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Injuries in alpine skiing: risk factors, injury mechanisms and prevention: a review of current evidence

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Abstract

Background.

Alpine skiing is a highly popular winter sport, with approximately 380 million skier days annually worldwide. Despite a decline in recreational injury rates over the past 40 years (from 5–8 to 0.5–3.0 injuries per 1,000 skier days), severe knee ligament injuries and traumatic brain injuries remain common. In elite racing, injury rates are substantially higher, reaching 36.2–36.7 injuries per 100 World Cup athletes per season.

Aim of the study.

This review synthesizes current evidence on risk factors, biomechanical injury mechanisms, and prevention strategies in recreational and competitive alpine skiing.

Materials and methods.

The review was conducted using publications published in the PubMed, Google Scholar and UpToDate. Our search included the following keywords: alpine skiing, anterior cruciate ligament, risk factors, injury mechanisms. References include systematic reviews, but also clinical trials, as well as case reports.

Conclusion.

Reducing alpine skiing injuries requires a multidisciplinary approach combining safer equipment, regulated standing heights, neuromuscular and core-stability training, video-based risk awareness, and safer slope and course design. Such interventions can significantly reduce injury risk, with video-based programs reporting a 45% reduction in ACL injuries.

Keywords: Alpine skiing, ski boot; ski geometry, risk factors, injury mechanisms, anterior cruciate ligament (ACL), injury prevention, skiing.

1. Introduction

Alpine skiing is a popular winter sport practiced by hundreds of millions of recreational and competitive skiers around the world; it is estimated that ski resorts worldwide record

approximately 380 million ski days annually. Although skiing offers significant health benefits, including improved cardiovascular fitness, muscle strength, and mental well-being, it is inherently associated with a high risk of acute injuries and chronic overuse injuries. In ski racing—which includes disciplines ranging from slalom (SL) and giant slalom (GS) to super-G (SG) and downhill (DH)—athletes travel at extreme speeds exceeding 130 km/h in speed events, experience enormous ground reaction forces (often exceeding 3.0–4.0 times body weight), and perform complex, rapid, multi-planar movements^[1].

Over the last forty years, epidemiological data indicate that the overall injury rate in recreational alpine skiing has decreased significantly, from approximately 5 to 8 injuries per 1,000 skier days in the early 1970s to between 0.5 and 3.0 injuries per 1,000 skier days in recent winter seasons. This successful reduction has been driven primarily by the universal adoption of self-releasing safety ski bindings, enhanced mechanical slope preparation and grooming, and widespread compliance with ski helmet usage. For instance, in the United States, helmet use rates soared from 25% in the 2002-2003 season to 90% in the 2023-2024 season, leading to a massive 62% to 67% reduction in any head injuries and severe traumatic brain injuries respectively on the slopes^[2].

Nevertheless, the incidence of severe knee joint ligament sprains and traumatic brain injuries has remained stubbornly high. In the competitive arena, including the elite International Ski Federation (FIS) World Cup (WC) circuit, European Cup (EC), and junior academy levels, the intensity of competition, aggressive equipment setups, and extreme snow preparation have resulted in an unacceptably high rate of catastrophic injuries. These injuries often lead to prolonged absence from training, subsequent surgical reconstruction, high re-injury rates, early-onset joint osteoarthritis, and premature career termination^[3].

To address this safety crisis, injury prevention research has traditionally been guided by van Mechelen's classic four-step 'sequence of prevention' model. Under this framework, researchers must first establish the extent of the injury problem (incidence and severity), second determine the underlying etiology and mechanisms of injury, third develop and implement targeted preventive interventions, and fourth evaluate the real-world effectiveness of these measures by repeating the first step^[4].

This review paper seeks to provide a comprehensive, multi-disciplinary synthesis of the current state of scientific evidence regarding risk factors, biomechanical injury mechanisms, and multi-level prevention strategies in both competitive and recreational alpine skiing, establishing a systematic roadmap to improve safety quality and health protection in winter sports.

2. Injury epidemiology and severity

Establishing the epidemiology of skiing injuries represents the essential first step in the risk management process. Prospective and retrospective injury surveillance systems have provided valuable quantitative data regarding the incidence, distribution, and severity of injuries across different competition levels and age groups^[5,6].

2.1. Competitive alpine skiing (World Cup & Junior Racers)

Among all Olympic winter sports, competitive alpine ski racing exhibits some of the highest injury rates. Long-term database tracking by the FIS Injury Surveillance System (ISS), which records injuries among World Cup athletes based on retrospective end-of-season interviews, reveals absolute injury rates of 36.2 to 36.7 injuries per 100 World Cup athletes per season^[7,8].

However, seasonal retrospective reporting is known to severely underestimate the true injury burden. Prospective, season-long tracking over 12-month periods shows that when injuries sustained during the off-season, team training, and those not requiring immediate medical attention are included, the absolute injury rate reaches 184.1 injuries per 100 athletes per season, with up to 95% of elite competitive skiers suffering at least one health problem annually^{5,6]}.

