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Biomechanics, Mechanisms, Prevention and Characteristics of Knee Injuries in in Recreational and Sports Alpine Skiing: A Narrative Review

1. **Mikołaj Szczęsny [MS]**
Independent Public Health Care Institution of the Ministry of Interior Affairs and Administration in Kraków, ul. Anonima Galla 25, 30-053 Kraków, Poland
https://orcid.org/0009-0003-1010-9712
mikolaj.szczesny@poczta.fm

2. **Małgorzata Katra[MK]**

Independent Public Health Care Institution of the Ministry of Interior Affairs and Administration in Kraków, ul. Anonima Galla 25, 30-053 Kraków, Poland

https://orcid.org/0009-0007-3772-3455

katramalgorzata@gmail.com

3. **Marcin Ślot [MS]**

Maria Skłodowska-Curie Voivodeship Specialist Hospital in Zgierz, Parzęczewska 35, 95-100 Zgierz, Poland

https://orcid.org/0009-0002-9947-9957

marcin.slot.poczta@gmail.com

4. **Adrian Pal [AP]**

Central Clinical Hospital of the Medical University of Łódź, ul. Pomorska 251 92-213 Łódź, Poland

http://orcid.org/0009-0004-0518-3923

adrian.b.pal@gmail.coml

5. **Krzysztof Cienkowski [KC]**

Central Clinical Hospital of the Medical University of Łódź, ul. Pomorska 251 92-213 Łódź, Poland

https://orcid.org/0009-0006-3887-3511

k.cienkowski@outlook.com

6. **Patryk Cegiełka [PC]**

Central Clinical Hospital of the Medical University of Łódź, ul. Pomorska 251 92-213 Łódź, Poland

http://orcid.org/0009-0007-8311-3279

patryk.cegielka@onet.pl

7. **Karolina Żeżawska [KZ]**

Central Clinical Hospital of the Medical University of Łódź, ul. Pomorska 251 92-213 Lodz, Poland

https://orcid.org/0009-0007-9563-5576

karolina250700@gmail.com

8. **Izabella Głowacka [IG]**

Faculty of medicine, Medical University of Lodz, Lodz, Poland

https://orcid.org/0009-0006-3645-268

iza.glowacka@icloud.com

9. **Aleksandra Adamczyk [AA]**

Wojewódzkie Wielospecjalistyczne Centrum Onkologii i Traumatologii im. M. Kopernika w Łodzi, Lodz, Poland

https://orcid.org/0009-0007-8002-385X

oolaadamczyk@gmail.com

10. **Maria Sicińska [MSi]**

Uniwersytecki Szpital Kliniczny nr 1 im N Barlickiego w Lodzi, Lodz, Poland

https://orcid.org/0009-0005-3768-8405

maria.sicinska@stud.umed.lodz.pl

Corresponding Author

Mikołaj Szczęsny

E-mail: mikolaj.szczesny@poczta.fm

Abstract

Background

Alpine skiing is a popular winter sport but is associated with a considerable risk of musculoskeletal injuries. Among them, knee injuries are the most frequent and clinically significant, particularly ruptures of the anterior cruciate ligament (ACL). The combination of high skiing speed, rotational forces, and interaction with modern ski equipment contributes to complex mechanisms leading to knee joint trauma in both recreational and competitive skiers.

Aim

The aim of this study was to review current knowledge on the biomechanics, mechanisms, characteristics, and prevention of knee injuries in alpine skiing.

Material and methods

A literature review was conducted using the following databases: PubMed, Scopus, and Web of Science. The review included publications published between 2000 and 2025. The following keywords and their combinations were used with Boolean operators: “alpine skiing”, “knee injury”, “ACL injury”, “anterior cruciate ligament”, “MCL injury”, “meniscus injury”, “ski injury epidemiology”, “injury mechanism”, “return to sport”, and “injury prevention in skiing”..

