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REVIEW

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We know a lot about little and little about a lot: A contextualized scoping review on injury prevention in alpine ski racing

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Abstract

Background: Our goal was to summarize and contextualize the available literature on alpine ski racing injury epidemiology, injury etiology, injury prevention measures, injury prevention context, and implementation issues.

Materials and Methods: We searched four electronic databases using predetermined search terms. We included original studies that assessed injury, injury risk factors, and injury mechanisms, and assessed and reported the effect of an injury prevention measure in alpine ski racing. Two authors independently conducted title–abstract screening, and one performed the full-text review. For data synthesis and categorization, we used the Translating Research into the Injury Prevention Practice framework and a modified and adapted version of the Haddon matrix.

Results: Of the 157 included studies, most corresponded to injury epidemiology and etiology, whereas few studies encompassed injury prevention measure development, implementation and evaluation. Preventive interventions targeting equipment, rules and regulations, course design and snow preparation were the most prevalent in the literature. Furthermore, various contextual factors in the current literature have been found, including gender, competition level, countries and federations, and time periods within a season.

Conclusions: We provided an in-depth and comprehensive overview of the current state-of-the-art in the alpine ski racing context. We know a lot about little and little about a lot across all the areas associated with injury prevention in such context. The limitations in the literature yield a road map for designing future

injury prevention studies to address the key gaps identified. A more comprehensive context-driven approach throughout all stages of injury prevention would benefit the ultimate implementation of effective preventive strategies.

KEYWORDS
alpine ski racing, contextual factors, injury prevention, knowledge gaps

1 | INTRODUCTION

The World Cup (WC) is the most prestigious international alpine skiing competition series, organized by the International Ski and Snowboarding Federation (FIS). Alpine skiing at the elite level is associated with high speeds and a high risk of musculoskeletal and brain injuries.[1–7] According to data from FIS, injury rates at the WC level averaged 36.5 injuries per 100 WC athletes during a competition season,[8,9] and rates differ by discipline.[8,10] Despite efforts over the last decade to improve alpine skier safety, injury rates have not substantially decreased.[1,3,11,12] Furthermore, when gradual onset injuries (formerly described as overuse injuries) and injuries sustained offseason are included, injury rates are even higher compared to including traumatic and in-season injuries only.[1,3]

Because of the complexity and multifactorial causes of injuries,[4,13–17] injury prevention necessitates a thorough understanding of the injury mechanisms and the situations leading to an injury.[13] Evidence regarding effective preventive strategies in alpine ski racing is limited and challenging due to small sample sizes, methodological limitations, and the constant evolution of injury factors, equipment, and competition rules and regulations.[1,18,19] It could be argued that to move athlete safety in alpine skiing forward, we need to resort to other and novel approaches and research methods (e.g., biomechanical and computer simulation, qualitative research).[4,10,13,14,20–24]

To support this call, first, in the context of injury prevention in alpine ski racing, a scoping review can help to identify current injury prevention strategies and identify knowledge gaps and areas that require further investigation. Such information will guide future research, policy development and implementation, and promote the safety and well-being of alpine skiers.[25] As a result, we conducted a scoping review to summarize and contextualize the available literature on alpine ski racing concerning injury epidemiology, injury etiology, and injury prevention measures.

2 | MATERIALS AND METHODS

We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analysis Extension for Scoping Reviews (PRISMA-ScR)[26] and the Joanna Briggs Institute (JBI) Guidelines on Scoping Reviews[27] to conduct this review. We registered the review's protocol in the Open Science Framework database (osf.io/ug463).

