[31] or arthroscopy[32] to obtain a detailed description of the pathology—for example, associated injury to the menisci or collateral ligaments, or localised cartilage injury, or bone bruises—can be used to predict the injury mechanisms. MRI studies after ACL injuries have reported a high prevalence of osseous contusions on the lateral femoral condyle and posterolateral injury of the tibia and soft tissue.[29 33 34] On the basis of these findings, as well as the high prevalence of osseous contusion directly over the terminal sulcus of the lateral femoral condyle, Speer *et al*[29] stated that valgus must have been a part of the injury mechanism, and suggested three different models to explain the pathological findings: (*a*) pivot shift injury of the posterolateral tibial rim and meniscus; (*b*) hyperextension injury of the anterolateral tibial rim and meniscus; (*c*) reduction after pivot shift event of the anterolateral tibial rim and meniscus. Studies investigating the associated joint damage after ACL injury may indeed be helpful in generating new hypotheses, and possibly rejecting others. However, the paper of Speer *et al* also illustrates that it is not possible to determine reliably the sequence of events leading to the observed findings on the basis of such studies alone. The essential question—and main limitation of clinical studies in general—is whether the damage occurs before, during, or as a result of the ACL rupture.

Another limitation of many of the studies using this approach to date is that they do not provide any other information about the injury situations causing the injuries, or are based on mixed samples of athletes from different sports and performance levels. This makes the pathology reported even more difficult to interpret. An exception is the study of Ferretti *et al*,[35] a retrospective report on the surgical findings in 52 volleyball players with ACL injuries. This study also provided information about playing position, what sports specific action the players were performing when injured, as well as kinematics and stance phase. Serious injury to the medial collateral ligament was found in seven cases, indicating valgus loading. However, in 34 cases the only macroscopic injury visible was ACL rupture.

Although exact descriptions of joint pathology can be obtained from arthroscopy, MRI, and other imaging studies, an accurate prediction of the detailed joint biomechanics leading to injury is difficult. Information on joint biomechanics alone may not be sufficient to develop ideas for prevention. Therefore it may be that the most important role of data from clinical examinations is that they can be used to support or contradict observations from other methods, such as interviews of the injured athlete or analysis of video tapes of the incident. This requires a prospective approach in which data from all three methods are collected in a standardised way.

VIDEO ANALYSIS

Today, sport is an entertainment industry, and most major international and national competitions and leagues are taped and televised, in some cases even at the youth level. This represents an excellent opportunity to collect videotapes of sports injuries and analyse their mechanisms.

Surprisingly, until recently, very few researchers have used systematic analysis of video tapes of incidents to analyse injury mechanisms, despite the fact that the first video analysis study was published by Silver and Gill more than 15 years ago on serious cervical spine injury in rugby.[36] To determine whether a change in the laws of the game was necessary or whether the existing laws were adequate to prevent neck injuries in rugby, their research was carried out by video recording several games of rugby and analysing the games later in slow motion to determine how injuries occurred. They found that most of the injuries occurred in the ruck and maul situation, and concluded that they were not due to bad luck but were caused by irresponsible actions. The laws of the game were being broken and not being enforced, indicating that stricter officiating could perhaps prevent injuries. Another early study using this approach is that of Ettlinger *et al*[37] on ACL injuries in alpine skiing. They used kinematic information collected from videotapes of recreational skiers and described the ‘‘phantom foot’’ injury mechanism as the typical movement pattern resulting in injury. They even used this information to educate skiers on how to avoid dangerous behaviour, and were able to reduce the rate of ACL injuries by 62% among professional skiing instructors and ski patrols using a video based ‘‘awareness training’’ programme.

Both of these early studies illustrate that systematic video analysis of injuries can potentially contribute information on the sports situation and athlete movement patterns, which can be used directly to prevent injuries. Recently, there has been a surge of papers using a similar approach to study the mechanisms of different injury types in several sports.[9 15 20 38–48] Our group[9 15 38–41] and others[44–48] have used video analysis to study the mechanisms of football injuries in a series of studies. These studies have mainly focused on describing the playing situation, athlete-opponent interaction, and refereeing, confirming results from questionnaire studies pointing to tackling duels and heading duels as high risk situations. Arnason *et al*[15] point to an interesting observation: that the exposed player's attention appeared to be focused away from the opponent challenging him for ball possession in 93% of the cases. However, a video based intervention study using ‘‘awareness training’’ modelled on the study of Ettlinger *et al*[37] did not affect injury risk.[49] Until now, whole body or joint biomechanics have been studied to a lesser degree in football injuries, but two recent studies by Andersen *et al* have examined the mechanisms of ankle[9] (fig 2) and head[41] injuries. For ankle injuries, the joint kinematics showed mostly supination trauma as expected. However, several of the incidents were triggered by an external medial force of the ankle (late tackle from the side) which brought the player out of balance, causing unexpected foot motion just before landing. This illustrates the importance of describing not only the joint specific biomechanics, but also the playing situation leading up to the injury. Similarly, another study showed that the most common injury mechanism for head injuries was elbow to head contact in heading duels.[41] The study suggested that the elbow was used actively at or above shoulder level. Thus both of these studies suggest that stricter rule enforcement or even changes in the laws of the game could lead to a reduced risk of injury.[9 41]

Although video analysis has the potential to be a more detailed and reliable way of analysing injury mechanism than athlete interviews, current methods for estimating kinematics from uncalibrated video sequences are inadequate.[50] Therefore, the video analysis approach has been more useful for describing the playing situation and athlete/opponent movements than detailed joint biomechanics, although a

