A DYNAMIC ANALYSIS OF KNEE LIGAMENT INJURIES IN ALPINE SKIING

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The aim of this study is to understand better the dynamic mechanisms of anterior cruciate ligament (ACL) rupture in alpine skiing. As a result of these findings, improvements in the boot-binding release systems are proposed. Six patients who sustained ACL rupture, aged 19 to 43 years, were studied. A step by step reconstruction of the accident was made using a questionnaire followed by an interview. The skiing equipment was tested in a specialized laboratory and the release levels of the boot-binding systems were measured in twist and in forward lean. ACL injury was confirmed by arthroscopy or surgery. Most patients had recent skiing equipment ; their binding systems were correctly mounted and in perfect working order. Release levels of the bindings were equal to or slightly above those suggested by the ISO standards. The mechanisms of injury were valgus-external rotation in knee flexion of more than 90°, internal rotation in knee flexion of more than 120° with anterior drawer loads, internal rotation-valgus in knee flexion of less than 30° with anterior drawer loads, external rotation-valgus in knee flexion of more than 120° with anterior drawer loads, external rotation in knee flexion of about 100° with anterior drawer loads and internal rotation-valgus.

Even with a modern boot-binding system, properly adjusted, ACL injury remains possible. The improvements in the current equipment should be concerned with the behavior when confronted with combined loads producing friction in the system. We concluded that for lateral release at the toe, there should be a better compensation of the vertical parasite forces and an improvement of the antifriction devices. In order to prevent excessive anterior drawer loads on the ACL an additional release direction of the binding system, especially backwards, could, if properly adjusted, enhance the opportunities of early release in a dangerous backward lean "out of control" position.

Keywords : alpine skiing ; ski injuries ; safety binding system ; anterior cruciate ligament ; knee injuries.
Mots-clés : ski alpin ; accidents de ski ; fixations de sécurité ; ligament croisé antérieur ; genou ligamentaire.

INTRODUCTION

Thirty years of progress in ski equipment and improvement in the binding release system have brought a decrease in the overall number of alpine skiing injuries as well as a decrease in the relative proportion of ankle and tibial injuries (4, 13, 14, 17, 19). However the number of knee ligament injuries has remained almost constant throughout the years, representing about 20% of all ski injuries (12, 13, 14, 17, 18, 19, 21). Furthermore, the severity of knee ligament injuries is increasing with a specific trend towards "isolated" or "principal injury" ACL rupture (2, 18).

The literature contains many statistical and epidemiological studies, but few "case reports" are available analyzing the dynamic mechanism of the injury. Several mechanisms have been reported. Combined external rotation and valgus of the

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knee when the skier "catches an inside edge" is commonly reported (18). Isolated ACL rupture in hyperextension of the knee may be caused by sudden arrest of the ski under heavy snow (18). A mechanism of ACL injury exclusively related to skiers, described as "boot-induced ACL rupture" by Johnson in 1982 (10), occurs when a skier lands on the ski tail after a jump (3, 8). The ski rotates down around its tail and forces the boot and the lower leg forward. The boot top produces an anteriorly directed force to the posterior part of the midcalf. This force produces an anterior drawer mechanism in the knee. McConkey (18) describes combined forces applied to the ACL while the skier is attempting to recover from a backwards fall. The skier's center of gravity shifting rearwards is counteracted first by passive locking of the ankle by the boot-top (3, 8, 10) and second by the skier's attempting to lock the knee by active contraction of the quadriceps. External load on the ACL caused by the "boot-induced" mechanism is combined with active eccentric quadriceps contraction which results in a "quadriceps-induced" anterior drawer which can induce ACL rupture (7, 18). Ettlinger recently described the "Phantom foot" (6) related to the unnatural lever produced by the rear part of the ski. The modern alpine ski is designed to turn when the weight is put on its edge. If the weight is on the inner edge of the ski during a backward fall, a sharp uncontrolled inward turn of the ski can be induced. This results in internal rotation of the tibia on the flexed knee, leading to an isolated ACL rupture.

It is now well known that ACL injuries occur frequently without the boot-binding mechanism being released (2, 5, 13). Modern bindings, together with a rigid boot, have been shown to be effective in preventing tibial fractures and ankle sprains. They seem to be much less effective in the prevention of knee injuries, especially ACL tears (1, 4, 7, 10, 12, 14, 16, 18, 22, 23, 24).