2.1 | Data sources and search strategy

We identified relevant studies through a systematic and sensitive literature search. Our search spanned articles published from January 1, 1997 to April 1, 2023, for which we used four electronic databases: PubMed, SPORTDiscus, Web of Science, and EMBASE (Supplementary Information S1). Our search terms were a combination of database-specific thesaurus terms and free-text terms in the title, abstract, text, and keywords related to (a) the population (alpine ski racers), (b) the concept (prevention AND injury), and (c) the context (alpine ski racing [all levels]). As our team of authors was international and spoke different languages, we searched for articles in English, German, French, and Spanish. In team meetings, we refined our search terms to guarantee that our search strategy identified all pertinent studies.[25,27,28] We also cross-checked reference lists of included papers, relevant systematic reviews, and literature reviews to extend the electronic database search. To ensure that we included only evidence related to the issues relevant to contemporary alpine ski racing, we limited our search strategy to the last 25 years, as it coincides with the widespread introduction of carving skis in alpine ski racing in the 1996/1997 season.[12]

2.2 | Eligibility criteria

We included studies that (a) described injury and injury risk factors in alpine ski racing; (b) analyzed inciting events leading to the injury situation as well as the immediate injury mechanisms in alpine ski racers; (c) assessed and reported the effect of an injury preventive intervention in alpine ski racing; (d) included participants who were nondisabled, healthy and physically active at the time of the injury; and (e) had original data regardless of the design.

2.3 | Study selection process

We imported all studies from the literature search and removed duplicates (EndNote version X8.1, Clarivate Analytics; USA). We examined all identified studies for relevance in two steps. First, based on titles and abstracts, two authors (OBM and MW) independently conducted the selection process for 20 studies, applying the predetermined eligibility criteria. Afterward, as a calibration exercise, they met to compare their study selection processes. As a result of their agreement, they continued with the independent title and abstract screening process. These two authors met to reach a consensus for eligibility after the first screening stage in case of disagreement. Second, we retrieved full-text articles from all potentially relevant studies. The leading author (OBM) independently conducted the full-text selection process, and discussed with a third author (EV) all studies for which a decision could not directly be made. Finally, we scrutinized the reference lists of the included papers and relevant systematic reviews for potential additional studies. We used a data chart to report reasons for all excluded articles during the full-text screening process (Figure 1).

2.4 | Data charting process

Three authors (OBM, EV, and JS) elaborated a tailored table for data extraction from the included studies after agreement within the study team and based on relevant alpine skiing injury and conceptual papers.[1,4,13,29–33] The data we extracted from the included full-text articles were (a) authors and date; (b) study design; (c) aim or focus; (d) sample characteristics (sample size, gender, and age); (e) competition level and alpine skiing discipline; (f) time of the season; (g) country; (h) injury definition; (i) method to report or record injury data; (j) injury mechanisms or inciting events; (k) injury prevention strategy; (l) compliance or adherence definition; (m) compliance or adherence rates; and (n) implementation context description. The leading author (OBM) performed the data extraction.

2.5 | Methodological quality assessment

We categorized all included studies by study design following an evidence-based practice on clinical research in sports medicine.[34] We did not assess the risk of bias in individual studies since our main goal was to summarize and contextualize the available literature on injury prevention in alpine ski racing. Previous reviews on sports injury prevention have used similar approaches.[35–37]

2.6 | Data synthesis

We present the extracted data through three steps.

2.6.1 | Contextual factors across studies

We contextualized the included studies based on gender, study design, age and level of competition, countries and federations, time of the season and alpine skiing disciplines. To rate the dimension of countries and federations, we considered large countries or federations as those classified in the FIS historical nation WC top 10 position.[38]

2.6.2 | The Translating Research into Injury Prevention Practice (TRIPP) framework

We categorized all studies using the TRIPP framework according to their research aims. The TRIPP framework provides an extension to the commonly used sequence of prevention. It includes two additional steps in the pathway from injury problem to real-world solution, for example, Stage 5 (description of the intervention context to inform implementation strategies) and Stage 6 (evaluation of the effectiveness of preventive measures in the implementation context).[32] We categorized the included literature into each stage of the TRIPP framework. We elaborated on the framework's main features of Stages 1 and 2. In Stage 1, we described the included studies' data regarding the injury definitions and reporting methods. In Stage 2, we used Kiers et al.[29] as a framework to classify injury risk factors and categorize them in relation to the alpine ski racing context. We arranged all the contextual factors across studies within the TRIPP framework. Moreover, we provided a full outline of all stages of the TRIPP framework based on the extracted data across studies in the Supplementary Information (S4–S9).

