

Knee Braces and Sleeves in Alpine Skiing: A Narrative Review of ACL Injury Mechanisms, Mechanical and Neuromuscular Effects, and a Proposed Clinical Decision Framework

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Abstract: Alpine skiing combines high speed, uneven terrain, and demanding lower-limb loading; anterior cruciate ligament (ACL) injury therefore remains a common concern. Knee braces and soft knee sleeves are used in rehabilitation and on the slope, but their effects on mechanical stability, proprioception, neuromuscular control, and injury prevention remain unsettled. This narrative review synthesizes literature on skiing-related ACL injury mechanisms, braces, sleeves, proprioception, and neuromuscular control. It first describes how ACL injuries occur in alpine skiing and then considers the potential mechanical and neural effects, as well as the limitations, of protective devices. To organize the practical implications of this evidence, the review also proposes a conceptual clinical decision framework integrating knee status, the primary purpose of device use, skiing exposure, and device fit and tolerance. The framework is intended to support individualized discussion rather than serve as a validated prediction or treatment algorithm. The review further considers active recovery during breaks and neuromuscular adaptation training. Its aim is to provide a reasoned basis for individualized device selection and future clinical research.

Keywords: Alpine Skiing; Anterior Cruciate Ligament; Functional Knee Brace; Prophylactic Knee Brace; Knee Sleeve; Proprioception; Neuromuscular Control

1. Introduction

Prophylactic knee braces (PKBs), functional knee braces (FKBs), and soft knee sleeves are frequently used to prevent ACL injury, support postoperative rehabilitation, and facilitate return to skiing. Braces may mechanically restrain the knee while influencing proprioception,

neuromuscular control, and the wearer's perception of stability; sleeves are used mainly for their sensory effects. Some reports also associate functional bracing with a lower risk of a second injury after ACL injury. However, direct brace-versus-sleeve comparisons remain scarce, possible adverse effects are relevant, and the effect on knee proprioception is still debated. Existing device-selection advice is often organized by sport situation alone and may not adequately distinguish a healthy recreational skier from a skier returning after ACL reconstruction, a person with functional instability, or an individual with active symptoms. This review therefore examines the structure, mechanisms, intended users, and potential drawbacks of these devices. It also proposes a conceptual, non-validated clinical decision framework that integrates knee status, primary use objective, skiing exposure, and fit and tolerance to guide individualized device discussion.

2. Principal Mechanical Mechanisms and Neuromuscular Contributors to ACL Injury in Alpine Skiing

Alpine ski equipment alters the way loads reach the knee. Rigid boots and bindings make the boot-ski unit a long lever from the foot to the proximal tibia ^[1, 2], creating a constrained rotational setting. With less opportunity for the ankle to absorb rotational shear, edge-generated loads can be passed more readily to the knee ^[1]. Knee injuries account for roughly 27%–41% of injuries at ski resorts ^[2], and ACL and medial collateral ligament (MCL) sprains are reported most often ^[3-5]. An ACL rupture commonly involves a prolonged surgical and rehabilitation course, direct and indirect costs, and reinjury rates of 19%–46.7% after return to sport ^[2]. These circumstances help explain why ACL injuries in skiing display characteristic movement patterns.

2.1 Core Biomechanical Injury Models

2.1.1 Excessive internal tibial rotation

Excessive inward rotation of the tibia around its long axis can twist the ACL beyond its tolerance and lead to rupture.

In alpine skiing, this loading pattern is represented by the slip-catch mechanism, a common route to internal rotation [6]. After the outside ski slips, the skier may try to regain grip with the inside edge. If that edge catches on ice or compact snow, the ski stops while the body continues forward and sideways under inertia, producing a large internal-rotation moment [7, 8].

The phantom-foot mechanism is seen more often in beginners. The unweighted uphill ski lifts from the snow, while the tail of the loaded downhill ski becomes embedded. A backward fall combined with this torsion can drive the knee into excessive internal rotation while it is hyperextended [7].

2.1.2 Excessive anterior tibial translation

Another skiing-specific pattern is the boot-induced anterior drawer (BIAD) mechanism. At landing, a rigid ski boot limits ankle dorsiflexion, so the ground-reaction force can drive the lower leg forward. At the same time, a posterior body force draws the thigh backward, creating an abrupt opposing shear force [7, 9]. This pattern is reported more often in freestyle than in recreational skiers [10].

2.1.3 Knee valgus

Knee valgus is a medial collapse of the knee that opens the medial joint space and compresses the lateral compartment; it often occurs together with internal tibial rotation.