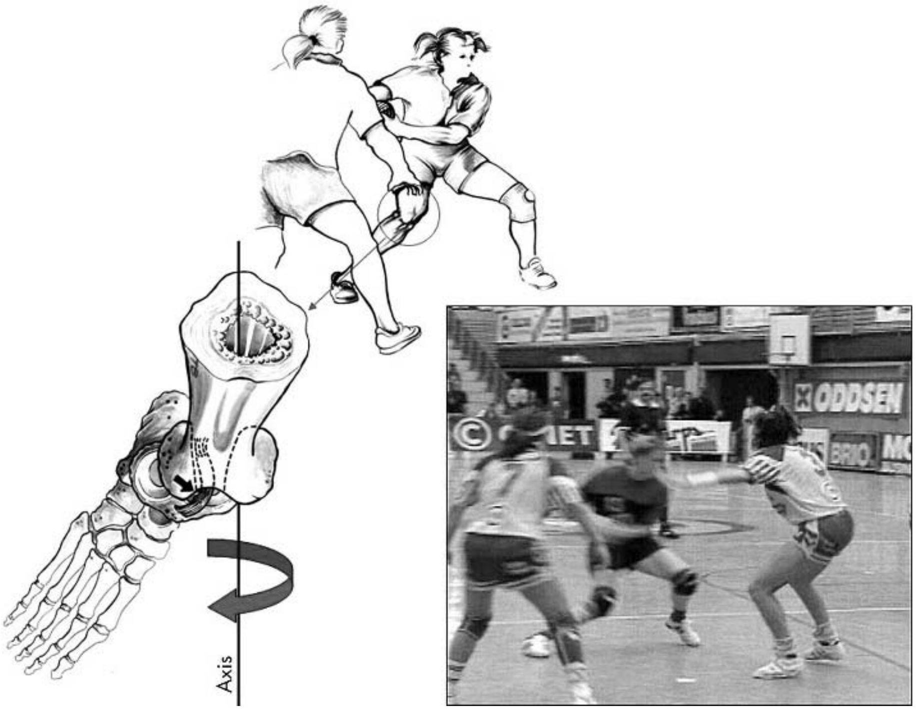

Figure 2 Illustration of the main injury mechanisms observed from systematic video analysis of anterior cruciate ligament injuries in team handball, a plant and cut movement with the knee close to extension resulting in a valgus-external rotation collapse of the push off knee.[20] Illustration reproduced with permission from Oslo Sports Trauma Research Center/T. Bolic.

new model based, image matching technique has recently been described.[50] To date, studies on the mechanisms for ACL injuries have only used simple visual inspection to extract joint kinematic information from video sequences (fig 3).[20 37 42 51] This could potentially represent a significant source of error, as it is not known to what extent it is possible to interpret segment attitudes and estimate joint angles in three planes simply through visual inspection. Finally, these methods cannot produce continuous estimates of joint angles and positions, which are necessary for a detailed biomechanical analysis of the injury mechanisms—for example, joint angle time histories, velocities, and accelerations. In contrast, methods have been developed to estimate impact biomechanics for head injuries.[43 52–54] McIntosh *et al*[52] examined video tapes from head impacts that resulted in concussion in Australian rules football and rugby to obtain estimates of closing speed and head impact energy. Using a similar approach, Pellman *et al*[43] later studied cases of concussions and significant head injuries from National Football League games to estimate the speed of impact from the game films. From these estimates, the situations were reconstructed in the laboratory using helmeted dummies to accurately measure the dynamics involved. In helmeted sports, it could even be possible to build accelerometers into the helmet to measure impact biomechanics directly in injury and non-injury situations and compare these data with the analysis of video recordings of the same incidents.

An obvious limitation of the video analysis approach is the quality of the video recording—for example, the image quality, the resolution of the athlete of interest, and the number of views available. It is not known to what degree a two or three camera recording improves the kinematics estimate from visual inspection. However, a recent study by Krosshaug and Bahr[50] indicates that additional camera views increase the accuracy of a model based, image matching technique for extracting human motion from uncalibrated video images. In addition, the viewing angle relative to the athlete will determine what variables are most reliable.[50] An important challenge is to determine the exact point of injury. In studies of ACL injuries, one report claims that the ''precise point of injury'' could be determined,[51] whereas another stated that finding the exact moment of ACL disruption was impossible.[42]

Another limitation, which must be kept in mind when interpreting the results, is that not all of the injuries reported by team medical personnel can be identified on the game tapes. In fact, about half of all injuries in football can be found on video.[15 39] The proportion of identified incidents ranges from all of the head injuries, about half of ankle and knee injuries, but only one third of hamstring strains. For example, hamstring strains may be difficult to study because they are mainly non-contact in nature. They probably result from sprinting, turning, or rapid increases in speed, which not always result in immediate and obvious disability to the player or take place in camera view near the ball. For the injury types for which a significant proportion of the injuries cannot be found on the tapes, it is possible that the injury mechanisms for the missing injuries differ from the recorded ones—for example, they are non-contact and less ''spectacular.'' This also means that studies based on video analysis alone,[46 55] without reliable medical information from the same matches, must be interpreted with caution. The completeness and diagnostic accuracy of the medical information is an important factor to consider when planning a video study.

Video analysis is a relatively new field, and most studies report sparsely on the methods used to standardise and assess the quality of the video analysis. In a study of ACL injuries in European team handball, Olsen *et al*[20] used a group of three experts, who independently described the injury mechanisms based on a standardised form with predetermined variables and categories. Although the accuracy is not known, a comparison between the examiners showed that the reliability was good. They also verified that their sample

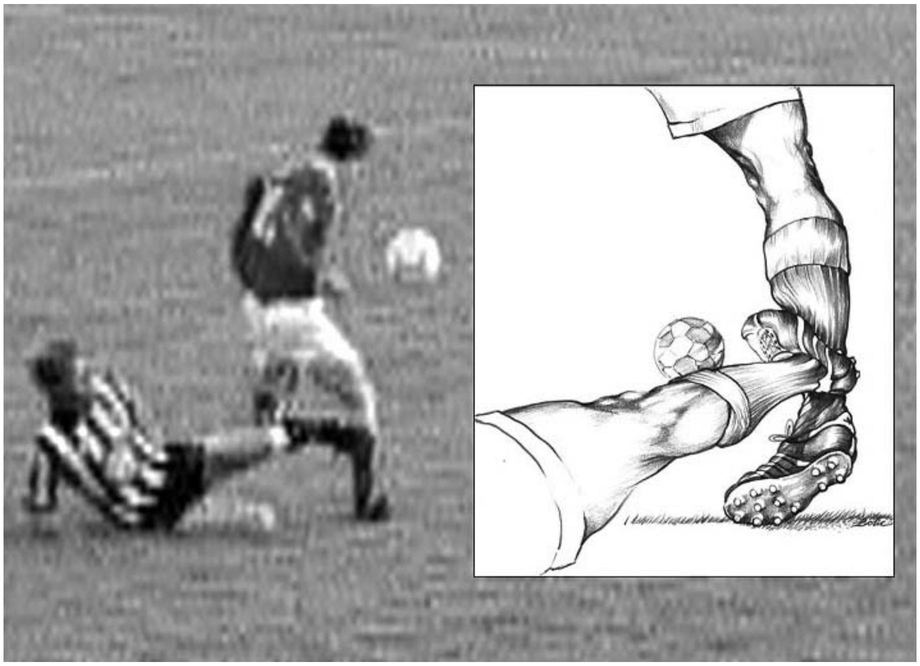

Figure 3 Typical mechanism for lateral ligament injury in football as observed from systematic video analysis: opponent contact to the medial side of the leg, causing the player to put weight on an inverted ankle.[9] Illustration reproduced with permission from Oslo Sports Trauma Research Center/T. Bolic.

of prospectively collected videos was representative, by comparing the descriptions of injury mechanisms obtained from interviews of a larger sample of athletes, including those that were captured on video.