2.6.3 | A modified and adapted version of the Haddon matrix (including TRIPP stages 4–6)

The Haddon matrix provides a conceptual framework to identify potential interventions across different intervention targets and stages of an injury event.[39] Influenced by previous literature,[37,39] we adapted the original Haddon matrix into a 5×4 matrix for the scope of our review (Table 1). We then categorized available preventive interventions into our adapted Haddon matrix.

Four authors (OBM, EV, JS, and CB) met through several meetings to determine the consistency of such approaches related to data extraction. Conceptual frameworks could

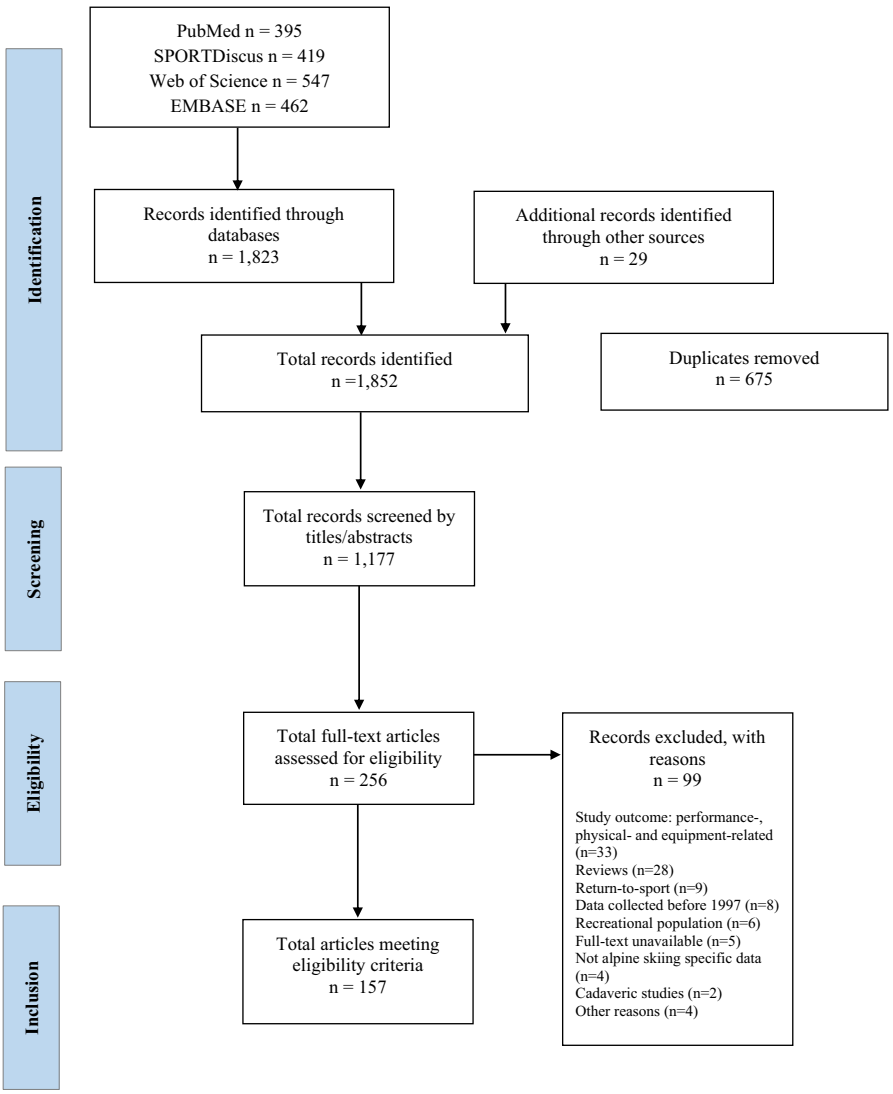

FIGURE 1 Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) flow diagram (*n*, the number of studies).

translate the study findings to alpine ski racing and all the involved alpine ski racing stakeholders and facilitate the identification and analysis of knowledge gaps.