Injury incidence is heavily dependent on the specific competition discipline, exhibiting a progressive increase that correlates with average speed. Retrospective FIS ISS data indicates that injury rates increase from Slalom (SL; 4.9 injuries per 1000 runs) to Giant Slalom (GS; 9.2 injuries per 1000 runs), Super-Giant Slalom (Super-G / SG; 11.0 injuries per 1000 runs), and Downhill (DH; 17.2 injuries per 1000 runs)^[1].

2.2. Recreational skiing

In recreational winter sports, the overall injury rate on public ski slopes has stabilized between 0.5 and 3.0 injuries per 1000 skier-days worldwide. In Switzerland alone, approximately 63,000 skiing and snowboarding injuries are recorded annually, with skiers accounting for 54,000 cases^[9]. While snowboarders have a higher overall rate of upper extremity injuries (specifically

wrist fractures and shoulder dislocations due to backward and forward falls), skiers suffer a disproportionate rate of internal knee ligament injuries, accounting for approximately one-third of all skiing-related trauma. Ruptures of the ACL represent 15% to 21% of all recreational skiing diagnoses^[10].

2.3. Injury severity and time-loss

The severity of injuries in alpine skiing is exceptionally high. Prospective surveillance indicates that 80.9% to 81.2% of all recorded injuries in World Cup racing are 'time-loss' injuries that result in an absence from training and competition^[7]. Nearly one-third (30.8% to 35.6%) of these injuries are classified as severe, requiring more than 28 days of absence. The knee joint represents the most vulnerable anatomical site, accounting for 35.6% of all competitive injuries, followed by the lower leg (11.5%) and the lower back (11.5%). Knee injuries are also the most disabling: 54.4% of all competitive knee injuries are severe, with ACL ruptures leading to an average absence of 6 to 9 months, frequently requiring surgical reconstruction. Traumatic brain injuries represent a leading cause of catastrophic morbidity and mortality, with severe traumatic brain injuries (TBIs) accounting for 23.7% of all head injuries sustained in competitive racing^[8].

2.4. Youth and adolescent ski racers

Injury patterns and rates in youth and adolescent skiers differ markedly from adult elite cohorts, yet they present a critical risk to long-term athletic development. A longitudinal 4-year follow-up study of competitive adolescent skiers aged 15 to 19 years [30] revealed that approximately one-third (33.3%) suffered from a traumatic knee injury, and every sixth skier (16.7%) sustained an ACL rupture. This injury burden led to an alarmingly high career drop-out rate: 61.9% of adolescent racers ended their competitive careers during the 4-year period, with 41% of those drop-outs directly citing health-related reasons (chronic knee pain, recurrent instability, and fear of re-injury)^[11].

Magnetic resonance imaging (MRI) of these athletes' knees at age 19 revealed that over 60% presented trauma-related abnormalities, including subchondral bone bruises, osteochondral lesions, and meniscus tears, highlighting the severe long-term degenerative risks.

In younger competitive skiers (aged 9 to 14 years), the overall injury incidence is descriptively lower (0.63 traumatic injuries and 0.21 overuse injuries per athlete over two seasons)^[12,13]. A retrospective study of Finnish junior ski racers, monitored 61 injuries in a cohort of 661 active racers. Lower extremity injuries were dominant, accounting for 64% of all cases, followed by the upper extremity (28%) and the head (8%). Falling on the same level (collision with the icy snow surface) was the primary mechanism of injury (49%), while collisions with on-slope obstacles (padding, net posts, or other skiers) represented 30% of injuries. Giant Slalom was the most common discipline for injury occurrence (56%), reflecting the high volume of training and racing runs in this discipline among youth cohorts, followed by Slalom (31%) and Super-G (13%)^[14].

Table 1: Skier and turn characteristics across competitive alpine disciplines

Discipline	Average Speed (m/s)	Typical Turn Radius (m)	Kinetic Energy (E _{kin})	Turn GRF Peak (BW)	Number of Jumps / Run
Slalom (SL)	10 - 12	10 - 15	Low	1.8 - 2.4	0
Giant Slalom (GS)	15 - 20	20 - 30	Moderate (~14-16 J/BW)	1.9 - 2.1	0 - 1
Super-G (SG)	22 - 28	35 - 45	High	1.5 - 1.8	~ 2
Downhill (DH)	30 - 35	50 - 80	Highest	1.3 - 1.6	4 - 5 (Doubled from SG)

The mechanical characteristics presented in Table 1 (compiled from Gilgien et al., 2014) ^[1] demonstrate a critical divergence in risk profiles.

3. Injury etiology: athlete-related - risk factors

To design effective injury prevention programs, the underlying etiology of sports injuries must be thoroughly understood. Athlete-related risk factors are biological, physiological and behavioral characteristics of the athlete that predispose them to injury under external loads.