Results

The knee joint accounts for approximately one-third of all alpine skiing injuries, with ACL rupture being the most common severe injury. Most cases occur through non-contact mechanisms such as slip-catch, phantom foot, dynamic snowplow, and landing back-weighted. These mechanisms involve valgus loading, tibial rotation, and anterior tibial translation. Major risk factors include high speed, fatigue, neuromuscular deficits, equipment characteristics, and environmental conditions.

Conclusions

Knee injuries in alpine skiing result from complex interactions between biomechanical forces, skiing technique, and equipment. Understanding these mechanisms is essential for prevention. Targeted neuromuscular training, skier education, and proper equipment adjustment may help reduce injury incidence and improve safety.

Keywords: alpine skiing, knee injury, ACL injury, anterior cruciate ligament, MCL injury, meniscus injury, ski injury epidemiology, injury mechanism, return to sport, injury prevention in skiing

1. Introduction

Alpine skiing is one of the most commonly practiced forms of physical activity during the winter season, both at recreational and competitive levels, with more than 100 million people participating annually [1, 2]. The dynamic development of skiing equipment technology, improvements in slope infrastructure, and the growing popularity of winter sports have contributed to an increasing number of individuals actively participating in this discipline [3, 4]. Despite advances in safety, alpine skiing remains a sport associated with a significant risk of injury, particularly following the introduction of carving skis [3].

Within the spectrum of injuries associated with alpine skiing, musculoskeletal injuries predominate, most frequently involving the knee joint [5]. The knee, as the largest joint of the lower limb, plays a crucial role in stabilization and load transmission during skiing. The specific characteristics of this discipline—high speeds, sudden changes in direction, rotational forces, and the long lever arm created by the ski—predispose athletes to ligament injuries and damage to intra-articular structures [6, 7].

Anterior cruciate ligament (ACL) injuries are of particular clinical importance, representing the most common severe knee injury among skiers [8, 9]. The literature also highlights a significant incidence of injuries to the medial collateral ligament (MCL), meniscal tears, and multiligament knee injuries [10]. The consequences of these injuries include prolonged inability to participate in sports, the need for surgical treatment, a risk of recurrence, and an increased likelihood of developing degenerative changes in the future [11].

Efforts have been undertaken to modify these risk factors through injury-prevention programs [12]. In a 34-year study, as of 2006, a 55% reduction in the overall injury rate was observed [13].

2. Methods

A literature review was conducted using the following databases: PubMed, Scopus, and Web of Science. The review included publications published between 2000 and 2025. The following keywords and their combinations were used with Boolean operators: "alpine skiing", "knee injury", "ACL injury", "anterior cruciate ligament", "MCL injury", "meniscus injury", "ski injury epidemiology", "injury mechanism", "return to sport", and "injury prevention in skiing".

3. Epidemiology of Knee Injuries in Alpine Skiing

The systematic collection of epidemiological data enables a rigorous assessment of the impact of evolving technical regulations on athletes' health [14].

Analysis of historical data indicates a reduction in the overall number of injuries. In the 1950s, the injury rate was approximately 7.6 per 1000 skier-days [15], whereas currently, due to advances in the design of safety systems, it fluctuates around 2.5–3.0 [15, 16]. Paradoxically, however, the transition to carving skis has intensified this risk. The aggressive edge geometry and increased torsional stiffness of modern skis force an immediate edge response and generate substantial shear forces. The shift from traditional skis (long and straight) to carving skis (with pronounced sidecut) constituted a major catalyst for epidemiological changes. The introduction of carving skis revolutionized the biomechanics of turning, resulting in a shift of load concentration from the distal parts of the lower limb to the knee joint [4].

The knee joint remains the most frequently injured anatomical region, accounting for approximately 35.6% of all injuries in alpine skiing [17]. The key pathology is rupture of the anterior cruciate ligament (ACL), which in modern skiing occurs in nearly every case of hospitalization due to a knee injury. Clinical analyses indicate that isolated ACL ruptures account for 35.5% of cases, whereas as many as 64.5% represent combined injuries. The most frequently involved concomitant structures include [4]:

• Medial collateral ligament (MCL): 50.5% of cases.

