THE KNEE INJURIES IN SKIING: MECHANISMS AND ASSESSMENT

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The purpose of this study is to describe the main mechanisms of knee injuries in skiing, and especially the dominant role of anterior cruciate ligament in these injuries. To complete classical clinical tests of ligamentous laxity and help defining the appropriate time to return to sports after an anterior cruciate ligament reconstruction, accurate 3D kinematic assessment of the weight-bearing knee joint is essential. Current limits of such an assessment are described. Then recent studies of patients with anterior cruciate ligament deficient and reconstructed, using a tibio femoral tracking device specially designed to analyse the kinematics of the knee, are presented.

KEY WORDS: Biomechanics of skiing accidents, ACL injury, Knee kinematics assessment.

KNEE INJURIES IN SKIING: When the total number of ski injuries is subdivided by involved body regions the knee is still the most frequently affected joint, distantly followed by the shoulder. Subdivided by sex, the dominance of knee injuries in women is prominent with close to 50%. Even so, in men they are still close to 30%.
The high injury risk in competitive skiing also poses a serious problem for the athletes. Since 2006, the FIS, together with the Oslo Sports Trauma Research Center (OSTROC), has been conducting an investigation to examine injury issues in the different Ski World Cup disciplines, to determine risk factors and to develop efficient countermeasures.
The summary of injury frequency clearly shows the large count of injuries with at least 1 – 3 days of training and competing pause and severe injuries. Severe injuries are defined by a resulting training and competing pause of more than 28 days. The data demonstrate that almost one in every three athletes sustains an injury every season.
Examined by injury localization, the data show the dominant role of knee injuries, analogous to recreational skiing. The data analysis yields a 39% ratio of knee injuries. The ratio even rises to 60% regarding severe injuries only. According to the data the anterior cruciate, ligament is involved in nearly half of all severe injuries and thus becomes the focus of all deliberations concerning underlying causes.

INJURY MECHANISMS: To develop efficient prevention strategies, one must know the underlying mechanisms as thoroughly as possible. Due to the dominant role of the injuries to the anterior cruciate ligament the most work exists on this topic.
A common cause for injuries in recreational skiing are sudden changes of direction of the lower limbs in relation to the torso. In the flexed knee they result in external rotation of the lower leg with concomitant opening up of the joint on the inner side (“valgus stress“), so that the otherwise stable ligament can eventually no longer withstand the present forces. Internal rotations with an outward tilt (“varus stress“) are also possible. High velocity is not necessary here - this mechanism often leads to anterior cruciate ligament injuries at minor speed or even while standing.
The phantom foot is claimed to be the most common mechanism for ACL injuries in recreational skiing. In this situation, the skier is out of balance backward with the hips below the knees. The uphill arm is back, and the upper body generally faces the downhill ski. The injury occurs when the inside edge of the downhill ski tail engages the snow surface, forcing the knee into internal rotation in a deeply flexed position. The ski acts as a lever to twist or bend the knee, hence the term ‘‘phantom foot” (Natri et al., 1999).

A comprehensive analysis of injury mechanisms in ski racing was conducted by the Bahr group in cooperation with the FIS (Bahr et al., 2005). The group concluded that the majority of injuries can be described with three respective mechanisms. The most common one was the so-called “Slip-Catch“, where the outer ski catches the inside edge, forcing the outer knee into internal rotation and valgus. A similar loading pattern was observed for the dynamic snowplow. Injury prevention efforts should focus on the slip-catch mechanism and the dynamic snowplow (alpine skiing, Bere et al., 2011).
The third described mechanism is typical of jumps. The athlete lands backward weighted after the jump with load to the ski tail at landing, giving it a forward rotation. The athlete tries to bring the body’s center of gravity frontward again to regain balance. The strain to the anterior cruciate ligament develops from the combination of tibiofemoral compression, the ‘boot induced anterior drawer’ and the quadriceps anterior drawer.
The work of Babiel & Alcan give an impression on the resulting forces (Babiel et al., 1997). These investigations could determine that in competitive ski racing the leg is loaded with compression forces of up to 7000 N during turns. This load is mainly carried by the outside leg.
Depending on the level of difficulty of slope, race course or mountain, all skiers are exposed to the same physical demands. Yet the athletes’ constitution and stamina differ.
The physical requirements for alpine skiing and the skier’s individual abilities must be brought in line.
Decent aerobic endurance abilities are an essential prerequisite for optimal injury prevention and protection from overload damage in both recreational and, especially, competitive alpine skiing (Zintl, 1998).
Powerful and fully functional muscles are to be obtained and preserved by appropriate training and immediate preparative measures, such as warm-up exercises. The forced posture of the foot in the ski boot and the boot’s notch effect at the edge lead to exceptional strain in alpine skiing.