During a slip-catch event, the skier attempts to regain the edge while also resisting substantial centrifugal force. The knee can therefore move into a marked medial-collapse position, producing dynamic valgus.

In a phantom-foot event, a backward fall may also produce valgus when the pelvis lies below the knee and control depends heavily on the inside edge.

2.1.4 Knee hyperextension

Hyperextension refers to knee extension beyond the usual range, with posterior recurvatum and increased ACL traction. If a skier lands after losing balance in the air with the knee nearly straight, the impact can move the tibia forward and push the already extended knee farther posteriorly, toward hyperextension [6].

2.1.5 Axial compressive force

Axial compression is an upward force applied

along the long axis of the lower-limb skeleton and may reach several times body weight.

Although axial compression alone is unlikely to rupture the ACL, posterior tibial slope can convert part of this force into anterior tibial translation. In BIAD and slip-catch events, high compression can therefore add to anterior translation and varus–valgus loading.

Summary: Skiing-related ACL rupture usually reflects combined rather than isolated loading. Slip-catch events combine internal rotation, valgus, and axial compression; phantom-foot events combine internal rotation with abnormal flexion–valgus loading; and BIAD events combine anterior translation, hyperextension, and axial compression. When these forces coincide, they may exceed ligament tolerance within a very short interval.

2.2 Reduced Joint Stability and Kinetic-Chain Imbalance

At high downhill speeds, passive ligament capacity cannot by itself oppose loads of several body weights and associated centrifugal forces. Functional stability of the knee consequently relies on substantial active muscle contraction [11].

2.3 Impaired Proprioception

Metabolic fatigue can degrade proprioception, leaving skiers slower to recognize and correct small postural deviations and potentially increasing injury risk.

3. Core Mechanisms, Physiological Risks, and Comparative Classification of Knee Protective Devices

Because ACL injury carries substantial consequences, many skiers use external protective devices. PKBs, FKBs, and soft knee sleeves nevertheless differ in construction, indications, and physiological effects.

3.1 Core Mechanical-Intervention Mechanisms and Neural-Arousal Effects

3.1.1 The four-point leverage system of functional braces

Functional braces are the most complex external devices intended to counter excessive ACL strain. Their design follows the four-point leverage principle [12]: specialized straps and rigid components establish resistance points anterior and posterior to both the femur and tibia. Table 1 summarizes how these mechanical principles apply to five skiing-related ACL injury

mechanisms and their principal limitations.

Table 1. Effectiveness of Functional Braces in Preventing Specific ACL Injury Mechanisms, Mechanical Principles, and Limitations

Injury Mechanism	Assessment of Protective Effect	Mechanical Protective Principle of the Brace	Limitations and Reasons for Failure
1. Knee hyperextension	High	At a selected flexion threshold, the hinge can restrict hyperextension and provide a mechanical stop [13].	At modest loads, an extension stop can offer clear mechanical restraint. In a high-load fall or impact, however, its protection still depends on brace fit, skin friction, and the external moment.
2. Excessive anterior tibial translation	Moderate	Four-point leverage: crossed straps positioned anterior to the thigh and posterior to the lower leg apply a posteriorly directed force to the proximal tibia.	Once anterior force at the knee exceeds 140 N, a brace cannot effectively reduce anterior tibial translation [12]. At high load, strap forces can exceed the traction tolerated by soft tissue, so the straps cannot restrain skeletal displacement.
3. Knee valgus	Low to moderate	Lateral supporting structures can provide some structural restraint of frontal-plane motion [13].	If the lever moment becomes excessive, lateral force from an edge catch can be transmitted through the metal struts and cause injury elsewhere.
4. Excessive internal tibial rotation	Very low	(No directly effective mechanical intervention)	When internal-rotation torque exceeds 8 N·m, the brace can rotate and slide together with the skin [12].
5. Axial compressive force	None	(No longitudinal shock-absorption structure)	The brace is not connected to the ski-boot sole and has no structure for longitudinal shock absorption. Over-tight strapping can also restrict normal flexion and promote a stiff landing, transmitting more impact to the body.

Mechanical restraint has clear limits. In lower-load situations such as gentle turns or slow braking, a functional brace can add some restraint. A high-load fall, rapid impact, or severe edge-catch rotation is different: the boot–ski complex generates a large moment, and brace strength and skin friction may not fully lock the joint [14, 15]. Injurious load can still reach the ligament.