• Medial meniscus (MM): 40.1% of cases.

4. Risk Factors

4.1. Sex and Age

Men are characterized by a higher overall absolute injury rate (RR 1.42) compared with women. However, with regard to the knee joint, no statistically significant differences in the incidence of injuries between sexes have been demonstrated [17].

Key demographic differences concern the age at the time of ACL rupture (men: 22.6 years; women: 19.9 years). A study by Haida et al. revealed an intriguing performance paradox: athletes after ACL reconstruction (G1) often achieve better sporting outcomes (FIS points, podium finishes) and have significantly longer careers than athletes who have never sustained this injury (G2) [18].

Table 1 The table shows the risk factors taken into account and their consequences for people practising alpine skiing

DEMOGRAPHIC FACTOR	IMPACT ON RISK PROFILE AND CAREER
Male Sex	Higher overall injury incidence; average career length in injured group (G1): 7.9 years vs. uninjured (G2): 4.5 years [17, 18].
Female Sex	Earlier ACL injuries (on average 2.7 years earlier than males); career length G1: 7.1 years vs. G2: 4.2 years [18].
Age at Injury	Key determinant of return to performance. Improvement in results after ACL injury is mainly possible in younger athletes, before peak performance (~25 years of age) [18].

4.2. Speed

There is a linear correlation between speed and injury risk. Speed disciplines (Downhill, Super-G) generate significantly higher injury rates than technical disciplines (Giant Slalom, Slalom). According to Flørenes et al. (2009), the risk increases from 4.9 injuries per 1000 runs in slalom to 17.2 in downhill. The relative risk for all injuries in downhill is 3.48 times higher than in slalom [17].

In high-energy disciplines, the ski acts as a lever arm, leading to "gear-induced" injury mechanisms [7]. Extreme rotational forces, which cannot be compensated for by muscular stabilization, are transmitted directly to the ligamentous structures of the knee.

5. Injury Mechanisms

Knee injury mechanisms in alpine skiing are complex and result from the specific interaction between skiing turn biomechanics, equipment design, and the action of external forces with high rotational moments [6, 8, 19].

In contrast to many other sports, where contact mechanisms predominate, the majority of severe knee injuries in alpine skiing are non-contact in nature [6, 7]. Injuries most often occur due to loss of control over the ski while the foot remains secured in the binding, leading to the transmission of substantial torsional forces to the knee joint.

5.1. Valgus-External Rotation

This is currently recognized as the most common injury mechanism among recreational skiers, accounting for approximately 32.9% of cases [5]. The biomechanical basis of this injury is the skier losing balance, with the center of gravity shifting forward over the knees. The inner edge of the front part of the ski catches the snow, causing sudden valgus stress and external rotation of the tibia [5, 20]. The long ski acts as a lever, amplifying the force (torque) applied to the joint [5, 20]. This mechanism almost always results in MCL injury, and in approximately 20% of cases, it is accompanied by simultaneous ACL rupture [5, 21].

5.2. Phantom Foot

One of the best-described ACL injury mechanisms in alpine skiing is the so-called "phantom foot" mechanism [5, 15]. It most often occurs when the skier loses balance backward while loading the tail of the ski. In this configuration: the hip is internally rotated, the knee is flexed, the foot is secured in the boot and binding, and the rear part of the ski acts as a long lever generating a rotational moment [5, 6, 20].

- Hip is internally rotated,
- Knee is flexed,
- Foot is stabilized in the boot and binding,
- Rear part of the ski acts as a long lever generating rotational torque.