In Switzerland, ever since work on the prevention of ski accidents was started in the 1960's, a large number of case studies have been carried out. In the last few years, the accent has been put on knee ligament injuries. In an effort to identify the different mechanisms of the lesions, we have relied especially on the method of subsequent reconstruction of the circumstances of the accident, by means of a questionnaire, interview and examination of the ski equipment. Apart from the subsequent reconstruction, we recorded and analyzed each fall transmitted by television during the World Cup races in the last few years. The material collected in this way provided useful indications which helped us realize that the spectrum of possible effects during a fall is extremely wide. Unfortunately these falls are rarely representative of those which occur during recreational skiing, which is in fact our subject of interest.

Aim of the study

In most skiing accidents, the mechanisms of injury to the ACL remain poorly understood. The aim of this study is to identify some of these mechanisms by a detailed study of a small number of cases, in order to find a practical means of prevention related to the skiing equipment. For equipment testing, a better knowledge of the injury mechanisms should lead to improved simulation in the laboratory, of the dangerous situations encountered in skiing.

At present, there exist only two methods of identifying the mechanism of ACL injury in alpine skiing. First, motion analysis using the observation of video tape recordings and second, the subsequent reconstruction of the injury mechanism. Film observation was felt to be the most promising method. Video tape recordings of falls allow detailed motion analysis and help in evaluating the forces involved during the fall. Unfortunately it is extremely difficult to obtain reliable evidence. The probability of observing a fall is low ; of observing a dangerous fall very low ; of observing a dangerous fall with a knee ligament injury even lower. Therefore, the probability of having a camera while observing a dangerous fall with an ACL injury is almost insignificant. In order to improve opportunities, specific circumstances in skiing must be chosen, such as during competitions or training. This of course limits the observation to imposed runs and to elite skiers. The results show a restricted selection of mechanisms of injury that are hardly representative of those which occur in the majority of recreational skiers. Out of the hundreds of falls recorded on television during the World Cup races in the last few years, only one resulted in a knee ligment injury. This concerned an ACL rupture during a downhill race, caused by a landing on the rear end of the skis following a jump (10). Furthermore, in most cases, motion analysis only allows a very approximate evaluation of the forces involved.

The second method is based on the reconstruction of the mechanism of injury through analysis of the following data : skier's description of the event (questionnaire and interview), diagnosis of the knee ligament injury, measurement of the release level of the binding system and possibly an eye-witness description of the event. In some cases, a complete and reliable reconstruction of the event can be obtained. This is possible when the skier has the analytic faculty of breaking down the event and of analyzing the motion, if the mechanism is not too complex and when the diagnosis is clearly established. In our experience, the easiest events to memorize are those in which the injury occurred at an early stage of the fall, when losing one's balance or when attempting to recover from an "out of control" situation. The mechanisms of injury that are identified in these situations remain fairly simple. At best, this method allows an evaluation of the principal forces involved. Even if their successive involvement is known, their intensity remains unknown.

Aware of the limits and complementary nature of both methods of investigation and of the paucity of other methods available, we chose the second one, strongly believing that it remains the most reliable to analyze the mechanisms of ACL injury in alpine skiing.

MATERIALS AND METHODS

In the present article, we have chosen to present 6 recent case studies with ACL injuries in alpine skiing, with or without associated lesions. One female and 5 males, ranging in age from 19 to 43 years (average age 29 years) were studied. Reconstruction of the forces leading to the ACL injury was attempted from the diagnosis of ACL injury, the interpretation of the patient's description of the events and a mechanical assessment in a specialized laboratory of the boot-binding security system.

Questionnaire

In the emergency treatment center, a questionnaire was given to the patient by the orthopedic surgeon. Multiple choice questions, suggesting diverse mechanisms of injuries using visual analogue sequences were proposed, allowing simple answers. This questionnaire was principally concerned with the following points :

— Morphology of the skier and his level of skiing
— Skiing conditions at the time of the accident
— Type of figure performed by the skier and his intentions before the fall
— Description of the fall.

The patient was asked to answer the questionnaire without help or time limit.