However, a range of potential selection biases can result from the availability of video tapes. The video approach is more likely to be used for matches played by elite professional athletes, where TV coverage is regular, and less likely in amateur, female, and youth sports. However, in a study on rugby headgear at the youth level by McIntosh *et al*,[56] as part of the study protocol they established a system to video record a representative sample of games to study the injury mechanisms. Moreover, training videos are often not available, and the injury mechanisms in training and match play may differ, as we would expect there to be less aggressive and foul play in training. Finally, most video analysis studies only describe events and situations leading to injury. Unless there is a representative control sample of non-injury situations, it cannot be determined if the characteristics of the injury situations are different from what normally takes place without resulting in injury. The assessment of the non-injury situations should, if possible, be carried out in a blinded fashion, although this may be difficult in some cases—for example, for ACL injuries—where an obvious valgus collapse follows many of the ruptures.[20]

In conclusion, analysis of video recordings of actual injuries can provide detailed descriptions of the mechanisms of sports injuries. However, studies must be planned to obtain representative video samples, and the accuracy of the methods can be questioned, especially the ability to describe detailed joint biomechanics.

LABORATORY MOTION ANALYSIS

In contrast, the strength of laboratory motion analysis is that it is possible to estimate kinetics and kinematics with much greater precision than is possible from analysing video recordings. However, injuries cannot be replicated in the laboratory for obvious reasons, and studies using motion analysis are therefore generally designed to mimic typical injury situations. For example, several laboratory studies have recently investigated side step cutting or jump landings in relation to non-contact ACL injuries.[57–61] They have aimed to study factors believed to be important in the different causation hypotheses—for example, by comparing knee flexion angles,[62–66] electromyographic activation patterns,[63 65 67] or net joint kinetics between men and women.[58 59 68 69] However, although it is possible to quantify the motion patterns for movements that are assumed to be similar to the situations in which injuries mainly occur,[5 20] it is difficult to predict to what extent the joint dynamics are in fact comparable. Unfortunately, laboratory and game biomechanics have not so far been compared. However, in order to create more ''match-like'' situations, different research groups have tried to simulate the game setting—for example, by introducing unexpected cutting[61 70] a static defender,[57] or catching a ball while landing.[71] All of these factors proved to increase joint loading, indicating that there are indeed significant differences between controlled laboratory trials and match situations that may lead to injury.

There are also other problems associated with traditional motion analysis techniques, which introduce errors in the estimates—for example, skin movement artefacts,[72 73] identification of bony landmarks,[74] and signal noise.[75 76] Key variables related to ACL injury mechanisms such as knee internal/external rotation and rotation moments have proved to be unreliable in high impact sporting motion.[72] Similarly, tibia to femur translation in a sporting event is too small to be measured with available imaging techniques based on surface markers.[72] Also, the standard net joint kinetics approaches, without the additional use of, for example, sophisticated mathematical models or results from cadaver studies, is incapable of estimating ACL force. Interpretation of the results is therefore troublesome in the sense that it is difficult to predict to what extent, if at all, the observed mechanics exposes the athlete to increased risk of injury.

One approach to assessing the relation between a particular movement pattern (as measured through laboratory analysis) and injury risk is to couple motion analysis with a prospective registration of injuries. One could even introduce an intervention programme designed to change biomechanics and reduce injury risk. Hewett *et al*[77] observed a significant decrease in peak forces and knee adduction/abduction moments in a group of 11 female volleyball players before and after four weeks of plyometric training. The same group later applied this programme to a group of 366 female high school athletes and found that knee injury risk was reduced, indicating that reducing peak landing forces or varus/valgus loading is effective in preventing knee injuries.[78] Further support for this hypothesis can be found in a recent prospective study among 205 female high school athletes, which shows that athletes who ruptured their ACL during the subsequent season displayed appreciably different knee posture and loading (greater abduction angle and moment, higher ground reaction force) in a pre-season laboratory jump/landing task compared with those who did not.[60] Although this is not a study of the injury mechanisms per se, it establishes increased dynamic valgus and high abduction loads as risk factors for injury among female athletes. In this way, it supports the valgus mechanism described by Olsen *et al*[20] from video analysis of ACL injuries in team handball. Taken together, these studies show that laboratory motion analysis can provide relevant information for understanding the mechanisms of sports injury.

IN VIVO STRAIN/FORCE MEASUREMENTS

In vivo studies of strain or forces represent another approach that can provide useful information on tissue loading in situations with similar characteristics to injury situations, and thus perhaps also relevant for injury. Some of the most utilised methods are strain gauges—for example, the Differential Variable Reluctance Transducer[79]—and buckle transducers[80] or fibre optic sensors[81] for measuring force. Lately, non-invasive methods such as ultrasonography[82] and MRI[83] have also shown their potential.

However, owing to the technical challenges,[79] the ability to perform sport specific movements using invasive techniques is at present limited. In addition, non-invasive studies are limited in that they cannot be applied in a sport relevant situation. In vivo studies have therefore generally focused on, for example, muscle-tendon biomechanics and rehabilitation, rather than injury mechanism research. An exception is the study by Cerulli *et al*,[84] in which ACL strain was measured in an athlete performing a one legged maximal jump on to a force plate. However, methodological limitations—for example, impingement problems[84] preventing the athlete from extending the knee, and wiring, preventing more than one step—prevent this from reflecting the real sporting situation. This was also indicated by their findings, as the maximal strain was only slightly higher than measured while the athlete was standing still on one leg.

INJURIES DURING BIOMECHANICAL EXPERIMENTS

For obvious ethical reasons, one cannot replicate injury situations in a experimental study on live subjects. In a few rare cases,[85 86] accidental sports injuries have occurred during research experiments. In a study set up to assess the biomechanics of weight lifting, Zernicke *et al*[85] videoed an Olympic weightlifter rupturing his patellar tendon in a clean and jerk. Net joint kinetics were determined, and the tensile loading of the patellar tendon before and during tendon trauma could be estimated. It was concluded that the maximal tendon stress was considerably greater in sporting situations than in a static setting. In the study of Barone *et al*,[86] kinematic input to a simulation model was collected at the landing from a jump on a ski slope. The researchers intended, from the motion obtained, to simulate the so called boot induced anterior drawer (BIAD) injury mechanism. Unfortunately, one of the skiers accidentally tore his ACL during one of the landings in a typical BIAD injury. It was then possible to evaluate electromyographic signals as well as the kinematics and provide a much more precise description of the injury mechanism than otherwise would be possible. The results showed that the injury seemed to take place at a much later stage than expected.