This results in a combination of:

- Internal rotation of the tibia,
- Valgus moment at the knee,

- Anterior displacement of the tibia relative to the femur,

which leads to exceeding the tensile strength of the ACL [6, 22]. Video analyses of injuries in professional alpine skiing confirm that this mechanism is among the most common in technical events such as slalom and giant slalom [5, 6, 23].

5.3. “Slip-Catch” Mechanism

The “slip-catch” mechanism most frequently occurs during an aggressive turn at high speed, when the inner edge of the ski suddenly “catches” the snow after a brief loss of contact. The sudden stop of the ski generates rapid external rotation of the tibia and a valgus force, leading to overload of the ACL and MCL. Biomechanical studies have shown that in this mechanism, the moments of force acting on the knee joint can exceed the physiological strength of the ACL, particularly with suboptimal trunk positioning and delayed neuromuscular response [6, 7, 24].

5.4. “Dynamic Snowplow” Mechanism

This mechanism primarily occurs in professional skiers during fall-line skiing or traverses [6]. The skier loses balance backward while unevenly loading the skis. It occurs in situations of asymmetric ski loading, valgus stress, and external rotation of the lower limb. The unloaded leg moves outward (splits position), while the loaded leg shifts from the outer to the inner edge [6]. This results in a “plow-like” position, which at high speed forces destructive internal rotation and valgus of the knee [6, 25]. In this mechanism, MCL injury predominates, often accompanied by partial ACL damage [26, 27].

5.5. Landing Back-Weighted Mechanism (Boot-Induced)

This mechanism occurs when the skier lands after becoming airborne with a backward-shifted center of gravity, loading the tails of the skis. This creates an unfavorable configuration of the lower limb segments, pushing the proximal tibia anteriorly and causing a rapid anterior translation of the tibia. Biomechanically, this maneuver simulates the anterior drawer test, leading to ACL rupture. The typical position includes:

- Excessive hip flexion,
- Knee joint relatively extended or moderately flexed,
- Increased loading on the rear part of the ski,
- Limited capacity for active neuromuscular control of the knee joint.

In this configuration, the knee flexor muscles (particularly the hamstrings), which physiologically serve a protective function for the ACL, are either insufficiently activated or positioned in a disadvantageous length–tension relationship [6, 15, 28].

Tab 2. Mechanisms of knee joint injuries in alpine skiing – clinical characteristics, risk factors

INJURY MECHANISM	LEVEL / GROUP	TYPICAL INJURIES	RISK FACTORS	SOURCE
Valgus-external rotation	Recreational skiers (beginners and intermediate)	ACL rupture and injury, MCL injury	Failure of ski binding release, low skill in falling, incorrect binding release setting (DIN)	[5, 29]
Phantom foot	Recreational skiers (especially aged 30–40 years)	ACL rupture	Long skis (acting as a lever), backward loss of balance, skis with aggressive sidecut	[5, 25, 29]
Slip-catch	Competitive athletes (World Cup)	ACL, often with concomitant cartilage and meniscal injuries	High speed, aggressive course preparation (hard snow), fatigue in the final phase of the race, technical errors	[25]
Boot-induced	Recreational and competitive skiers (especially speed disciplines)	Isolated ACL rupture	Loss of control over the inner ski, tactical errors, challenging snow conditions	[25]
Dynamic snowplow	Elite athletes	ACL rupture	Loss of control over inside ski, tactical errors, difficult snow conditions	[25]

6. Characteristics of Knee Injuries in Alpine Skiing

6.1. ACL Injuries

Isolated ACL injuries in skiing are rare, accounting for only 18% to 35.5% of cases [9, 30]. Most injuries are complex, with ACL damage accompanied by: MCL injury in approximately 50.5% of cases [4]; meniscal injuries, with lateral meniscus tears more frequent than medial (the ACL–MCL–lateral meniscus triad occurs nine times more often than the classical O'Donoghue triad) [16]; and bony structures, where valgus loading increases the incidence of tibial plateau fractures [21].