CURRENT LIMITS OF KINEMATIC ASSESSMENT: Given the dominant role of ligaments, especially the ACL, in the stability control of the six degrees of freedom of the knee, it is essential to evaluate the biomechanics of the knee in 3D. Physical examinations, e.g. Lachman, anterior drawer and pivot shift tests (Benjaminse et al., 2006), are the first steps of the diagnosis of an ACL tear, and MRI is also classically used (Rubin et al., 1998). Quantified movement analysis in 3D of ACL injured knees is essential to supplement objectively the clinical results of ligamentous laxity. Moreover, abnormal knee kinematics has been thought to be one of the possible reasons for long-term development of degenerative changes after ACL reconstruction. Then, 3D kinematic assessment can also help defining the appropriate time to return to sports after an ACL reconstruction.

Nevertheless, the functional movements of a weight-bearing knee joint are difficult to quantify in a sufficiently accurate way to allow an appropriate analysis of the kinematic changes caused by a pathology. Indeed, using non-invasive motion analysis systems, there are significant errors in this assessment associated with movements of soft tissues, particularly on the thigh, and with the sliding of the skin around the joint (Cappozzo et al., 1996). Moreover, these artefacts are extremely difficult to correct since their frequency is very close to that of the analyzed motion (which makes filtering inefficient) and they are also very dependent on the task performed (Fuller et al., 1997) or even on the morphology of the subject.

Currently, there is no method proposed to compensate for soft tissue artefacts meaning that the errors caused in the joint kinematics cannot be completely corrected. However, many approaches have been explored.

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KINEMATIC ASSESSMENT OF ACL INJURED KNEES: One approach consists in getting direct access to the bones via a dynamic (biplane fluoroscopy) or static (biplane radiography in several positions) imaging system. In this case, the challenge is to register three-dimensional models of the patient's bone on these two-dimensional images. Indeed, the absence of extrinsic information, such as balls of tantalus (banned in many countries) or prosthesis, makes the registration poorly reproducible.

To limit the errors associated with soft tissue artefacts while continuing to use a non-invasive protocol, another approach consists in using a tibio femoral tracking device specially designed to analyse the kinematics of the knee. One of them has been developed by the LIO (research Laboratory in Imagery and Orthopedics) in Montreal. The accuracy of tracking the movements of the underlying bone by such a device was assessed by comparing the kinematics obtained from external markers fixed to this device and that obtained by calibrated fluoroscopy for flexion up to 65° (Sati et al., 1996). The mean error was 0.4° in varus-valgus, 2.3° in axial rotation and 2.4 mm in anteroposterior translation.

Postural and functional calibration were developed to define, using this device, the anatomical axes on which the kinematic parameters are calculated. Many studies have been carried out to verify the reproducibility of rotations and translations of the knee assessed in this way. Hagemeister et al. (Hagemeister et al., 2005) reported a mean error in repeatability less than 0.8° for all rotations and 2.2 mm for anteroposterior translation (0.4° and 0.8 mm respectively, interoperator) for 15 subjects and 3 operators. A second study (Labbe et al., 2008) also verifies the reproducibility when the device is systematically repositioned on the subject before taking new measurements on 15 subjects and 3 operators. In this case, the intra-class correlation coefficients vary between 0.88 and 0.94. Due to these good results, associated with high clinical potential of an objective assessment of knee kinematics in motion (Lustig, Magnussen, Cheze, & Neyret, 2012), this device was marketed under the name KneeKG™.

The results of two recent studies using the KneeKG™, one assessing the kinematic patterns of ACL deficient patients (Shabani et al., 2014), and the other one assessing the kinematic patterns of ACL reconstructed knees (Shabani et al., 2015) will be presented. In particular, the results show that the rotational instability after ACL reconstruction remains an issue, which could be solved by extra-articular lateral reinforcement.

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