Of course, studies in this category are both rare and undesired. We must therefore consider other approaches for gaining insight into the injury mechanisms. However, although it is difficult to draw general definite conclusions from such single-case studies, they do provide extremely valuable insight into the injury mechanisms when they do occur.

CADAVER AND DUMMY STUDIES

Cadaver studies investigating the anatomy and function of joints and ligaments are numerous.[87–89] A common approach has been to measure the kinematics before and after cutting one or more ligaments of, for example, the knee.[90 91] From such studies, gross estimates of ligament function can be obtained, classifying the ligaments into ''primary restraints'' and ''secondary restraints'', depending on their effect on joint angular or translational motion. It is also possible to mimic the assumed injury mechanism and load an intact cadaver joint to failure, to see if the mechanism produces the intended pathology. A technically more sophisticated approach is the use of strain gauges or force transducers to assess ligament function under different loading conditions. The classic study of Markolf *et al*[92] of combined loads that generated high ACL forces has provided valuable insight into ACL function. Similarly, Berns *et al*[93] also studied combined loading, but measured strain instead of force. Bahr *et al*[94] measured the forces in the anterior talofibular ligament and calcaneofibular ligament as well as the motion in the tibiotalar and subtalar joints during aggressive loading, using buckle transducers. The results confirmed that the anterior talofibular ligament acts as the primary restraint in inversion, during which injuries typically occur.

Although these studies are important in understanding ligament function, their value in injury mechanism research is limited, as lower loads cannot be extrapolated to failure level with confidence.[93] Unfortunately, the validity of cadaver studies is also often hampered by the fact that specimens are old and/or not representative of an athletic population.[95] In addition, the freezing and thawing process reduces the ultimate load of the tissue.[96]

In most studies, muscular support is lacking, although some cadaver studies has also simulated muscle forces in, for example, the quadriceps and/or hamstrings.[97–99] DeMorat *et al*[98] recently conducted a controlled cadaver study in which it was demonstrated that aggressive quadriceps loading in 20° flexion could actually take the ACL to failure, by applying a 4500 N force within one second. A mean anterior displacement of 19.5 mm was measured during the violent quadriceps contractions, and more than half of the knees sustained gross ACL injury at the femoral insertion level. Unfortunately, even in studies in which muscle forces are simulated, the actual muscle force patterns that contribute to the joint dynamics in a real injury situation are unknown, and would probably be difficult to reproduce in such a set up even if they were known.

Another approach used in sports injury research is the use of dummies or physical models, which are well known in car crash testing. Such dummies—for example, the Hybrid III family of dummies—have excellent biofidelity, and can be instrumented with, for example, load sensors and accelerometers.[100] As mentioned above, this approach has been used in laboratory research on the mechanisms for head injury[43] and to test protective equipment such as helmets.[101] As dummies are passive—that is, they lack muscles—the types of injuries that can be investigated using this approach are obviously limited. Nevertheless, in those situations in which the assumptions are met, dummy studies have proven useful.

MATHEMATICAL MODELLING

Sophisticated mathematical modelling and estimation of ''close to injury situations'' or simulation of injury situations has become increasingly popular. Some models take into account whole body dynamics,[102–104] whereas others model only, for example, the knee joint[105] or different aspects of the ACL.[106] Through such models, it is possible to establish the relation between, for example, the measured kinematics, ground reaction forces, and ACL force.[104] Hence, motion analysis using the traditional inverse dynamics approach can be taken to the next level with such approaches, although the challenges are significant.

The advantage of the simulation approach is that one can study different injury mechanisms in a computer environment, thus avoiding any hazard to athletes. Depending on the models, one can study cause-effect relations, for example, between neuromuscular control and knee loading,[102] or intercondylar geometry and ACL impingement.[105]

McLean *et al*[107] developed a three dimensional simulation model for side stepping that could predict body kinematics, ground reaction force, and three dimensional joint forces and moments with relatively good accuracy. Anterior-posterior force could also be calculated from this model. In their next study,[102] Monte Carlo simulations of neuromuscularly perturbed motion were performed based on data from 10 male and 10 female subjects. It was found that the mean estimates of peak anterior drawer force were never positive—that is, the ACL was not loaded in the recorded situations, and also rarely in the simulations. As stated by McLean *et al*, because the muscle activation patterns in the model were not measured but predicted, it is expected that for individual muscles they will not perfectly resemble the true activations. An alternative approach could have been to use (scaled) electromyography as input.[108 109] Another shortcoming in this model was the lack of realistic modelling of joint contact surface—for example, tibial plateau slope—which has been shown to be important for ACL loading.[103]

Owing to the complexity of 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—for example, injury producing—situations may possibly suffer.[102]

The fact that an injury model nearly always needs to be validated, either in a non-injury situation or in vitro, clearly adds a degree of uncertainty to its use. Still, the biggest challenge is probably how to verify that the simulated injury pattern actually resembles what is experienced in real life. This is illustrated well with the experiment of Barone *et al*.[86] If the injury had not occurred during their BIAD experiment, chances are that a ''solution'' not present in the real world could have been found, because the observed injury kinematics differed significantly from all the other non-injury ski jump landings.

ASSESSING THE EVIDENCE

As seen from the description of the various research approaches, evidence relevant for understanding the mechanisms of sports injury can be obtained from widely different methods and study designs. Therefore the traditional evidence hierarchy[110] cannot be applied in this setting. Important insight can be gained from studying the events preceding (for example, the velocity at impact, the playing situation), at (for example, the loads), or after (for example, 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—for example, by studying the loading patterns in a side step cutting manoeuvre in the laboratory 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.[3] 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 behaviour), as well as to include a description of whole body and joint biomechanics at the time of injury.[3]

It is obvious from the different research approaches used that 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.[111] 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 patellar 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 the bone fails.[112]

These premises can be studied with different approaches. For instance, through cadaver experiments[92] and in vivo studies,[113] we know that knee flexion must be approximately 30° or less to enable anterior shear forces through the patellar 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 on key factors—for example, flexion angle estimates.[20 42 51] To achieve greater accuracy, laboratory studies can be used to measure joint angles,[59 65 69] muscle activation patterns,[114 115] and joint loading.[57–59 69 116] However, as 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 validity of evidence from such studies can be questioned. Cadaver studies, on the other hand, can examine directly how the ACL is influenced by the quadriceps force, as shown by, for example, DeMorat *et al*.[98] However, the relevance of this study to actual non-contact ACL injuries was questioned, as a mathematical modelling approach showed that the experimental set up did not replicate the dynamics involved in a sporting situation.[102] Mathematical models can potentially test all the implicated premises. However, again their relevance can be questioned, as 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 achieved using one or more of the categories: cadaver studies, motion analysis studies, and in vivo studies.