3.1.2 Neuromuscular arousal and proprioceptive remodeling

A mechanical barrier may fail under extreme impact, yet cohort data in skiers after ACL reconstruction found a 2.74-fold higher subsequent knee-injury risk in nonusers than in functional-brace users [16]. One possible explanation is altered proprioceptive input. Contact between a brace or sleeve and periarticular skin and deep fascia may improve joint-position and movement sense in some populations [17]. Whether that sensory feedback changes muscle activation during skiing after ACL injury remains to be established.

3.2 Potential Clinical Metabolic Costs and Physiological Risks

The stability and sensory effects of braces may

come with physiological costs. By adding an external constraint to the lower limb, a brace can create problems in four main areas.

3.2.1 Restricted local blood flow and ischemic metabolic stress

To limit migration during vigorous movement, sleeves and brace straps are often tightened around the thigh and calf. Deep knee flexion and extension in skiing can raise interface pressure at brace edges and interfere with venous return. The resulting compression may raise intramuscular pressure and reduce local muscle blood flow and oxygenation [18, 19], increasing the likelihood of metabolic fatigue.

3.2.2 Increased metabolic cost

Brace weight and resistance to joint motion can raise the energetic cost of exercise [19]. During dynamic activity, structural braces have been associated with 3%–8% increases in oxygen consumption, heart rate, and minute ventilation, together with higher perceived fatigue [20].

3.2.3 Restricted muscle force production

Brace use may reduce peak quadriceps force [13, 18], with both potential protective and adverse consequences. When the knee is near extension, quadriceps loading may increase ACL strain.

Therefore, reduced quadriceps force could lower ACL loading during certain near-extension tasks^[21, 22]. However, adequate quadriceps strength is also important for power production, knee-flexion control, and shock absorption. Studies following ACL reconstruction have associated quadriceps weakness with altered landing mechanics and interlimb loading asymmetry^[23]. A brace-related reduction in quadriceps force may therefore impair power, deceleration control, and shock absorption, particularly during flexed, weight-bearing, or repeated eccentric tasks. This reduction should be regarded as a conditional trade-off whose effects depend on knee-flexion angle, movement task, the magnitude and timing of muscle force, and concurrent hamstring activation^[22, 24]. Because

the available bracing evidence was obtained during perturbed walking rather than alpine skiing^[13], the overall protective or adverse effect during skiing remains uncertain.

3.2.4 Uncontrolled mechanical migration

A brace can migrate distally during vigorous activity^[25]. Its hinge may then no longer align with the knee's true center of rotation, reducing support and creating shear stress in the surrounding soft tissue, with resulting discomfort.

3.3 Parameterized Comparison of Prophylactic Knee Braces, Functional Knee Braces, and Soft Knee Sleeves

Table 2 places the three common devices side by side, comparing their form, materials, intended users, and clinical-use considerations.

Table 2. Comparison of Three Common Knee Protective Devices

	Prophylactic Knee Braces (PKBs)	Functional Knee Braces (FKBs)	Soft Compression Knee Sleeves
Form and structural components	Single- or double-upright metal/composite-plastic struts, linked by hinges and multiple adjustable straps; relatively bulky but highly adjustable.	A rigid closed-frame design, usually with bilateral polycentric hinges; highly customized and fitted with a strict four-point or multipoint strap-leverage system.	A tubular fabric sleeve, closed or patellar-opening; usually without rigid hinges, although some models include a silicone patellar ring or soft lateral stays.
Materials	Aluminum-alloy frame, conventional plastic-composite body, neoprene lining, and nylon straps.	Lightweight aluminum alloy or high-strength carbon fiber.	High-density neoprene, knitted elastic fibers, spandex, and internal silicone anti-slip strips.
Primary target population	For people with structurally healthy knees who face high risk in contact sports, chiefly to reduce primary ligament injury—especially MCL injury—from direct lateral impact ^[26] .	For athletes returning to high-level skiing after ACL reconstruction, people with nonoperatively managed ACL deficiency, and patients with chronic multidirectional instability or severe osteoarthritis.	For healthy recreational skiers, beginners, and people with mild knee discomfort, patellar maltracking, mild degenerative osteoarthritis, or a need for basic warmth.
Consensus and current application	Evidence that PKBs reduce MCL-injury risk in contact sports is inconsistent and does not support routine use in healthy athletes ^[27] . Evidence for primary ACL-injury prevention in alpine skiing is even more limited.	May be considered for skiers returning to high-intensity skiing after ACL reconstruction or for people with nonoperatively managed ACL functional instability. A cohort study found fewer subsequent knee injuries among brace users after ACL reconstruction ^[16] , but this result should not be generalized to every high-demand population.	Soft sleeves cannot mechanically prevent ligament rupture. They may improve joint-position sense in some groups, while warmth and comfort are additional considerations ^[17, 28] .