3.1. Biological and anatomical sex-based disparities

A profound sex gap exists in the epidemiology of alpine skiing knee injuries. In recreational alpine skiing, female skiers face twice the risk of sustaining any knee injury compared to their male counterparts, and their risk of sustaining a rupture of the anterior cruciate ligament is three times greater than males^[10]. When examining youth and adolescent competitive athletes, this disparity is even more pronounced.

In Swedish and Austrian ski high schools, female competitive skiers (aged 15 to 19 years) are approximately 3.5 times more likely to suffer ACL ruptures during their adolescence compared to male skiers. In contrast, at the elite, international World Cup level, the epidemiological evidence regarding sex differences is contradictory; some recent longitudinal registries suggest higher knee injury rates in female elite skiers, while several historical studies found no significant differences, potentially due to high physical selection pressures and comparable exposure levels at the highest tier of competition^[13,15].

The anatomical, hormonal, and neuromuscular differences that distinguish males and females underpin this sex gap. From an anatomical perspective, females possess a narrower intercondylar notch, a thinner and mechanically weaker ACL, a wider pelvis (which increases the dynamic Q-angle and valgus loading), and a lower center of gravity. A lower center of gravity in females predisposes them to lower-extremity injuries by altering the leverage of external forces, whereas men's higher center of gravity and increased mass are more frequently associated with upper body and shoulder trauma^[16,17].

3.2. Age and physiological vulnerabilities

Age represents a critical, non-modifiable intrinsic risk factor that exhibits different patterns in recreational and competitive skiing. In recreational skiing, multiple case-control studies indicate that older age is independently associated with an increased risk of sustaining an ACL injury^[18]. This pattern is closely linked to age-related physiological decline, including progressive reduction in skeletal muscle mass (sarcopenia), slower neuromuscular reflexes, reduced ligamentous and tendon compliance, and decreased core and balance capabilities.

Conversely, in competitive ski racing, youth and adolescence represent a peak period of vulnerability. Adolescent competitive skiers (aged 15 to 19 years) who are undergoing rapid

physical growth and biological maturation are at an exceptionally high risk of traumatic knee injuries, with one-third suffering a knee injury and every sixth skier rupturing their ACL during their four years of high school ^[19].

The high risk in adolescent racers is attributed to growth-related changes, where rapid bone elongation temporarily outpaces neuromuscular control adaptation, resulting in coordination deficits, decreased joint position awareness, and increased dynamic knee valgus.

3.3. Skiing ability and skill level

The impact of skiing ability on ACL injury risk differs fundamentally between recreational and competitive populations. In recreational skiing, there is a clear, inverse relationship between skill level and injury risk. Case-control studies consistently prove that less-skilled skiers (such as beginners and intermediates) have a 6,7-fold higher risk of sustaining an ACL injury compared to highly skilled skiers (advanced and experts).

Less-skilled skiers suffer from poor technical coordination, inappropriate body positioning (frequently falling behind the ideal fore-aft balance), and an inability to control speed or perform efficient turning. When confronted with unexpected terrain perturbations or edge-catch situations, they lack the automated muscle activation patterns required to recover, resulting in uncontrolled falls where the ski acts as a massive lever arm to bend or twist the leg^[10].

In contrast, in competitive ski racing, a high performance level is associated with an increased risk of ACL injury. Athletes ranked in the Top 30 of the FIS World Cup standings demonstrate a significantly higher risk of severe knee injuries and ACL ruptures compared to lower-ranked elite competitors. This apparent paradox is explained by the extreme mechanical demands placed on top-level racers^[20].

World Cup athletes ski at higher average speeds, execute turns at larger edge angles with minimal skidding, and frequently choose aggressive line tactics close to gate panels and terrain transitions. In their quest to minimize run times, they operate at the absolute limit of physical control. When a technical error occurs, the kinetic energy involved is exceptionally high, and they will attempt risky recovery maneuvers to save the run rather than safely sliding out, exposing their knees to extreme, uncompensated valgus and rotational torques^[20,21].

3.4. Psychological Risk-Taking Behavior and Sensation Seeking

Behavioral patterns represent a critical, modifiable intrinsic risk factor. Case-control studies in recreational skiing have demonstrated that self-reported risk-taking behavior is independently and strongly associated with ACL injury risk. In competitive ski racing, risk-taking behavior is an inherent requirement for performance, as racers must accept high speeds and high-amplitude jumps to achieve success. However, poor risk management and overconfidence can lead to catastrophic tactical mistakes^[10].