Checking of the equipment

The patient's skiing equipment was collected immediately and assessed by the LMA-SFIT. Data concerning the equipment characteristics (make, model), dimensions of the boots, condition of material, possible errors in setting, adjustment and function of the bindings, measurement of the level of release were evaluated and noted. Release levels of the boot-binding system were measured both in twist and forward lean positions and compared to those given in the setting tables of the Swiss Council for Accident Prevention bfu (25), for the skier concerned.

Diagnosis

The clinical assessments of functional knee stability were performed and documented according to the OAK Knee evaluation charts (20). Clinical evaluation was performed in the emergency room by the same orthopedic surgeon and repeated under anesthesia prior to reconstructive surgery and/or arthroscopy. Arthroscopic and/or surgical findings were recorded on special forms.

Interview

Two to six weeks after injury, the patient was interviewed more closely and was asked to reconstruct the unfolding of events of his accident. The patient's answers to the questionnaire and the results of the equipment evaluation by the LMA-SFIT were discussed. Helped by a deformable wooden articulated mannequin, the patient was asked to describe his successive body positions and sensations, such as sudden pain, giving

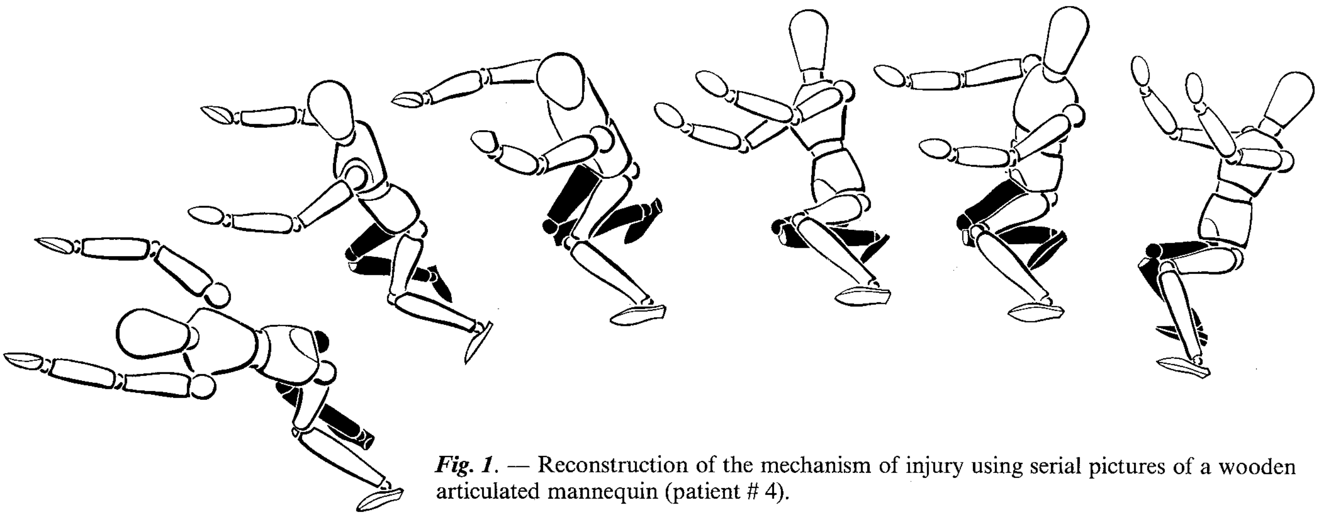

Fig. 1. — Reconstruction of the mechanism of injury using serial pictures of a wooden articulated mannequin (patient # 4).

way, snapping, or loss of power. Serial pictures of the mannequin illustrating the accident accompanied the interview (fig. 1).

RESULTS

The histories of the 6 injured skiers are outlined in table I. Two of them (patients 1 and 4) are described in detail and taken as examples.