The standard management for skiers is surgical treatment involving ACL reconstruction using autografts, most commonly from the hamstring tendons or the quadriceps tendon [30]. The most frequent consequence of injury is muscular deficits. Studies show that even five months post-surgery, skiers exhibit significant deficits in quadriceps strength (on average −21% compared with the healthy leg) and jump power (−13%) [30]. Rehabilitation should focus on neuromuscular training, deep core strengthening, and sport-specific eccentric strength training at knee flexion angles typical for skiing (approximately 70°) [7, 27].

The expected rehabilitation period ranges from 6 to 12 months. Professional athletes return to competition on average one year (approximately 364 days) after surgery [7, 30]. Return to initial sporting performance and the slopes occurs after one year, whereas a return to pre-injury full performance (measured by FIS points) is a long-term process. Statistics indicate that athletes regain or improve their results on average 3.1 to 3.8 years after the injury [18]. A key success factor is the age at the time of injury—athletes operated on before the age of 25 have a significantly higher chance of improving performance in their subsequent career [18].

6.2. Meniscal Injuries

Meniscal injuries represent a significant component of the clinical picture in alpine skiing. They most frequently occur as concomitant injuries with ACL and MCL tears [9, 16]. The prevalence of meniscal injury in combination with acute ACL rupture among skiers ranges from 23% to 55% [16, 21]. Among elite alpine skiers, this prevalence appears even higher; one study of operative reports from competitive athletes found that 61% of individuals with ACL injuries also had concomitant meniscal damage [9].

Furthermore, complex intra-articular injuries, such as single-column tibial plateau fractures (type B3), are significantly associated with concurrent meniscal injuries due to the high energy transmitted to the joint during the trauma [31]. A characteristic feature of skiing-related knee injuries is the predominance of lateral meniscus (LM) damage. Studies indicate that the "unhappy triad" in alpine skiing—comprising the ACL, medial collateral ligament, and lateral meniscus—occurs nine times more frequently than the classical triad involving the medial meniscus [16, 21].

The biomechanical explanation for this pattern involves "entrapment" of the lateral meniscus beneath the lateral femoral condyle during high-torque loading [16]. This typically occurs at increased knee flexion angles; when the knee undergoes an anterolateral rotation coinciding with ACL rupture, the trapped meniscus is subjected to destructive shear forces [16].

Treatment of meniscal injuries in skiers emphasizes joint preservation through arthroscopic repair using inside-out suture techniques for intra-articular structures [16]. Recovery from meniscal and ligament injuries in alpine skiing is a prolonged process requiring specialized rehabilitation. Among competitive athletes, the average return to competition after primary ACL reconstruction and associated structures is approximately 9.1 months, whereas in cases of complex injuries, this period may extend up to 13.5 months [9, 30].

6.3 MCL Injuries

Knee injuries account for approximately one-third of all injuries recorded among alpine skiers [2, 20]. The medial collateral ligament (MCL) has historically been recognized as the most frequently injured ligamentous structure in this group of athletes, accounting for up to 60% of all knee injuries in some studies [16]. The MCL remains a key element in skiing-related pathologies, particularly in female athletes, who exhibit a higher susceptibility to MCL injuries, typically of lower severity (Grade I and II – partial tears) [29].

The consequences of MCL injuries are determined by the extent of tissue damage and the presence of concomitant injuries. Most isolated MCL injuries in skiers are Grade II [2]. The ligament healing process involves three phases: inflammatory (up to 72 hours), repair and regeneration (up to 6 weeks), and remodeling (lasting up to one year). Despite a high potential for spontaneous healing, scar tissue may remain mechanically weaker (regaining approximately 70% of the original strength), predisposing to residual laxity [16].