What is already known on this topic

Sports injury mechanisms cannot be studied using direct experimental techniques. Other possible approaches are: athlete interviews; clinical studies (radiography, MRI, and CT); video analysis; laboratory motion analysis; in vivo strain/force measurements; injuries during biomechanical experiments; cadaver and dummy studies; mathematical modelling.

What this study adds

- 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 behaviour), as well as include a description of whole body and joint biomechanics leading up to, and at the time of, the injury.
- For most injury types, as no single research approach is adequate in terms of validity, accuracy, and completeness of information provided, it is necessary to combine a number of different approaches to describe the mechanisms fully.

This example is used to illustrate why, in many cases, it is 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 comparison of the findings from one study with those of another. However, there are examples of studies that have successfully combined different approaches in one study. As previously mentioned, Pellman *et al*[43] in their study on head injuries in American football achieved greater validity and accuracy by combining video analysis and a dummy study, than if such studies were performed separately. Likewise, Olsen *et al*[20] combined athlete interviews and video analysis to increase the validity of the video analysis. Unfortunately, clinical or MRI findings of additional knee joint damage that could provide further information to interpret loading patterns were not reported in this, nor in any of the other studies that included video analysis.

RECOMMENDATIONS

Injury mechanisms can be described using different research approaches with a focus on different elements of the inciting event, and suggestions for preventive measures may originate from each category. It is therefore important to investigate all aspects of the injury mechanism. We have reviewed eight different research approaches to the study of the mechanisms of injuries in sport, each with its possibilities and limitations. For most injury types, one research approach alone will not be sufficient to describe all aspects of the injury situation, and it is therefore necessary to combine a number of different research approaches to describe the mechanisms fully. For example, relevant combinations of research approaches that could provide a broader and more precise understanding could be combining athlete interviews, video analysis, and clinical studies, or combining video analysis and cadaver/dummy/mathematical simulation studies.

Authors' affiliations

T Krosshaug, T E Andersen, O-E O Olsen, G Myklebust, R Bahr, Oslo Sports Trauma Research Center, Norwegian University of Sport and Physical Education, Oslo, Norway

Competing interests: none declared

REFERENCES

1 **van Mechelen W**, Hlobil H, Kemper HC. Incidence, severity, aetiology and prevention of sports injuries. A review of concepts. *Sports Med* 1992;**14**:82–99.
2 **Meeuwisse WH**. Assessing causation in sport injury: A multifactorial model. *Clin J Sport Med* 1994;**4**:166–70.
3 **Bahr R**, Krosshaug T. Understanding the injury mechanisms: a key component to prevent injuries in sport. *Br J Sports Med*, 2005;in press..
4 **Arnold JA**, Coker TP, Heaton LM, *et al.* Natural history of anterior cruciate tears. *Am J Sports Med* 1979;**7**:305–13.
5 **Arendt E**, Dick R. Knee injury patterns among men and women in collegiate basketball and soccer. NCAA data and review of literature. *Am J Sports Med* 1995;**23**:694–701.
6 **Orchard J**, Seward H. Epidemiology of injuries in the Australian Football League, seasons 1997–2000. *Br J Sports Med* 2002;**36**:39–44.
7 **Junge A**, Dvorak J, Graf-Baumann T, *et al.* Football injuries during FIFA tournaments and the Olympic Games, 1998–2001: development and implementation of an injury-reporting system. *Am J Sports Med* 2004;**32**:80S–9S.
8 **Ekstrand J**, Walden M, Hagglund M. A congested football calendar and the wellbeing of players: correlation between match exposure of European footballers before the World Cup 2002 and their injuries and performances during that World Cup. *Br J Sports Med* 2004;**38**:493–7.
9 **Andersen TE**, Floerenes TW, Arnason A, *et al.* Video analysis of the mechanisms for ankle injuries in football. *Am J Sports Med* 2004;**32**:69S–79S.
10 **Natri A**, Beynnon BD, Ettlinger CF, *et al.* Alpine ski bindings and injuries. Current findings. *Sports Med* 1999;**28**:35–48.
11 **Gray J**, Taunton JE, McKenzie DC, *et al.* A survey of injuries to the anterior cruciate ligament of the knee in female basketball players. *Int J Sports Med* 1985;**6**:314–16.
12 **Fetto JF**, Marshall JL. The natural history and diagnosis of anterior cruciate ligament insufficiency. *Clin Orthop* 1980:29–38.
13 **Myklebust G**, Maehlum S, Engebretsen L, *et al.* Registration of cruciate ligament injuries in Norwegian top level team handball. A prospective study covering two seasons. *Scand J Med Sci Sports* 1997;**7**:289–92.
14 **Myklebust G**, Maehlum S, Holm I, *et al.* A prospective cohort study of anterior cruciate ligament injuries in elite Norwegian team handball. *Scand J Med Sci Sports* 1998;**8**:149–53.
15 **Arnason A**, Tenga A, Engebretsen L, *et al.* A prospective video-based analysis of injury situations in elite male football: football incident analysis. *Am J Sports Med* 2004;**32**:1459–65.
16 **Hawkins RD**, Fuller CW. A prospective epidemiological study of injuries in four English professional football clubs. *Br J Sports Med* 1999;**33**:196–203.
17 **Ronning R**, Gerner T, Engebretsen L. Risk of injury during alpine and telemark skiing and snowboarding. The equipment-specific distance-correlated injury index. *Am J Sports Med* 2000;**28**:506–8.
18 **Langran M**, Selvaraj S. Increased injury risk among first-day skiers, snowboarders, and skiboarders. *Am J Sports Med* 2004;**32**:96–103.
19 **Strand T**, Tvedte R, Engebretsen L, *et al.* [Anterior cruciate ligament injuries in handball playing. Mechanisms and incidence of injuries]. *Tidsskr Nor Laegeforen* 1990;**110**:2222–5.
20 **Olsen OE**, Myklebust G, Engebretsen L, *et al.* Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am J Sports Med* 2004;**32**:1002–12.
21 **Nakajima H**, Kondo M, Kurosawa H, *et al.* Insufficiency of the anterior cruciate ligament. Review of our 118 cases. *Arch Orthop Trauma Surg* 1979;**95**:233–40.
22 **Chong RW**, Tan JL. Rising trend of anterior cruciate ligament injuries in females in a regional hospital. *Ann Acad Med Singapore* 2004;**33**:298–301.
23 **McNair PJ**, Marshall RN, Matheson JA. Important features associated with acute anterior cruciate ligament injury. *N Z Med J* 1990;**103**:537–9.
24 **Feagin JA Jr**, Curl WW. Isolated tear of the anterior cruciate ligament: 5-year follow-up study. *Am J Sports Med* 1976;**4**:95–100.
25 **Harner CD**, Paulos LE, Greenwald AE, *et al.* Detailed analysis of patients with bilateral anterior cruciate ligament injuries. *Am J Sports Med* 1994;**22**:37–43.
26 **Speer KP**, Warren RF, Wickiewicz TL, *et al.* Observations on the injury mechanism of anterior cruciate ligament tears in skiers. *Am J Sports Med* 1995;**23**:77–81.
27 **Bahr R**, Bahr IA. Incidence of acute volleyball injuries: a prospective cohort study of injury mechanisms and risk factors. *Scand J Med Sci Sports* 1997;**7**:166–71.
28 **Bahr R**, Lian O, Bahr IA. A twofold reduction in the incidence of acute ankle sprains in volleyball after the introduction of an injury prevention program: a prospective cohort study. *Scand J Med Sci Sports* 1997;**7**:172–7.
29 **Speer KP**, Spritzer CE, Bassett FH III, *et al.* Osseous injury associated with acute tears of the anterior cruciate ligament. *Am J Sports Med* 1992;**20**:382–9.