3 | RESULTS

3.1 | Identification of studies

We provide a flowchart of the systematic steps involved in the study identification process (Figure 1). Of the 1852 potential studies, 1177 were screened by title and abstract, 256 were full-text reviewed, and 157 were eventually included.

3.2 | Characteristics of the included studies: Providing context across studies

The full details of the study characteristics of the 157 studies are presented in Supplementary Information S2. Studies represented data from 37308 participants, of whom 44% were females ($n = 10868$) and 56% were males ($n = 14019$; Supplementary Information S3). Altogether, 139 (85.28%) studies were quantitative, including 108 observational (77.7%) and 31 (22.3%) experimental designs; four included qualitative methods (2.45%); 17 (10.43%) involved other study types (e.g., editorial, pilot study, test–retest study); and three were manuals (1.84%). Moreover, a general classification of study designs (Supplementary Information S3) is provided.

Across all studies, participants represented a diversity of competition levels and ages. Studies also depicted a wide array of times of season and countries and federations studied. Most studies explored elite levels such as WC (24.31%) and European Cup (EC; 13.30%) settings (43.12%) involving large countries and federations (57.21%), and they were conducted during the winter season (33.97%). Notwithstanding, 32% of the studies were conducted in youth categories. Regarding alpine skiing disciplines, giant slalom and slalom disciplines were the most studied (56.64%). Such contextual data (Supplementary Information S3) were extracted only when provided in the studies.

TABLE 1 Definitions used for the modified and adapted Haddon matrix concerning the prevention of alpine ski racing.

Dimension level	Definition
Dimension A: intervention target	
Athlete: alpine skier (*host*)	Interventions designed to change individual alpine skier attitudes, knowledge, and behaviors (e.g., encourage the use of protective equipment, raise awareness about risks, improve the physical status, skills, and technique).
Equipment, rules and regulations: sports activity (*agent/framework)*	New or modified sports equipment related to alpine skiing, and new or modified rules in alpine skiing to change alpine skiers' behaviors related to alpine skiing.
Course design and snow preparation: sports activity (*agent/framework)*	New or modified course setting designs and snow preparation techniques related to alpine skiing (e.g., lower the height of jumps, improve the energy-absorption qualities of safety nets, improve snow conditions).
Context (*environment*)	Interventions designed to change the physical, sociocultural, and policy setting or context within which the sports injury occurs.
Multicomponent or multiple interventions	Interventions that include multiple interventions targets.
Dimension B: time window or time frame in which an injury occurs	
Pre-event	Interventions designed to prevent the sports injury event from occurring, reduce the injury risk to an acceptable level before participation, and build the capacity of the alpine skier before the injury event.
Event	Interventions designed to be effective at the time of the injury event.
Post-event	Interventions designed to minimize the consequences of a sports injury event through treatment and rehabilitation and returning the alpine skier to the "pre-event" status.
Multiple time windows	Interventions that include multiple interventions, including different time windows in which an injury occurs (within a study).

TABLE 2 Classification of the included studies into the Translating Research into Injury Prevention Practice (TRIPP) framework.