Patient number 1 was a 43-year-old expert skier, fit and well trained for skiing. His skiing equipment was recent and kept in good working condition. The twist release level of the bindings was 15 to 20% above the bfu advised level (25). The forward lean release level was 37% above the bfu recommendation. The patient reported that inadvertent forward release occurred occasionally while skiing. At the time of injury, skiing conditions were good and the snow tightly packed. The skier was practicing successive giant slalom turns. While turning to the right, full weight was applied to the left downhill ski. Just before shifting weight to the right, the inside edge of the right ski caught in the snow. With no weight at all on the right ski, the ski diverged widely and slid forwards accelerating at the same time. The skier assumed a sitting position with the knee flexed more than 90°. Applying weight on the rear part of the right ski's inside edge curved the ski towards the left and brought it rapidly under the skier. The skier fell laterally to the right with the skis parallel. Release of the bindings did not occur. A "pop" coming from the right knee was clearly perceived, while the right foot was felt to be pulled laterally. At this moment, the leg was nonweight bearing due to a strong activity of the hip flexor muscles (fig. 2). Diagnosis at reconstructive surgery confirmed an ACL rupture with a bucket handle tear of the medial meniscus, a posterior oblique ligament tear and a grade II MCL sprain.

The supposed mechanism of injury was a large valgus displacement of the tibia accompanied by external rotation, in knee flexion of more than

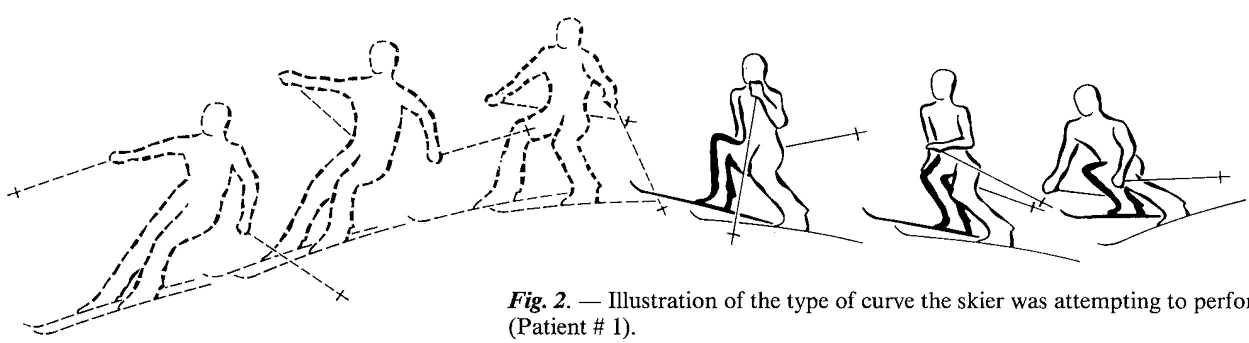

Fig. 2. — Illustration of the type of curve the skier was attempting to perform (Patient # 1).

Table I. — Case histories

Patient	Age (years)	Sex	Skier's skill	Release levels of the binding		Binding release	Snow condition Skiing maneuver or event	Time of Fall relative to Injury
				in twist	in forward lean			
1	43	M	Expert	15-20% above*	37% above*	no	Packed snow Giant slalom type of curve	after injury
2	26	M	Intermediate	low, irregular AFD missing	low	no	Hard packed snow Hit from rear by a skier, while stopped and passive	together
3	41	F	Advanced	14% above* AFD missing	48% above*	no	Packed snow Getting off a chair lift, ski is trapped on the neighbor's ski	together
4	39	M	Expert	according to bfu	according to bfu	no	Deep powder Successive turns	after injury
5	29	M	Advanced	25% above*	12% above*	no	Bumpy, packed soft and heavy snow Uphill turn, overriding	no fall
6	18	M	Expert Triathlete	High competition setup	High competition setup	no	Hard, icy packed snow Giant slalom Recovery from a late turn	no fall

Table I. — Case histories (*continued*)

Diagnosis	Knee flexion at the time of injury (degrees)	Mechanism of injury	Forces involved centered at ankle joint	Preventive technical measures proposed
ACL rupture POL tear bucket handle tear of medial meniscus Grade II MCL	90-110	Valgus Little external rotation	Fy, Mz	Lateral release at the heel
ACL rupture MCL rupture POL tear medial meniscus detached from POL	> 120	Internal rotation Anterior drawer	Fz, My	Release in backward lean
ACL avulsion Grade II MCL	0-30	Internal rotation-valgus	Mz, Fx, Fy	Lateral release at the heel AFD
ACL rupture Grade I-II MCL	> 120	External rotation-valgus Anterior drawer	Fz, Mz, Fy, (My)	Improved AFD or compensating device, very efficient with a high Fz
ACL rupture	90-110	External rotation Anterior drawer	Mz, Fz, My	Improved AFD or compensating device, very efficient with a high Fz Release in backward lean
ACL avulsion	~ 90	Internal rotation-valgus	Mz, Fz, My	Improved AFD or compensating device, very efficient with a high Fz

M : Male ; F : Female ; * Release level of the binding compared to bfu setting tables (25), given in % ; AFD : Anti-Friction Device.