30 **Vellet AD**, Marks P, Fowler P, *et al.* Accuracy of nonorthogonal magnetic resonance imaging in acute disruption of the anterior cruciate ligament. *Arthroscopy* 1989;**5**:287–93.

31 **Fanucci E**, Masala S, Gaudioso C, *et al.* [Computerized tomography assessment of bone damage following injury of the anterior cruciate ligament]. *Radiol Med (Torino)* 1995;**89**:608–12.

32 **Noyes FR**, Bassett RW, Grood ES, *et al.* Arthroscopy in acute traumatic hemarthrosis of the knee. Incidence of anterior cruciate tears and other injuries. *J Bone Joint Surg [Am].* 1980;62: 687–95, 757).

33 **Rosen MA**, Jackson DW, Berger PE. Occult osseous lesions documented by magnetic resonance imaging associated with anterior cruciate ligament ruptures. *Arthroscopy* 1991;**7**:45–51.

34 **Spindler KP**, Schils JP, Bergfeld JA, *et al.* Prospective study of osseous, articular, and meniscal lesions in recent anterior cruciate ligament tears by magnetic resonance imaging and arthroscopy. *Am J Sports Med* 1993;**21**:551–7.

35 **Ferretti A**, Papandrea P, Conteduca F, *et al.* Knee ligament injuries in volleyball players. *Am J Sports Med* 1992;**20**:203–7.

36 **Silver JR**, Gill S. Injuries of the spine sustained during rugby. *Sports Med* 1988;**5**:328–34.

37 **Ettlinger CF**, Johnson RJ, Shealy JE. A method to help reduce the risk of serious knee sprains incurred in alpine skiing. *Am J Sports Med* 1995;**23**:531–7.

38 **Andersen TE**, Larsen O, Tenga A, *et al.* Football incident analysis: a new video based method to describe injury mechanisms in professional football. *Br J Sports Med* 2003;**37**:226–32.

39 **Andersen TE**, Tenga A, Engebretsen L, *et al.* Video analysis of injuries and incidents in Norwegian professional football. *Br J Sports Med* 2004;**38**:626–31.

40 **Andersen TE**, Engebretsen L, Bahr R. Rule violations as a cause of injuries in male norwegian professional football: are the referees doing their job? *Am J Sports Med* 2004;**32**:62S–8S.

41 **Andersen TE**, Arnason A, Engebretsen L, *et al.* Mechanisms of head injuries in elite football. *Br J Sports Med* 2004;**38**:690–6.

42 **Boden BP**, Dean GS, Feagin JA Jr, *et al.* Mechanisms of anterior cruciate ligament injury. *Orthopedics* 2000;**23**:573–8.

43 **Pellman EJ**, Viano DC, Tucker AM, *et al.* Concussion in professional football: reconstruction of game impacts and injuries. *Neurosurgery* 2003;**53**:799–812.

44 **Fuller CW**, Smith GL, Junge A, *et al.* The influence of tackle parameters on the propensity for injury in international football. *Am J Sports Med* 2004;**32**:43S–53S.

45 **Fuller CW**, Junge A, Dvorak J. An assessment of football referees' decisions in incidents leading to player injuries. *Am J Sports Med* 2004;**32**:17S–22S.

46 **Hawkins RD**, Fuller CW. An examination of the frequency and severity of injuries and incidents at three levels of professional football. *Br J Sports Med* 1998;**32**:326–32.

47 **Fuller CW**, Smith GL, Junge A, *et al.* An assessment of player error as an injury causation factor in international football. *Am J Sports Med* 2004;**32**:28S–35S.

48 **Giza E**, Fuller C, Junge A, *et al.* Mechanisms of foot and ankle injuries in soccer. *Am J Sports Med* 2003;**31**:550–4.

49 **Arnason A**, Engebretsen L, Bahr R. No effect of a video-based awareness program on the rate of soccer injuries. *Am J Sports Med* 2005;**33**:77–84.

50 **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**:919–29.

51 **Teitz CC**. Video analysis of ACL injuries. In: Griffin LY, eds. *Prevention of noncontact ACL injuries.* Rosemont, IL: American Association of Orthopaedic Surgeons, 2001:87–92.

52 **McIntosh AS**, McCrory P, Comerford J. The dynamics of concussive head impacts in rugby and Australian rules football. *Med Sci Sports Exerc* 2000;**32**:1980–4.

53 **Roh JO**, Watkinson EJ. Video analysis of blows to the head and face at the 1999 World Taekwondo Championships. *J Sports Med Phys Fitness* 2002;**42**:348–53.

54 **McCrory PR**, Berkovic SF. Video analysis of acute motor and convulsive manifestations in sport-related concussion. *Neurology* 2000;**54**:1488–91.

55 **Rahnama N**, Reilly T, Lees A. Injury risk associated with playing actions during competitive soccer. *Br J Sports Med* 2002;**36**:354–9.

56 **McIntosh AS**, McCrory P, Finch CF, *et al.* Rugby headgear study. *J Sci Med Sport* 2003;**6**:355–8.

57 **McLean SG**, Lipfert SW, Van Den Bogert AJ. Effect of gender and defensive opponent on the biomechanics of sidestep cutting. *Med Sci Sports Exerc* 2004;**36**:1008–16.