Furthermore, many recreational skiers, beginners, and non-local tourists often lack a basic knowledge of the International Ski Federation (FIS) rules of conduct, which govern safe speed limits and overtaking. This knowledge deficit can lead to reckless skiing and a higher incidence of high-speed collisions. Collision injuries are significantly more severe than isolated falls, and they transfer massive amounts of uncoordinated kinetic energy directly into the knee joints^[9]

3.5. Neuromuscular Control, Asymmetry, and Lumbar-Core Stability

Neuromuscular control and limb symmetry play fundamental roles in knee stabilization during the high-force phases of alpine skiing. Dynamic lower-limb asymmetries, particularly during pivoting or squatting tasks, and a tendency for dynamic knee valgus (valgus collapse) are critical risk factors. Laboratory-based exploratory studies using advanced optical systems (like DynaKnee) and smart force plates demonstrate that dynamic knee valgus (characterized by a marked increase in the Q-angle during a single-leg squat compared to a relaxed stance) increases the mechanical tension of the ACL. Interestingly, elite ski racers often exhibit significantly higher (34.9% greater) asymmetry in their Q-angle symmetry index during laboratory single-leg squats compared to well-trained recreational skiers. This pronounced one-sided dominance and dynamic valgus asymmetry represent a severe latent vulnerability, making the athlete highly susceptible to ACL failure if a perturbation occurs on their weaker limb. Furthermore, core and lumbar-pelvic stability is a critical factor for trunk control and injury prevention^[22].

A 10-year longitudinal study of young competitive ski racers demonstrated that insufficient core strength and core strength imbalances (between the trunk flexors and extensors) are independent and powerful risk factors for ACL injuries. Better relative core flexion strength has been proven to be highly protective, with only 20% of physically robust athletes sustaining

traumatic injuries compared to those with core imbalances. Superior core stability allows the skier to maintain a stable, centered trunk, enabling them to absorb and compensate for unexpected ground-reaction forces, rotational perturbations, and aggressive leg oscillations on the snow. It prevents the center of mass from drifting backward, which would otherwise initiate catastrophic knee-loading scenarios^[16].

4. Equipment and environment-related risk factors

This group of risk factors involve the equipment worn by the skier and the physical environment in which they operate. In alpine skiing, the skier's foot is rigidly locked into a stiff ski boot, which is clamped into a release binding mounted on a riser plate attached to the ski. This rigid interface means that any force generated by the ski-snow interaction is directly translated through the boot-binding unit to the skier's skeleton. It is estimated that approximately 80% of all lower-extremity skiing injuries are equipment-related^[10,23].

4.1. Ski geometry and the self-steering carving effect

The introduction of short and highly shaped 'carving' skis in the late 1990s revolutionized skiing performance by making turning easier and more efficient. Carving skis are characterized by a pronounced sidecut (where the tip/shovel and tail are significantly wider than the waist), resulting in a small construction sidecut radius (typically between 11 and 17 meters for recreational skis). When edged and loaded, a carving ski exhibits a powerful, self-steering effect where the ski automatically bends and guides itself along a defined circular arc on its edge, minimizing lateral skidding and friction. While this increases speed and performance, it also introduces major mechanical hazards^[24,25].

In uncontrolled situations, such as a sudden loss of balance, a ski with a small sidecut radius will carve inward sharply and aggressively. Due to the high edge grip, the ski does not slide or skid, resulting in an abrupt and massive transfer of torque and compression force directly into the knee joint, forcing it into excessive valgus and internal rotation. Case-control studies indicate that a wider ski tip (broad shovel) is independently associated with an increased ACL injury risk. This is because a wide, aggressive tip shovel is much more likely to catch the snow edge abruptly during steering, especially for less-skilled skiers using shorter skis^[24].

4.2. Standing height and riser plate regulations

Standing height refers to the vertical distance between the bottom of the running surface of the ski and the sole of the ski boot. With the development of carving skis, manufacturers introduced elevated binding riser plates (lifters) to allow skiers to reach greater maximum edge angles before the ski boot contacts the snow surface ('boot-out'), as well as to increase the torsional stiffness of the ski. However, increased standing height acts as a powerful mechanical lever, magnifying the lateral and rotational forces transmitted to the leg and knee joint during carving and skidding turns. Due to major safety concerns, the International Ski Federation (FIS) began regulating standing height in 1998, imposing a maximum limit of 50 mm for competitive ski racers^[21,26].

In recreational skiing, standing height remains a highly critical risk factor. Biomechanical field studies comparing giant slalom skis with different standing heights (50 mm versus 40 mm) demonstrate that a reduced standing height of 40 mm significantly reduces the acting ground-reaction forces by 2.5% during the turn phase in which the greatest knee and spinal disc loading occurs (center of mass direction change II). Reduced standing height also limits the risk of adversely catching the ski edge on the snow^[26].

However, a decreased standing height slightly increases the turn cycle duration (+2.2%), which can slightly reduce performance. Since competitive and recreational skiers are unlikely to adopt equipment that compromises performance on their own initiative, anchoring these safety specifications in equipment regulations is essential for injury prevention^[26].

4.3. Ski Boot sole abrasion

The ski-binding-boot system relies on a standardized, low-friction interface between the front and rear soles of the ski boot and the corresponding contact plates of the safety binding, regulated by the International Organization for Standardization (ISO) 5355 standard. This standard provides precise tolerance ranges for the dimensions of the boot toe and heel (specifically 19 ± 1 mm for the toe and 30 ± 1 mm for the heel) to ensure predictable mechanical release when pre-set torque thresholds are exceeded. However, recreational skiers frequently

walk extensive distances with their ski boots on hard surfaces, such as asphalt, concrete, and gravel, which leads to massive friction-induced wear and abrasion of the boot sole^[27,28].