90°. On a coordinate system centered at the ankle joint (fig. 3), loads involved are **Fy** and **Mz**.

Patient number 4 was a 39-year-old excellent recreational skier. His skiing equipment was recent. The twist release level of the bindings was checked by muscle power. The twist and the forward lean release level of the bindings measured were in accordance with the bfu advised levels. At the time of injury, the patient was skiing in deep powder snow in a steep forest. In successive curves, the skier started turning to the right with the knees in full flexion, especially the right uphill knee. Suddenly the tip of the right ski was pulled laterally uphill, almost forcing the skier to sit on his bindings. A loud snap was felt in the right knee while in flexion. The skier finally fell downhill to the left (fig. 1). The diagnosis at surgery confirmed a femoral avulsion of the ACL and a grade II MCL sprain. The mechanism of injury was explained as being external rotation-valgus in knee flexion of more than 120° with combined anterior drawer loads. Centered at the ankle joint, the two main forces involved are **Mz** and **Fz** (fig. 4).

The mechanism observed for the other patients included : internal rotation of the leg in knee flexion of more than 120° with combined anterior drawer loads, internal rotation-valgus in knee flexion of less than 30° with combined anterior drawer loads, external rotation in knee flexion of about 100° with combined anterior drawer loads and internal rotation-valgus.

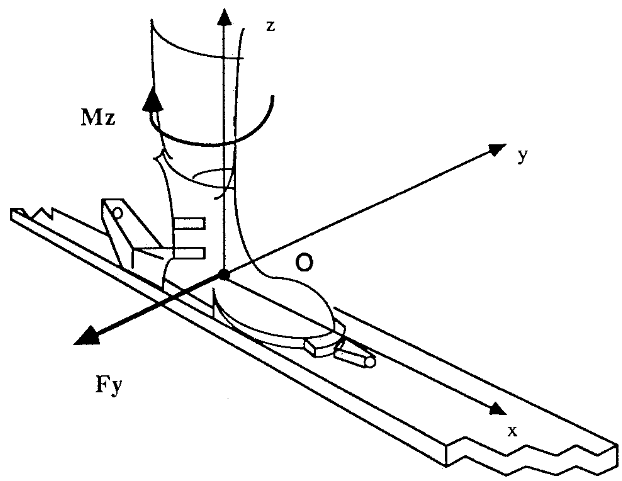

Fig. 3. — Loads involved in patient # 1, centered at the ankle joint. 0, x, y, z = Coordinate system centered at the ankle joint. Fx, Fy, Fz = forces acting from the ski to the boot ; Mx, My, Mz = moments acting from the ski to the boot.

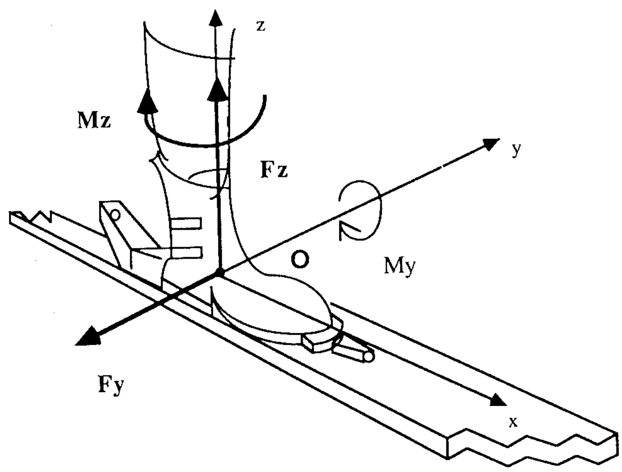

Fig. 4. — Loads involved in patient # 4.