4. Optimal Responses to the Dual Nature of Bracing and Specific Wearing Strategies

The preceding comparison shows that device choice depends on the user and the skiing context. Table 3 identifies contextual considerations that

can inform this choice, but skiing technique alone should not determine device selection. A practical approach should also account for knee status, the intended purpose of device use, and fit and tolerance, while maintaining sport-specific neuromuscular training.

Different Contexts(see table 3)

4.1 Precise Selection of Protective Devices for

Table 3. Contextual Considerations for Knee-Protective Device Selection in Alpine Skiing

Skiing technique	Primary risk	Recommended protective device	Mechanical-intervention mechanism and rationale for use
Carving / giant slalom turns	High propensity to trigger the slip-catch mechanism	Functional brace or prophylactic brace with robust hinges	At high impact, soft devices offer limited support; a rigid frame is required for meaningful mechanical protection.
Parallel turns	Accumulation of routine muscle fatigue or occasional loss of balance	Healthy individuals: soft knee sleeve; prior ACL injury: functional brace	Extreme mechanical restraint is not usually required. The main value lies in supporting sensorimotor feedback.
Short skidded turns	Ligament traction and sprain caused by movement breakdown or reduced control	Soft knee sleeve	A soft sleeve does not mechanically constrain the knee. It preserves freedom of movement while providing basic proprioceptive input.
Moguls / variable snow	Rapid eccentric–concentric muscle actions causing fatigue over a short period; rigid rebound forces due to inadequate flexion–extension	Healthy knee: soft knee sleeve; involved limb: low-profile, close-fitting functional brace	A soft sleeve provides warmth and proprioceptive input. A heavier brace raises metabolic cost and may migrate distally during repeated vertical flexion and extension.

4.2 Proposed Clinical Decision Framework for Individualized Device Selection

The evidence summarized in this review supports a proposed conceptual framework rather than a validated clinical algorithm. The framework begins with the skier's knee status, then considers the primary purpose of device use, skiing exposure, and device fit and tolerance. It is intended to prevent context-based recommendations from being applied

indiscriminately across clinically different users. In particular, active pain, recurrent effusion, giving way, marked instability, neurological symptoms, or poor device tolerance should prompt clinical assessment rather than routine device selection. Across all pathways, knee devices should be regarded as adjuncts to, rather than substitutes for, neuromuscular training, technique optimization, and fatigue management(see Figure 1).

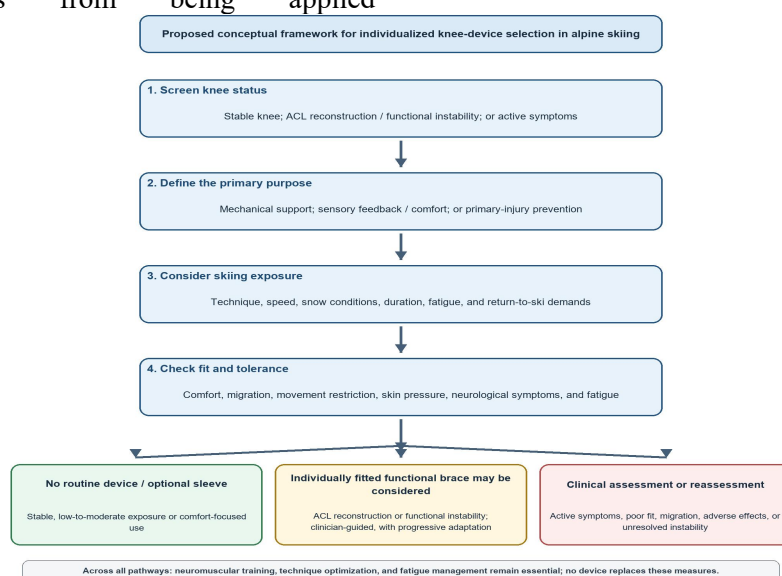


Figure 1. Proposed Conceptual Decision Framework for Individualized Selection of Knee Braces and Sleeves in Alpine Skiing. This Framework is not a Validated Clinical Prediction or Treatment Algorithm

Table 4. Simplified Final Recommendation Table for Knee-Device Selection in Alpine Skiing