MCL injuries rarely occur in isolation under high-force conditions. In approximately 20–57% of cases, MCL injury is accompanied by ACL rupture [2, 16]. A common consequence is the so-called "unhappy triad,"

Current sports medicine standards indicate that most MCL injuries in skiers (even Grade III) can be managed conservatively using hinged braces, provided that concomitant ACL reconstruction is performed if the ACL is also ruptured [16]. Surgical repair of the MCL is considered mainly in cases of extreme instability in full extension that does not respond to orthopedic stabilization. Prognosis for skiers with isolated MCL injuries is generally very good, with return to full activity following restoration of full range of motion and muscular strength [16, 32].

6.4. Fractures

Modern alpine skiing, despite significant advances in safety technology, remains a high-risk sport. Historically, the introduction of rigid plastic ski boots and standardized binding systems led to a 92% reduction in ankle fractures [21, 29]. However, stiffening the lower leg resulted in the transfer of loading forces to higher segments, leading to an increased incidence of proximal tibial fractures [21, 33]. Currently, fractures account for approximately 18.8% of all injuries in alpine skiing [17].

In the literature, skiing-related fractures are primarily classified according to anatomical location and mechanism of injury. The most common type of tibial fracture among recreational skiers is a tibial shaft fracture (63%), often spiral in nature, resulting from failure of the ski binding release mechanism [5, 33]. There is a noticeable increasing trend in tibial plateau fractures, associated with the widespread use of carving skis and the aging population of skiers [5, 31, 33]. Type B (partial intra-articular) and Type C (complex) fractures are correlated with higher BMI, high speed, and hard snow conditions [5, 31]. “Boot-top” fractures occur at the edge of the boot cuff due to lever forces during forward falls [21].

Treatment and therapeutic management depend on the complexity of the injury (AO classification). In bicondylar tibial plateau fractures, a two-stage strategy is preferred. The first stage involves external stabilization (external fixator) to allow soft tissue consolidation, followed by open reduction and internal fixation (ORIF) with a plate after an average of 6.4 days. Approximately one-third of patients with complex tibial fractures develop compartment syndrome, requiring immediate fasciotomy [31].

Bone fractures in skiing are mostly classified as severe injuries, resulting in an absence from sport exceeding 28 days [9, 17, 27]. The initial phase of bone tissue regeneration typically lasts 6–12 weeks, but full remodeling and recovery of muscular strength may take up to one year [16]. Professional athletes returning from major bone-ligament injuries resume competition on average after one year (approximately 364 days) [30]. Sporting performance and FIS points are initially reduced, with recovery to pre-injury form and improvement generally occurring 3.1 to 3.8 years after the accident [18].

7. Injury Prevention

To protect the knees from injury, skiers should primarily focus on neuromuscular training, deep core strengthening, and lower limb strength training, with particular attention to landing and braking techniques [7, 27]. Research indicates that general physical fitness alone is insufficient—specific exercises that enhance body control in unpredictable situations on the slope are crucial [7, 9].

7.1. Neuromuscular and Balance Training

This type of training is considered one of the most effective methods for preventing ACL ruptures [7, 27]. Its goal is to improve joint coordination and stability under dynamic conditions. The training typically involves exercises performed on balance platforms or unstable surfaces, teaching both the muscles and the athlete to respond quickly to loss of balance. This is especially important given the challenges posed by ski equipment, including stiff boots, which can impair the skier’s ability to maintain balance [7, 27].

7.2. Core Muscle Strengthening

Insufficient strength or uneven tension in the abdominal and back muscles is a proven risk factor for ACL injuries in skiers. By improving trunk control and increasing core muscle tension, the transfer of hazardous forces to the knees during turns and jumps is reduced, resulting in fewer injuries. Recommended exercises aim to strengthen the muscular "corset" and prevent the adoption of backward-leaning positions, which are responsible for many injuries [7, 27, 34].

7.3. Lower Limb Strength Training

Not only raw strength but also balance between muscle groups is essential.

- **Quadriceps:** Must be sufficiently strong to control horizontal braking and stabilize the knee during landings.
- **Hamstrings:** Proper strength and reaction speed help limit anterior tibial translation, protecting the ACL.