58 **Salci Y**, Kentel BB, Heycan C, *et al.* Comparison of landing maneuvers between male and female college volleyball players. *Clin Biomech (Bristol, Avon)* 2004;**19**:622–8.

59 **Pollard CD**, Davis IM, Hamill J. Influence of gender on hip and knee mechanics during a randomly cued cutting maneuver. *Clin Biomech (Bristol, Avon)* 2004;**19**:1022–31.

60 **Hewett TE**, Myer GD, Ford KR, *et al.* Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes. A prospective study. *Am J Sports Med,* 2005;in press..

61 **Ford KR**, Myer GD, Toms HE, *et al.* Gender differences in the kinematics of unanticipated cutting in young athletes. *Med Sci Sports Exerc* 2005;**37**:124–9.

62 **McLean SG**, Neal RJ, Myers PT, *et al.* Knee joint kinematics during the sidestep cutting maneuver: potential for injury in women. *Med Sci Sports Exerc* 1999;**31**:959–68.

63 **Malinzak RA**, Colby SM, Kirkendall DT, *et al.* A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clin Biomech (Bristol, Avon)* 2001;**16**:438–45.

64 **Huston LJ**, Vibert B, Ashton-Miller JA, *et al.* Gender differences in knee angle when landing from a drop-jump. *Am J Knee Surg* 2001;**14**:215–19.

65 **Fagenbaum R**, Darling WG. Jump landing strategies in male and female college athletes and the implications of such strategies for anterior cruciate ligament injury. *Am J Sports Med* 2003;**31**:233–40.

66 **James CR**, Sizer PS, Starch DW, *et al.* Gender differences among sagittal plane knee kinematic and ground reaction force characteristics during a rapid sprint and cut maneuver. *Res Q Exerc Sport* 2004;**75**:31–8.

67 **Cowling EJ**, Steele JR. Is lower limb muscle synchrony during landing affected by gender? Implications for variations in ACL injury rates. *J Electromyogr Kinesiol* 2001;**11**:263–8.

68 **Chappell JD**, Yu B, Kirkendall DT, *et al.* A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. *Am J Sports Med* 2002;**30**:261–7.

69 **Decker MJ**, Torry MR, Wyland DJ, *et al.* Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clin Biomech (Bristol, Avon)* 2003;**18**:662–9.

70 **Besier TF**, Lloyd DG, Ackland TR, *et al.* Anticipatory effects on knee joint loading during running and cutting maneuvers. *Med Sci Sports Exerc* 2001;**33**:1176–81.

71 **Cowling EJ**, Steele JR. The effect of upper-limb motion on lower-limb muscle synchrony. Implications for anterior cruciate ligament injury. *J Bone Joint Surg [Am]* 2001;**83**:35–41.

72 **Reinschmidt C**, Van Den Bogert AJ, Nigg BM, *et al.* Effect of skin movement on the analysis of skeletal knee joint motion during running. *J Biomech* 1997;**30**:729–32.

73 **Cappozzo A**, Catani F, Leardini A, *et al.* Position and orientation in space of bones during movement: experimental artefacts. *Clin Biomech* 1996;**11**:90–100.

74 **Della Croce U**, Cappozzo A, Kerrigan DC. Pelvis and lower limb anatomical landmark calibration precision and its propagation to bone geometry and joint angles. *Med Biol Eng Comput* 1999;**37**:155–61.

75 **Cappello A**, LaPalombara PF, Leardini B. Optimization and smoothing techniques in movement analysis. *Int J Biomed Comput* 1996;**41**:137–51.

76 **Woltring HJ**. On optimal smoothing and derivate estimation from noisy displacement data in biomechanics. *Hum Mov Sci* 1985;**4**:229–45.

77 **Hewett TE**, Stroupe AL, Nance TA, *et al.* Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. *Am J Sports Med* 1996;**24**:765–73.

78 **Hewett TE**, Lindenfeld TN, Riccobene JV, *et al.* The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. *Am J Sports Med* 1999;**27**:699–706.

79 **Beynnon BD**, Fleming BC. Anterior cruciate ligament strain in-vivo: a review of previous work. *J Biomech* 1998;**31**:519–25.

80 **Fukashiro S**, Komi PV, Järvinen M, *et al.* In vivo achilles tendon loading during jumping in humans. *Eur J Appl Physiol* 1995;**71**:453–8.

81 **Finni T**, Komi PV, Lepola V. In vivo human triceps surae and quadriceps femoris muscle function in a squat jump and counter movement jump [In Process Citation]. *Eur J Appl Physiol* 2000;**83**:416–26.

82 **Maganaris CN**, Paul JP. Tensile properties of the in vivo human gastrocnemius tendon. *J Biomech* 2002;**35**:1639–46.

83 **Bey MJ**, Song HK, Wehrli FW, *et al.* A noncontact, nondestructive method for quantifying intratissue deformations and strains. *J Biomech Eng* 2002;**124**:253–8.

84 **Cerulli G**, Benoit DL, Lamontagne M, *et al.* In vivo anterior cruciate ligament strain behaviour during a rapid deceleration movement: case report. *Knee Surg Sports Traumatol Arthrosc* 2003;**11**:307–11.

85 **Zernicke RF**, Garhammer J, Jobe FW. Human patellar-tendon rupture. *J Bone Joint Surg [Am]* 1977;**59**:179–83.

86 **Barone M**, Senner V, Schaff P. ACL injury mechanism in alpine skiing: analysis of an accidental ACL rupture. In: Johnson RJ, eds. *Skiing trauma and safety: 12th edition, ASTM STP 1345.* West Conshohocken, PA: American Society for Testing and Materials, 1999;**12**:63–81.

87 **Girgis FG**, Marshall JL, Monajem A. The cruciate ligaments of the knee joint. Anatomical, functional and experimental analysis. *Clin Orthop* 1975:216–31.

88 **Furman W**, Marshall JL, Girgis FG. The anterior cruciate ligament. A functional analysis based on postmortem studies. *J Bone Joint Surg [Am]* 1976;**58**:179–85.

89 **Rong GW**, Wang YC. The role of cruciate ligaments in maintaining knee joint stability. *Clin Orthop* 1987:65–71.

90 **Veltri DM**, Deng XH, Torzilli PA, *et al.* The role of the cruciate and posterolateral ligaments in stability of the knee. A biomechanical study. *Am J Sports Med* 1995;**23**:436–43.

91 **Matsumoto H**, Suda Y, Otani T, *et al.* Roles of the anterior cruciate ligament and the medial collateral ligament in preventing valgus instability. *J Orthop Sci* 2001;**6**:28–32.