Stage 1: Injury surveillance ($n=62$)	[1–3,5,8,9,18,19,40–94]
Stage 2: Establish the etiology and mechanisms of injury ($n=72$)	[10,13,14,22,24,46,51,54,65,75,79,84,92,95–154]
Stage 3: Develop preventive measures ($n=19$)	[20,100,110,124,133,135,138,155–165]
Stage 4: "Ideal conditions"/scientific evaluation ($n=3$)	[18,163,166]
Stage 5: Describe the intervention context to inform implementation strategies ($n=6$)	[21,29,167–170]
Stage 6: Evaluate the effectiveness of preventive measures in the implementation context ($n=3$)	[12,171,172]
Others: Other studies and supporting documents not related to any stage ($n=9$)	[107,143,173–179]

3.3 | TRIPP framework

We classified the included studies into their respective TRIPP framework stages (Table 2 and Figure 2). A detailed description of all studies per stage is provided in Supplementary Information S4–S9. Most of the studies were categorized into the first two stages of the framework ($n=62$ for Stage 1, $n=72$ for Stage 2), meaning that most studies described injury epidemiology and etiology. In contrast, only 19 studies described the development of preventive measures (Stage 3), and a minority of studies involved the last three stages of the TRIPP framework ($n=3$ for Stage 4, $n=6$ for Stage 5, and $n=3$ for Stage 6). Not all studies fit a TRIPP framework stage because they were studies whose research aim did not fit within any stage or were supporting documents. Nevertheless, they both provided added pieces of information.

Furthermore, we detailed a contextualized classification of the included studies into every stage of the TRIPP framework focused on the methodological factors previously analyzed (Figure 3 and Table 3).

3.3.1 | Stage 1: Injury definition and surveillance (Supplementary Information S4)

In the studies on injury surveillance, we found heterogeneity in the injury definitions employed and in the injury collection and reporting methods. In this

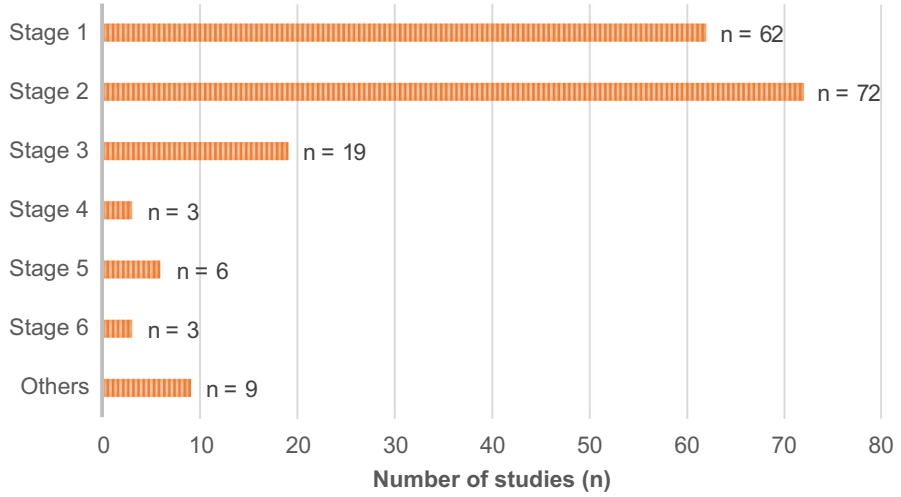

FIGURE 2 Classification of the included studies into the Translating Research into Injury Prevention Practice (TRIPP) framework. Stages of the TRIPP framework: (1) injury surveillance; (2) establish etiology and mechanisms of injury; (3) develop preventive measures; (4) "ideal conditions"/scientific evaluation; (5) describe intervention context to inform implementation strategies; (6) evaluate the effectiveness of preventive measures in implementation context; and "others."

order, Fuller et al., injury definitions ($n = 18$),[180,181] the International Olympic Committee (IOC) approach ($n = 16$),[182] and the Oslo Sports Trauma Research Centre (OSTRC) definition ($n = 5$)[183,184] were the most employed definitions. While some countries and federations developed their injury surveillance method, most of the studies used validated tools such as the OSTRC questionnaire on health problems[183,184]; the IOC injury surveillance system for multisport events and the electronic report forms in the Winter Olympic Games (WOG) events[182]; and the FIS Injury Surveillance System (ISS) based on annual retrospective interviews.[19] Different terminology and criteria were found regarding the duration of the season, the different periods within the season, and the alpine skiers' competition level.