This mechanical abrasion is a powerful and independent risk factor for ACL injury. Case-control studies prove that recreational skiers with ACL injuries exhibit significantly greater sole abrasion at the toe and heel compared to uninjured controls. Greater sole abrasion at the toe increases the risk of an ACL injury 2.5- to 3.2-fold in females and 1.9-fold in males, while heel abrasion is associated with a 1.3- to 1.5-fold increased risk. Severe abrasion alters the vertical height of the boot sole, introduces uncontrolled play within the boot-binding interface, and increases friction. This prevents the safety binding from releasing at the pre-set torque during a fall, transforming the ski into a rigid lever that twists the lower leg relative to the femur, resulting in immediate ACL rupture^[10].

4.4. Equipment ownership: rented versus owned gear

Equipment ownership represent a highly significant, and often overlooked, extrinsic risk factor. Large-scale epidemiological studies indicate that approximately 32% of recreational skiers use rented skis. Crucially, the risk of sustaining an ACL injury is three times higher for skiers using rented skis compared to those using their own skis. When stratified by skill level, this risk is particularly pronounced in highly advanced and expert skiers, where the use of rented or borrowed skis increases the ACL injury risk by nearly 8-fold in more skilled females and by about 10-fold in more skilled males. This is likely because advanced skiers are more prone to renting and testing innovative, highly aggressive skis (such as rocker or slalom carving skis) that they may not fully control or be familiar with^[10].

Compared to owned skis, rented skis are characterized by shorter lengths, smaller sidecut radii, narrower widths, lower absolute standing heights, but significantly higher standing height ratios. While shorter and narrower skis make turning easier for intermediate skiers, they also act as more reactive and aggressive levers in out-of-balance situations. Furthermore, busy ski-rental facilities often face high volume pressures, resulting in less personalized attention and less precise binding adjustments compared to personal gear setups. Conversely, once owned equipment is purchased, its mechanical effectiveness begins to decline due to use, highlighting the critical need for regular, professional safety checks at least once per season^[10,29].

4.5. Environmental Conditions, Artificial Snow, and Course Design

Climate change and snow-poor winters have led to an increasing reliance on artificial (machine-made) snow to ensure slope coverage, particularly in alpine resorts. Artificial snow is generated by spraying water into cold air, resulting in smaller ice grains, higher density, and different thermal properties than natural snow^[9,30].

When groomed, artificial snow creates an extremely hard, uniform, and icy surface. This icy surface promotes exceptionally high downhill speeds and significantly longer braking distances, massively increasing the kinetic energy involved during falls and collisions. While well-groomed slopes are generally safer, insufficient grooming or warm temperatures can accelerate the formation of moguls (alternating soft and hard snow patches), which challenge balance and trigger knee perturbations. Furthermore, spatial mapping in Swiss alpine resorts reveals strong spatial clustering of ski accidents. Approximately 33% of all injuries occur on just 3% of the total resort slope length, mainly concentrated on steep, narrow, and high-traffic runs, as well as slope intersections^[9].

In competitive ski racing, the combination of high skiing speed, terrain transitions (convex/concave compressions), and small turn radii represents a major hazard that increases ground-reaction forces. Moreover, direct gate contact and collision with stiff poles or gate panels account for approximately 30% of all competitive injury cases, where hooking the ski tip in a gate panel ('gate hooking') triggers immediate, catastrophic knee valgus and tibial internal rotation^[8,20].

Topographic terrain transitions (such as concave/convex compressions) challenge the athlete's trunk control and balance. Jumps are particularly hazardous, with speed-discipline (Downhill) courses containing double the number of jumps compared to Super-G. Jumps are dangerous if take-off speeds are excessive, preparation times are short, or landings are situated in flat terrain^[1].

5. Biomechanical and kinematic injury mechanisms

A precise kinematic and mechanical understanding of how injuries occur (the 'inciting event') is the cornerstone of designing effective, targeted prevention strategies. Alpine skiing involves unique joint loading patterns due to high speed, responsive equipment, and the constraint of rigid ski boots.