Example exercises include squats, lunges, and eccentric exercises performed at knee flexion angles typical for skiing (approximately 70°) [7, 27, 35].

7.4. Technique Training (Landing and Change of Direction)

Many injuries result from poor technique during high-speed maneuvers [7, 9, 27]. Skiers should practice "soft" landings on both skis with bent knees. Avoiding landings on fully extended legs directly protects against boot-induced injury mechanisms [20, 34]. Exercises should teach safe hip and knee flexion during sudden deceleration, reducing mechanical stress on the ligaments [7].

7.5. Awareness Training

Although not a physical exercise, educational programs (e.g., Vermont Ski Safety) have demonstrated effectiveness. They teach skiers to recognize critical moments (e.g., when one arm falls backward and hips drop below knee level) and automatically respond defensively: extending the arms forward, keeping skis together, and maintaining hands over the skis [34]. Fatigue is also an important risk factor; therefore, endurance training and proper recovery on the slope (e.g., active rest between runs) further help protect the knee joint [9, 27].

8. Discussion

Knee injuries remain one of the most significant health problems in alpine skiing, affecting both recreational skiers and elite athletes. The findings of this narrative review confirm that the knee joint is the most frequently injured anatomical region in alpine skiing, with anterior cruciate ligament (ACL) rupture representing the predominant severe injury pattern. The high incidence of ACL injuries is strongly related to the specific biomechanical demands of alpine skiing, which involve high velocities, large ground reaction forces, and the interaction between the skier and modern ski equipment.

Although the overall injury rate in alpine skiing has decreased over the past decades due to improvements in protective equipment, slope management, and binding release systems, the relative proportion of knee injuries has remained consistently high. Previous epidemiological studies indicate that the knee accounts for approximately one-third of all skiing-related injuries, with ACL injuries representing the majority of cases requiring hospitalization or surgical treatment. This suggests that technological advances in equipment have shifted the distribution of injuries rather than eliminating the risk entirely.

Several characteristic mechanisms have been identified in the literature, including the slip-catch, phantom foot, dynamic snowplow, and landing back-weighted mechanisms. Despite differences in movement patterns, these mechanisms share common biomechanical features, such as excessive internal or external tibial rotation, valgus loading of the knee joint, and anterior tibial translation relative to the femur. When these forces exceed the structural tolerance of the ACL, ligament rupture may occur.

The interaction between the skier and equipment appears to play a particularly important role in injury development. Modern carving skis, characterized by aggressive sidecut geometry and high torsional stiffness, allow for more dynamic and precise turns but also generate higher rotational forces acting on the lower extremity. In situations where the skier loses balance or the ski edge suddenly engages with the snow surface, the ski may act as a long lever arm transmitting large torque to the knee joint. Similarly, the rigidity of modern ski boots may limit the natural dissipation of forces, potentially increasing the mechanical load transferred to the knee structures. These equipment-related factors may partly explain the shift in injury patterns observed since the introduction of carving skis.

Another important aspect highlighted in the literature is the role of intrinsic and extrinsic risk factors. Among intrinsic factors, neuromuscular control, muscle strength balance, fatigue, and sex-related anatomical and hormonal differences have been identified as potential contributors to injury risk. Female athletes have been reported to exhibit a higher relative risk of ACL injury in many sports, although epidemiological data in alpine skiing are somewhat inconsistent. Fatigue appears to be a particularly relevant factor, especially in competitive skiing, where many injuries occur during the final phases of a run when neuromuscular control and reaction time may be compromised.

Extrinsic risk factors include snow conditions, slope preparation, competition speed, and equipment setup. High-speed disciplines such as downhill and super-G expose athletes to significantly greater mechanical loads compared with technical disciplines such as slalom or giant slalom. Hard snow surfaces and aggressive course settings may further increase injury risk by generating sudden edge engagement and high torsional forces at the knee joint.