DISCUSSION

In some cases, the ACL injury occurred in an attempt to recover from an uncontrolled situation prior to a fall. In the majority of cases, the injurious force leading to ACL injury occurred in a different and delayed situation other than the initial loss of balance. This emphasizes the importance of a detailed interview with the skier in addition to the questionnaire, in order to fully understand the dynamic mechanism of ACL injury.

In each case, the ACL injury occurred without bindings being released. However the binding release levels, relatively high in most cases, were acceptable for the kind of skiing practiced by the injured skiers. Most injuries described in this study occurred with recent binding systems, correctly adjusted and maintained, with a setup close to those recommended by the current bfu (25) or ISO (11) tables.

The influence of vertical forces leads to friction and high twist release levels of the binding systems. These parasite forces must be neutralized through improved antifriction devices and/or through efficient systems of compensation. Sophisticated systems of compensation, studied to neutralize these parasite forces, exist, but for marketing reasons are efficiently adapted initially on first-class bindings reserved for expert skiers or competitors. There is a demand for adequate systems of compensation properly adapted to the majority of recreational skiers (5).

The current type of binding with an upward release mechanism (Look, Marker) only has a coupled twist-upward release system. We know that efforts in a backward lean position are vastly different from one skier to another. In order to prevent inadvertent releases, manufacturers must set the relative release level upward/twist very high. Therefore the upward release is useless as a protector. A separate upward and twist release system would better protect the knee and its ligaments. Knowing that it may give additional problems at the ski shop, we still believe that there is a potential for preventing ACL injury by an upward release at the toe. However we believe that this potential is a long way from being put into use because of the type of bindings existing with a coupled upward-twist release mechanism only.

For binding setting, recent studies (9, 15, 21, 24, 26) have shown that adequate settings, allowing release of the boot in dangerous situations and avoiding inadvertent release in normal skiing conditions, are much more difficult to find for skilled skiers than for average ones.

Another point confirmed in our study concerns the release setting in twist and forward lean. It is obvious that the probability of early release in a dangerous situation will be higher for a lower setting. For the skilled skier particularly, there is a very narrow margin or no margin at all between "just sufficient" for skiing and "too much" in a dangerous fall. Despite higher settings than recommended, some skiers in this study occasionally experienced inadvertent release in forward lean. It appears that the possibility to obtain better protection by having lower settings would be minimal for the release in forward lean. For the twist release however the potential of protection through lower settings is better. According to our experience gained during practical tests for certification of the bindings, we determined that many skilled skiers could use lower settings for twist release than indicated in the bfu (25) or ISO (11) setting tables, without inadvertent release.

In order to find the optimal settings, bindings should first be set with a setting device according to the current bfu or ISO setting tables. From this setting, the skier should try to gradually lower the setting for the twist release to the limit allowing the skier to ski without inadvertent release. This setting should not necessarily be the same for all skiing conditions.