5.1. Anterior Cruciate Ligament (ACL) Injury Mechanisms

Systematic video analysis of real-world injury cases in the World Cup has identified three primary, skiing-specific non-contact ACL injury mechanisms:

- The slip-catch mechanism: this represents the most frequent mechanism, accounting for approximately half of all ACL injuries, typically occurring while steering out of the fall line during a carved turn. The skier becomes out of balance in the backward and inward direction, causing them to lose snow contact and pressure on the outer ski. As they attempt to recover, the outer ski abruptly gains snow contact, and its inside edge catch the snow surface. Due to the carving geometry, the ski immediately carves inward. This forces the knee into extreme joint compression, rapid valgus, and internal tibial rotation, causing immediate ACL rupture^[28,31].
- The dynamic snowplow mechanism: this mechanism exhibits a highly similar kinematic sequence and loading pattern to the slip-catch. However, in the dynamic snowplow, it is the inside edge of the unweighted inner ski (rather than the outer ski) that abruptly catches the snow surface. The inner ski is rapidly forced into an inward, carving trajectory, driving the inner knee into extreme dynamic valgus and internal tibial rotation under high load^[31,32].
- The landing back-weighted mechanism: this mechanism typically occurs during jump landings. Due to backward-directed angular momentum obtained at takeoff, the skier loses balance in the air and lands heavily on the ski tails with a large 'clap angle' (tibiofemoral hyperextension). At initial snow contact, a forward-directed angular momentum rotates the skis forward, while the skier's center of mass continues to fall backward. To prevent a backward fall, the skier executes an explosive eccentric quadriceps contraction while the knee flexors are relaxed. The reaction force from the snow, acting through the rigid back of the ski boot, drives the tibia forward relative to the femur, creating a massive 'anterior drawer' stress that ruptures the ACL^[32].

5.2. Head Impacts and Traumatic Brain Injuries

Traumatic brain injuries represent a leading cause of severe morbidity in winter sports. Biomechanical drop-tower tests conducted directly on ski slopes using an instrumented magnesium headform (6 kg) dropped from heights of 1.5 m, 2.0 m, and 3.0 m (corresponding

to speeds of 5.3 m/s, 6.1 m/s, and 7.5 m/s) on soft, hard, and very hard snow analyzed head linear acceleration and the Head Injury Criterion (HIC)^[2].

The results demonstrated that head acceleration is highly dependent on snow stiffness and impact speed. During non-helmeted impacts on hard and very hard snow at 7.5 m/s (27.6 km/h), peak linear accelerations always exceeded the 80G threshold and HIC values exceeded the 1000 limit (the threshold for skull fractures and severe TBI). Impact durations ranged from 6 ms on very hard snow to 20 ms on soft snow, proving that soft snow acts as a powerful energy absorber. Crucially, the study revealed a complex interaction between helmet use and snow deformation^[2].

On hard snow, the average peak acceleration of the helmeted headform was actually higher than unhelmeted impacts. This is because the helmet increases the contact surface area, preventing the head from penetrating deep into the snow, which limits the snow's natural energy absorption. At 7.5 m/s on very hard snow, however, this trend reversed and unhelmeted impacts generated significantly higher accelerations and HIC, demonstrating that standard-compliant helmets (EN 1077 and ASTM 2040) are essential to absorb energy at high impact velocities when the snow can no longer deform^[2].

5.3. Non-Contact Posterolateral Leg Deceleration and Tibial Plateau Fractures

While ligamentous ruptures are common, non-contact injury situations can also result in severe articular bone trauma, specifically lateral tibial plateau compression fractures. A novel biomechanical model proposed by Trobec et al. (2020) explains how these fractures can occur during carving turns without any direct crash or collision. The mechanism is initiated by a sudden, involuntary inward turn of the inner ski during a carved turn, caused by hitting a snow brim, a hollow depression, or an obstacle. This sudden deceleration of the inner ski causes the inner leg to swing posterolaterally relative to the skier's moving body^[33].

The posterolateral rotation of the leg, boot, and ski continues until the anatomical constraints of the hip and knee joints limit any further movement, resulting in a nearly instant stop. This abrupt deceleration of the relatively heavy lower leg and heavy ski equipment releases massive inertial energy. Since the inner leg is frequently unloaded and the musculature is relaxed, the joint cannot actively absorb the force. The accumulated kinetic energy is dissipated over a very small bone area in the lateral tibial plateau, producing extreme compressive stress that exceeds the structural strength of the bone, resulting in a severe compression fracture. This model

highlights that non-contact, gear-induced forces can cause severe osteochondral failure even in the absence of a fall.

5.4. Concomitant Ligamentous and Meniscal Injury Patterns

Isolated ACL ruptures represent only a portion of skiing-related knee trauma. The high forces and complex lever arms involved in skiing injury mechanisms frequently result in multi-structural knee damage. Epidemiological studies using magnetic resonance imaging (MRI) diagnoses indicate that 64.5% of skiing-related ACL injuries are accompanied by concomitant injuries, while only 35.5% are isolated tears. In recreational carving skiers, the most common concomitant diagnoses are injuries to the medial collateral ligament (MCL) in 50.5% of cases, the medial meniscus (MM) in 40.1%, and the lateral collateral ligament (LCL) in 22.5%^[34].

The classic 'unhappy triad' (combined ACL, MCL, and medial meniscus injuries) is also frequently observed. This represents a major shift from the pre-carving era, where grade I and II MCL sprains on traditional, long skis were the most common knee injury and were mostly treated conservatively. With carving gear, the ACL is now predominantly affected in all knee injuries requiring hospitalization. In elite professional racers, MRI evaluations of knees at the age of 19 years reveal that over 60% of athletes present trauma-related abnormalities, including cartilage lesions and meniscus tears. These extensive concomitant pathologies significantly complicate surgical reconstruction and physical rehabilitation, markedly delaying the return-to-sport timeline and increasing the risk of early-onset osteoarthritis^[34].