Clinical or skiing profile	Suggested decision output	Key conditions and cautions
Stable knee; low-to-moderate recreational exposure; no clear mechanical-support goal	No device is routinely required; a soft sleeve may be used if preferred for comfort or warmth.	A sleeve should not be represented as a mechanical method of preventing ACL rupture.
Stable knee; high perceived risk but no prior ACL injury or instability	Do not routinely select a rigid prophylactic brace solely for primary ACL-injury prevention.	Direct evidence for primary ACL prevention in alpine skiing is limited; prioritize technique, conditioning, and neuromuscular training.
Return to skiing after ACL reconstruction, or ACL deficiency with functional instability	An appropriately fitted functional brace may be considered after individualized clinical discussion.	Use should be paired with progressive adaptation and return-to-ski rehabilitation; it does not replace objective readiness assessment or neuromuscular training.
Active pain, recurrent swelling, giving way, marked instability, neurological symptoms, or poor fit / migration	Defer routine device selection and seek clinical assessment or reassessment.	Address the underlying clinical problem and device fit before high-demand skiing.

4.3 Simplified Final Recommendation Table

Table 4 summarizes the final decision outputs of the proposed framework. The wording is deliberately conditional because available evidence does not support routine use of a single device for all skiers or all skiing conditions.

5. Brace-Specific Adaptation and Systematic Neuromuscular Training in Daily Practice

5.1 Brace-Specific Adaptation Training

Changes in Muscle-Activation Patterns and Electromyography (EMG) During Skiing With a Knee Brace

In double-leg landing tasks, a prophylactic knee brace has been associated with altered lower-limb biomechanics and greater hip energy absorption [29]. Routine training can therefore include targeted neuromuscular adaptation exercises to accommodate possible bracing-related changes and limit compensatory loading or early fatigue.

5.1.1 Enhancing eccentric load absorption of the hip and core musculature (load transfer)

A brace may increase support at the knee, but a ski boot still fixes the ankle and can transmit large ground-reaction forces proximally to the hip. Skiers should therefore train eccentric capacity of the hip extensors (gluteus maximus and hamstrings) and the trunk. Adequate hip strength helps the skier tolerate these external loads without an early forward trunk lean or trunk collapse.

5.1.2 Gradual adaptation to brace wear

Speed, agility, and functional performance may decline when a brace is first introduced [30]. For

that reason, a new brace should not first be worn on a competition day or during a high-intensity ski session. Instead, skiers can introduce it gradually in ordinary training and adjust wear time and training volume according to comfort, movement control, and fatigue.

5.2 Intermittent Release and Slow Dynamic Stretching (SDS)

On the slope, skiers can use simple measures to address the circulatory restriction and metabolite accumulation that may accompany rigid straps or soft sleeves.

Blood-Flow Reset During Lift Intervals: After a demanding descent, while waiting in line, or during a chairlift ascent, skiers may release or markedly loosen the main constraining straps, especially those over the popliteal neurovascular region and above the gastrocnemius. Reducing this pressure may improve venous clearance of lactate, hydrogen ions, inflammatory mediators, and other metabolites.

Active-Recovery Mechanisms of Slow Dynamic Stretching (SDS): Sitting still is a common choice during lunch or between-run breaks. In high-level alpine skiers, however, light active recovery between runs was associated with lower blood lactate, faster later runs, and fewer incomplete runs than sitting [31]. Post-fatigue work in soccer players suggests that SDS may support recovery of neuromuscular control and performance [32]. Studies in healthy adults also suggest possible benefits for strength and flexibility, although its specific effects in alpine skiing still need direct study [33].

5.3 Systematic Neuromuscular Training (NMT): Returning to Fundamentals

Regardless of design or technology, the skier's own neuromuscular training (NMT) remains central to ACL-injury prevention. Sensory feedback and muscular capacity provide the biological basis for control, so targeted NMT should remain a routine part of training.

6. Conclusion

Knee braces and sleeves are not stand-alone solutions for ACL protection in alpine skiing. Their use requires balancing possible mechanical and sensory benefits against potential drawbacks, including discomfort, device migration, and increased metabolic cost.

This review proposes a conceptual decision framework based on knee status, the purpose of device use, skiing exposure, and device fit and tolerance. It is intended to support individualized decision-making rather than serve as a validated clinical algorithm. Soft sleeves may be considered for comfort or sensory feedback in stable knees, whereas functional braces may be considered for selected skiers returning after ACL reconstruction or with functional instability. Active symptoms, recurrent swelling, giving way, or poor tolerance should prompt clinical assessment.

Regardless of device choice, neuromuscular training, technique optimization, fatigue management, and gradual adaptation remain essential for safer skiing and ACL-injury prevention.

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