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SAMENVATTING

J. F. FISCHER, P. F. LEYVRAZ, A. BALLY. Biomechanische analyse van kniebandletsels in alpenski.

Tijdens de afgelopen 30 jaar heeft de verbetering van de veiligheidsbindingen een globale vermindering van de ski-ongevallen voor gevolg ; het aantal bandletsels t.h.v. de knie blijft echter vrij hoog en de ernst van deze letsels zou zelfs toenemen. Deze studie beoogt een betere benadering van de biomechanica van de kniebandletsels, aan de hand van enige, in detail grondig onderzochte, gevallen. Met de verkregen resultaten moet een concrete verbetering van de bindingssystemen kunnen voorgesteld worden. Beschrijving van vaststellingen bij 6 patiënten tussen 19 en 43 jaar, met een ruptuur van de voorste kruisband. Het ongeval werd stap voor stap gereconstrueerd, met behulp van een vragenlijst, waarbij het ongeval sekwentieel ontleed wordt ; daarna volgt een interview. Al de uitrustingen werden in een gespecialiseerd laboratorium onderzocht, met meting van de „veiligheidsgraad" o.m. schoenfixaties, zowel bij torsie als bij val naar voren. De klinische diagnose van de kniebandletsels werd gedokumenteerd volgens de OAK, bevestigd bij arthroscopie of ter gelegenheid van de reparatieve heelkunde. In de meerderheid van de gevallen waren de veiligheidsbindingen nieuw, correct geplaatst en juist geregeld. De veiligheidsgraad van de bindingen was gelijk of licht groter dan aanbevolen door bfu. De oorzaken van het letsel waren een exorotatie-valgus in flexie, groter dan 90°, een endorotatie in flexie, groter dan 120°, met uitgelokte voorste schuiflade, een endorotatie in flexie, kleiner dan 30°, met uitgelokte voorste schuiflade, een exorotatie-valgus in flexie, groter dan 120°, met uitgelokte voorste schuiflade, een exorotatie in flexie op ongeveer 100°, met uitgelokte voorste schuiflade en endorotatie-valgus.
Ondanks correct geregelde en moderne veiligheidsbindingen bleven de bandletsels van de knie en o.m. van de voorste kruisband mogelijk. De verbetering van de huidige systemen zouden een nog betere werking moeten nastreven, door uit de samengestelde inwerkende krachten de fricties in het systeem te registreren. De auteurs konkluderen dat voor de zijwaartse loslating van het systeem, de bijkomende vertikale spanning alsmede de anti-frictie mechanismen moeten verbeterd worden. Om overmatige belasting van de voorste kruisband door de uitgelokte voorste schuiflade te voorkomen, zou een bijpassende veiligheid achteraan de binding met juiste spanning aangewezen zijn.
In geval van ongekontroleerde val naar achter, dan is de kans van loslaten van de binding duidelijk groter.

RÉSUMÉ

J. F. FISCHER, P. F. LEYVRAZ, A. BALLY. Analyse des mécanismes d'entorses ligamentaires du genou dans les accidents de ski alpin.

Bien que trente ans d'amélioration des systèmes de fixations de sécurité aient permis une diminution globale des taux d'accidents relatifs au ski alpin, le taux de lésions ligamentaires du genou est resté élevé et leur sévérité semble augmenter. La présente étude vise à une meilleure compréhension des mécanismes d'entorses ligamentaires du genou à partir d'un nombre limité de cas analysés en détail. Les résultats obtenus doivent permettre de proposer des améliorations concrètes des systèmes de sécurité actuels. Six patients de 19 à 43 ans, victimes d'une lésion ligamentaire du genou avec rupture du ligament croisé antérieur sont présentés. La reconstitution de l'accident a été réalisée pas à pas, en utilisant un questionnaire décomposant l'accident en séquences, suivi d'un interview. L'examen de l'équipement fut réalisé dans un laboratiore spécialisé où les niveaux de déclanchement des systèmes de sécurité chaussure-fixations ont été mesurés en torsion et en chute avant. Le diagnostic clinique des lésions ligamentaires du genou effectué et documenté selon l'OAK fut confirmé par arthroscopie ou lors de la chirurgie réparatrice. Dans la plupart des cas, le matériel de sécurité était récent, correctement monté et adéquatement réglé. Les niveaux de déclanchement des fixations de sécurité étaient égaux ou légèrement supérieurs à ceux recommandés par le BFU. Les mécanismes lésionnels décrits furent une rotation externe-valgus en flexion de plus de 90°, une rotation interne en flexion de plus de 120° avec un tiroir antérieur induit, une rotation interne en flexion de moins de 30° avec un tiroir antérieur induit, une rotation externe-valgus en flexion de plus de 120° avec tiroir antérieur induit, une rotation externe en flexion d'environ 100° avec un tiroir antérieur induit et une rotation interne-valgus.

Malgré des fixations de sécurité modernes et adéquatement réglées, les lésions ligamentaires du genou et notamment du LCA restent possibles. L'amélioration des équipements actuels devrait concerner leur comportement lorsqu'ils sont soumis à des efforts combinés qui produisent des frictions dans le système. Nous avons conclu que pour le déclanchement latéral de la butée, la compensation des efforts parasites verticaux doit être améliorée ainsi que les mécanismes antifriction. Afin de prévenir des efforts excessifs en tiroir antérieur sur le LCA, une direction de déclanchement supplémentaire vers l'arrière pourrait, si elle est adéquatement réglée, augmenter les chances de déclanchement précoce en cas de chute en arrière incontrôlée.