6. Prevention

In response to the multi-factorial etiologies and complex mechanisms identified, contemporary sports science has co-developed comprehensive, systemic prevention and risk management frameworks to sustainably protect athlete health.

6.1. Systemic risk management

Bonell Monsonís et al. convened an international panel of experts to co-develop a structured, systematic risk management framework specifically tailored to competitive alpine skiing. This framework integrates a multi-level socio-ecological view, recognizing that effective prevention

requires coordinated action across organizational, environmental, equipment, course setting, and individual levels^[35].

The co-developed framework consists of two main operational components:

- The Competitive Alpine Skiing Prevention Wheel: A visual, multi-layered wheel that maps key stakeholders (athletes, coaches, equipment technicians, medical staff, local organizers, national federations and FIS), their risk priorities, the five main domains (Organisational, Snow, Equipment, Course Setting, and Athlete), and the targets for risk interventions across a graded, progressive timescale (short-, mid-, and long-term).
- The Decision-Making Tree: A step-by-step sequence that operationalizes the Prevention Wheel into sports practice, guiding stakeholders through: (1) risk identification (problem definition, impact, and temporality), (2) risk assessment (identifying domains, intervention areas, timeframes, and resources), and (3) risk mitigation (taking action based on structured reasoning)^[35,36].

5.2. Technological Innovations in Ski, Boot, and Mechatronic Binding Systems

Since the ski-binding-boot system acts as the primary transmitter of forces, optimizing this unit is a critical priority. To reduce the aggressiveness of carving skis, researchers developed and evaluated giant slalom ski prototypes with increased sidecut radii (from the baseline 27 m up to 30, 35, and 40 m) and reduced profile width. Biomechanical evaluations on water-injected courses proved that skis with greater sidecut radii (35 m and 40 m) significantly reduced the ski's aggressiveness (by decreasing the ground-reaction forces under the forefoot of the outside leg) and lowered average kinetic energy. Crucially, the 35 m prototype (P35) provided substantial preventative gain without compromising the external attractiveness of the skier's carving technique for spectators, leading to the successful implementation of the 35 m sidecut radius regulation by FIS^[24].

Furthermore, safety bindings must evolve beyond purely mechanical, passive release systems. Today's bindings only sense forces translated at the boot-ski interface near the ankle, failing to protect the knee from complex rotational and valgus torques. A technological paradigm shift is the development of mechatronic safety-release bindings that synergistically integrate mechanics, electronics, and control theory. These advanced systems incorporate smart sensors (measuring strain on the ski boot, knee angles, or muscle activation patterns via electromyography) into a real-time release algorithm, enabling the binding to calculate the

knee's safe loading envelope and trigger an active release during slip-and-catch or landing back-weighted scenarios. Additionally, load-limiting binding plates and ski boots with rear-spoiler release mechanisms show great promise in mitigating backward-falling forces^[25].

6.3. Neuromuscular conditioning

Dynamic neuromuscular conditioning focusing on core stability, lower extremity alignment, and plyometric landing control (avoiding extended, stiff landing knee angles) is essential^[11,13]. Furthermore, return-to-sport decisions following ACL reconstruction must be guided by objective, data-driven metrics rather than arbitrary timelines.

Morris et al. (2026) trained machine learning (ML) classification models (such as random forests and support vector machines) using 23 countermovement jump (CMJ) force-time metrics obtained from elite skiers. The models achieved high classification accuracy (balanced accuracy up to 0.88, AUC up to 0.95) in distinguishing healthy controls from athletes recovering from ACL reconstruction. Features corresponding to the propulsion phase (explosive force and rate of force development) were identified as the most critical indicators of neuromuscular recovery, providing a powerful clinical screening tool to monitor rehabilitation progress and prevent re-injury^[17].

Table 2: Laboratory and on-snow-derived biomechanical variables in elite racers and recreational skiers

Biomechanical Metric	Elite Racers	Recreational Skiers	P-Value / Statistical Significance
Lab Q-Angle S.I. Asymmetry	34.9% Higher Asymmetry	More Symmetric (Lower)	p = .002 (Large Effect)
On-Snow Edge Similarity	Highly Symmetric (> 90%)	Low Symmetry Index	p < .05 (Racers 16.3% higher)
On-Snow Pressure Symmetry	High Symmetry (> 90%)	High Asymmetry	p < .05 (Racers 48% better)
On-Snow Fore-Aft Balance	55% - 60% (Optimal Range)	Backward Drift Tendency	p < .05 (Racers 5.8% closer)

The data in Table 2 (compiled from Kékesi et al., 2026)^[22] highlights a fascinating divergence: while elite racers exhibit higher underlying anatomical asymmetry in the lab (likely due to sports specialization and unilateral loading), their advanced skiing technique on the snow (measured via CARV insoles) allows them to maintain highly symmetric edge angles and pressure distribution, thereby protecting their joints during normal turns.