The clinical consequences of ACL injuries in alpine skiing are substantial. These injuries are typically associated with long rehabilitation periods, often ranging from six to twelve months, and may lead to persistent functional deficits or long-term degenerative changes in the knee joint. Although many elite athletes successfully return to competition following ACL reconstruction, the injury may influence career trajectory, performance consistency, and long-term joint health. Moreover, combined injuries involving the MCL, menisci, or articular cartilage are common and may further complicate treatment and recovery.

Given the high incidence and severe consequences of knee injuries in alpine skiing, effective preventive strategies are of particular importance. Current evidence suggests that neuromuscular training programs aimed at improving balance, dynamic joint stability, and landing mechanics may reduce the risk of ACL injuries. Strength training focused on the hamstrings, quadriceps, and core musculature may also enhance joint stability and reduce excessive forward tibial displacement during high-load movements. In addition to physical conditioning, skier education regarding proper technique, safe falling strategies, and awareness of risky body positions may further contribute to injury prevention.

From a practical perspective, injury prevention in alpine skiing should adopt a multifactorial approach combining athlete preparation, technical skill development, and equipment optimization. Adjustments in binding settings, ski geometry, and boot stiffness may potentially influence injury risk, although further biomechanical research is required to determine optimal configurations. Similarly, course design and competition regulations may play an important role in limiting excessive speeds and reducing exposure to high-risk situations.

Despite the growing body of literature on alpine skiing injuries, several gaps remain. Many studies focus primarily on elite athletes, while less is known about injury mechanisms and prevention strategies in recreational skiers, who represent the largest population of participants. Furthermore, most available studies are observational, and there is a need for prospective research evaluating the effectiveness of targeted prevention programs. Future research should also integrate biomechanical analysis, wearable sensor technology, and video-based injury surveillance to better understand real-time injury mechanisms and develop evidence-based prevention strategies.

In summary, knee injuries—particularly ACL ruptures—continue to represent a major challenge in alpine skiing. These injuries result from complex interactions between biomechanical forces, skier technique, equipment characteristics, and environmental conditions. A comprehensive understanding of injury mechanisms and risk factors is essential for developing effective preventive strategies aimed at improving athlete safety and reducing the long-term burden of knee injuries in alpine skiing.

9. Conclusions

Knee injuries represent the most frequent site of severe trauma in alpine skiing, affecting both competitive athletes and recreational skiers [1, 2]. The most common injuries involve the anterior cruciate ligament (ACL), which result from a complex, multifactorial mechanism [6, 7].

Most ACL injuries are non-contact in nature and are associated with characteristic biomechanical mechanisms such as slip-catch, dynamic snowplow, landing back-weighted, and phantom foot [6, 13, 14]. These mechanisms involve a combination of anterior tibial translation, rotation, and valgus moments at the knee joint, often amplified by the interaction between the skier and the equipment [6, 7, 10].

Key risk factors include female sex, fatigue, deficits in neuromuscular control, and high skiing speeds [3, 11, 15]. Appropriately designed preventive training programs can effectively reduce injury risk [12, 16]. Despite a high rate of return to sport following ACL reconstruction, these injuries are associated with prolonged rehabilitation and an increased risk of future degenerative changes [8, 18].

In summary, an effective strategy for reducing knee injuries in alpine skiing should be multifaceted, incorporating educational initiatives, optimization of skiing technique, equipment modifications, and targeted neuromuscular training programs. Further high-quality prospective studies are needed to evaluate the effectiveness of preventive interventions across different skier populations.

Disclosure:

Author's contribution:

Conceptualization: MS, MK, AP;

Methodology: MS, MK, PC;

Formal analysis: MK, KC, MSl;

Investigation: MSi, KZ, IG;

Resources: AA, MSi, MK;

Data curation: AA, KC**;**

Writing – original draft: PC, MK, MSl;

Writing – review & editing: AP, MS;

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