92 **Markolf KL**, Burchfield DM, Shapiro MM, *et al.* Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res* 1995;**13**:930–5.

93 **Berns GS**, Hull ML, Patterson HA. Strain in the anteromedial bundle of the anterior cruciate ligament under combination loading. *J Orthop Res* 1992;**10**:167–76.

94 **Bahr R**, Pena F, Shine J, *et al.* Ligament force and joint motion in the intact ankle: a cadaveric study. *Knee Surg Sports Traumatol Arthrosc* 1998:115–21.

95 **Woo SL**, Hollis JM, Adams DJ, *et al.* Tensile properties of the human femur-anterior cruciate ligament-tibia complex. The effects of specimen age and orientation. *Am J Sports Med* 1991;**19**:217–25.

96 **Clavert P**, Kempf JF, Bonnomet F, *et al.* Effects of freezing/thawing on the biomechanical properties of human tendons. *Surg Radiol Anat* 2001;**23**:259–62.

97 **Markolf KL**, O'Neill G, Jackson SR, *et al.* Effects of applied quadriceps and hamstrings muscle loads on forces in the anterior and posterior cruciate ligaments. *Am J Sports Med* 2004;**32**:1144–9.

98 **DeMorat G**, Weinhold P, Blackburn T, *et al.* Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury. *Am J Sports Med* 2004;**32**:477–83.

99 **Renstrom P**, Arms SW, Stanwyck TS, *et al.* Strain within the anterior cruciate ligament during hamstring and quadriceps activity. *Am J Sports Med* 1986;**14**:83–7.

100 **Mertz HJ**. Anthropometric test devices. In: Nahum AM, Melvin JW, eds. *Accidental injury. Biomechanics and prevention.* New York: Springer-Verlag, 2002:89–102.

101 **McIntosh AS**, Janda D. Evaluation of cricket helmet performance and comparison with baseball and ice hockey helmets. *Br J Sports Med* 2003;**37**:325–30.

102 **McLean SG**, Huang X, Su A, *et al.* Sagittal plane biomechanics cannot injure the ACL during sidestep cutting. *Clin Biomech (Bristol, Avon)* 2004;**19**:828–38.

103 **Pflum MA**, Shelburne KB, Torry MR, *et al.* Model prediction of anterior cruciate ligament force during drop-landings. *Med Sci Sports Exerc* 2004;**36**:1949–58.

104 **Simonsen EB**, Magnusson SP, Bencke J, *et al.* Can the hamstring muscles protect the anterior cruciate ligament during a side-cutting maneuver? *Scand J Med Sci Sports* 2000;**10**:78–84.

105 **Fung DT**, Zhang LQ. Modeling of ACL impingement against the intercondylar notch. *Clin Biomech (Bristol, Avon)* 2003;**18**:933–41.

106 **Hirokawa S**, Tsuruno R. Three-dimensional deformation and stress distribution in an analytical/computational model of the anterior cruciate ligament. *J Biomech* 2000;**33**:1069–77.

107 **McLean SG**, Su A, Van Den Bogert AJ. Development and validation of a 3-D model to predict knee joint loading during dynamic movement. *J Biomech Eng* 2003;**125**:864–74.

108 **Lloyd DG**, Besier TF. An EMG-driven musculoskeletal model to estimate muscle forces and knee joint moments in vivo. *J Biomech* 2003;**36**:765–76.

109 **Zheng N**, Fleisig GS, Escamilla RF, *et al.* An analytical model of the knee for estimation of internal forces during exercise. *J Biomech* 1998;**31**:963–7.

110 **Brighton B**, Bhandari M, Tornetta P III, *et al.* Hierarchy of evidence: from case reports to randomized controlled trials. *Clin Orthop* 2003:19–24.

111 **Kirkendall DT**, Garrett WE Jr. The anterior cruciate ligament enigma. Injury mechanisms and prevention. *Clin Orthop* 2000:64–8.

112 **Lee M**, Hyman W. Modeling of failure mode in knee ligaments depending on the strain rate. *BMC Musculoskelet Disord* 2002;**3**:3.

113 **Fleming BC**, Beynnon BD, Nichols CE, *et al.* An in vivo comparison of anterior tibial translation and strain in the anteromedial band of the anterior cruciate ligament. *J Biomech* 1993;**26**:51–8.

114 **Colby S**, Francisco A, Yu B, *et al.* Electromyographic and kinematic analysis of cutting maneuvers. Implications for anterior cruciate ligament injury. *Am J Sports Med* 2000;**28**:234–40.

115 **Cowling EJ**, Steele JR, McNair PJ. Effect of verbal instructions on muscle activity and risk of injury to the anterior cruciate ligament during landing. *Br J Sports Med* 2003;**37**:126–30.

116 **Besier TF**, Lloyd DG, Ackland TR. Muscle activation strategies at the knee during running and cutting maneuvers. *Med Sci Sports Exerc* 2003;**35**:119–27.

ECHO

Head on tackle scores a memorable injury

Axial fine section computed tomogram through C1 ring showing anterior arch midline cleft with diastasis (arrowheads).

Caution is the watchword for neck injuries sustained in contact sports, as the first ever reported case of an atlas fracture in an adult sports player has shown. Keeping to a defined clinical system of examination, x ray investigations, and interpretation is essential for a correct diagnosis, however rare that diagnosis may be. The telling sign in this case— swelling behind the pharynx—could be the only clue to a serious injury.

The 28 year old male 16 stone (102 kg) rugby player sustained the injury meeting a tackle head on during a match. Immediately he felt a dull pain throughout his neck, greatly worsened by trying to run. Later the pain focused in the axial area, and his head felt heavy and loose.

A lateral spine radiograph taken two days later showed pronounced soft tissue swelling behind the pharynx in the upper cervical spine. An open mouth view showed a slight asymmetry in the atlas-axis joints and minor lateral displacement of the C1 vertebra. Reassessment of the radiographs at a regional neurological centre prompted a computed tomographic examination through the C1 ring, which disclosed a rare—probably congenital—anterior arch midline cleft with separation of the anterior cartilaginous joint. The joint would be prone to breakage with axial compression loading if incomplete ossification of the C1 ring persisted into adulthood.

The man had his neck immobilised in an Aspen collar cervical orthosis for about 10 weeks or so. The atlas cleft remained, but the swelling and neck movement were normal. Unsurprisingly, he was advised to avoid contact sports.

Leigh–Smith, *et al. Emergency Medicine Journal* 2005;**22**:225–226

Please visit the *British Journal of Sports Medicine* website [www.bjsportmed.com] for a link to the full text of this article.