6.4. Video-based education

Educating skiers and coaches about injury-prone situations is a powerful, low-cost preventative tool. In Sweden, a prospective intervention study evaluated the effectiveness of an educational ACL injury prevention program in ski high schools. The intervention integrated a specialized educational video (developed in collaboration with the Swedish Ski Federation and inspired by the Vermont Skiing Safety Research Group) that taught coaches and skiers to recognize critical risk situations (such as slip-and-catch and out-of-balance recovery) and perform specific physical exercises (indoor hop tests and on-snow exercises like shuffle, back-and-forth, and turns with lifted inner ski)^[37].

The results of this 2-year prevention study were highly successful, demonstrating a 45% reduction in the ACL injury incidence rate among the intervention group compared to historical controls. This proves that enhancing risk awareness helps skiers avoid technical mistakes and make safer tactical choices on the snow. Similarly, for recreational skiers, showing instructional videos on ski resort televisions and social media has been proven to decrease collision frequency by 50%, highlighting the power of educational campaigns in promoting safer slope behavior^[9,23].

6.5. Spatial risk management

Organizational and environmental modifications by ski resort operators and race directors represent essential spatial prevention strategies. Since 33% of resort accidents cluster on just 3% of slope length (steep, narrow, high-traffic runs and intersections), resculpting and widening these bottleneck terrain zones, rerouting steep stretches, and implementing strict speed management (such as 'slow' signs and patrol presence) can substantially reduce injury rates. Furthermore, training and racing areas for competitive clubs must be securely marked and completely separated from recreational slopes to prevent catastrophic collisions^[9].

In competitive ski racing, course setting plays a major role in speed and force management. In slalom, biomechanical studies prove that avoiding minimal gate offsets and increasing course set-up spacing significantly reduces ground-reaction forces and back-loading patterns. In speed disciplines (Super-G and Downhill), planning terrain transitions and gate placements to avoid blind, high-speed jumps and ensuring adequate, unobstructed spill zones lined with safety A- and B-nets are critical for mitigating crash severity. Additionally, ensuring uniform snow

grooming and avoiding abrupt changes in snow preparation techniques within a single course prevent unexpected edge-catch perturbations^[38].

7. Discussion

Despite significant research progress over the last two decades under the guidance of the FIS Injury Surveillance and Prevention Programme (ISPP), several critical methodological gaps remain in the scientific literature, limiting the implementation of highly effective injury-prevention measures.

The vast majority of sports safety literature in competitive alpine skiing remains descriptive and observational. Approximately 80% of published studies focus on establishing injury epidemiology and describing injury situations, while only 20% evaluate the development, implementation, or long-term clinical effectiveness of etiology-derived preventive measures. To progress in winter sports safety quality, the scientific community must transition from descriptive research to rigorous intervention studies (van Mechelen's third and fourth steps), testing the real-world safety gains of proposed technologies, training protocols, and rule changes.

Injury surveillance at the youth and adolescent level remains sparse and inconsistent. While the FIS ISS provides high-quality retrospective data for elite World Cup racers, youth academies and regional performance centers lack standardized, prospective injury and illness registration systems. Since youth skiers are skeletally immature and undergo rapid biological growth, they face unique risk factors (such as apophysitis and skeletal maturation delays) that are completely absent in adult elite cohorts. Standardizing prospective injury reporting in youth cohorts is essential to protect young athletes and establish healthy long-term athletic development^[39,40].

8. Conclusions

Anterior cruciate ligament injuries in alpine skiing represent a critical safety and health concern that exhibits unique biomechanical and epidemiological profiles in recreational and competitive cohorts. In recreational skiing, ACL injury risk is primarily driven by lower skiing

skill levels, female sex, rented or borrowed equipment ownership, greater binding standing height ratios, and severe ski boot sole wear. In competitive ski racing, injuries are dominated by extreme physical demands, high velocities, and gear-induced forces that force the knee into destructive valgus and internal rotation during turning (such as the slip-and-catch and dynamic snowplow mechanisms) or jump landing.

Mitigating this persistent injury burden requires a comprehensive, multi-disciplinary approach that integrates equipment design, standardized regulations, athletic preparation, and slope management. Priorities include the immediate revision of ISO binding standards to include female-specific safety factors, strict regulations on standing heights, and the development of active mechatronic bindings. Furthermore, systematically implementing neuromuscular core-stability training, equilateral exercise protocols, and video-based risk awareness programs has proven highly effective in reducing ACL injury incidence by up to 45%.

Resort operators and race organizations must proactively modify identified slope hotspots, implement speed management, and optimize course setting offsets. By uniting these strategies, the winter sports community can establish a safer, sustainable, and high-performance environment for alpine skiers of all levels.

Disclosure

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