3.3.2 | Stage 2: Establish the etiology and mechanisms of injury (Supplementary Information S5)

We identified athlete-related risk factors (e.g., fatigue, physical aspects, athletes' race preparation, and crash behavior) as the most common injury risk factors investigated (54%, $n = 52$). Approximately, 40% of the included studies explored course setting- and equipment-related factors (19%, $n = 18$; and 17%, $n = 17$; respectively), while only 10% ($n = 10$) of the research covered snow-related injury risk factors. The top 10 injury risk factors included snow-related ($n = 4$), equipment-related ($n = 1$), athlete-related ($n = 4$), and course setting-related features. Moreover, following the work of Kiers et al.[29] we added references and examples for the provided injury risk factors (Supplementary Information S5).

The injury mechanisms described in the literature included injuries occurring after a turning or landing from a jump.[10] Specifically, in ACL injuries, four injury mechanisms were reported: "slip-catch,"[14,22,99] "dynamic snowplow,"[14,22,99] "landing back-weighted,"[14,22,99] and "slipping edge-catch."[14,22,99,139] Likewise, the main mechanisms for head and face injuries consisted of skiers rolling, yawing, or pitching (backward or forward) after turning, or landing after a jump.[141,142]

3.4 | A modified and adapted version of the Haddon matrix—From the development of prevention strategies to implementation context (Stages 3–6; Supplementary Information S6–S9)

Most studies ($n = 19$, 61%) addressed the preventive effect of sports activity interventions (Table 4). Ten studies ($n = 10$, 32%) evaluated the preventive effect of a collection of equipment, rules and regulations. Furthermore, another nine studies (29%) focused on the preventive effect of course setting design and snow preparation, whereas the effect of athlete-related interventions was assessed in four studies (13%). Context-related ($n = 4$) and multicomponent/multiple interventions ($n = 4$) were investigated in 26% of the studies.

The event phase was the most prevailing time window regarding intervention strategies ($n = 21$, 68%). One-third of interventions ($n = 11$, 35%) aimed at course design and snow preparation measures, while seven studies evaluated the effect of skis and the ski-plate-binding boot system in the event phase (23%). In contrast, few injury prevention studies targeted sport activity interventions in the pre-event phase ($n = 5$, 16%). Furthermore, we found context interventions across

all phases, four and three preventive strategies in the pre-event and event phases. Only one intervention was found in the post-event phase (3%). No injury prevention strategies were identified targeting alpine skiers in the event and post-event phases.

3.4.1 | Intervention context

The intervention context of the implementation studies largely diverges. It included youth, elite and specifically international WC alpine skiers, including Switzerland, Austria, Canada, and Sweden.[12,21,163,166,168,170–172] The rest of the studies comprised stakeholders from different competition levels and professional backgrounds from 28 countries,[29] Canadian alpine skiing racing coaches,[169] and physiotherapy services during the 2018 PyeongChang WOG.[167]

3.4.2 | Implementation studies

Implementation studies belonging to stage five of the framework included the description of the establishment of the FIS Injury Surveillance System in the 2006–2007 season.[21] A lack of spinal protective devices, guidelines, and policies regarding their use in Canadian youth alpine skiing has been acknowledged.[169] During the 2018 WOG, the main reasons for athletes visiting the physiotherapy services, the causes of injuries recorded, and the type of treatments provided were disclosed.[167] In 2020, Swiss athletes' perceptions, beliefs, and experiences of sports-related concussion (SRC) determined four major shortfalls in alpine ski racing athletes' understanding of SRC about its definition, symptomatology, diagnosis and return-to-play protocols.[168] Likewise, an assessment of alpine ski racing stakeholders' perceptions of key injury risk factors pointed out contrasting perspectives depending on the stakeholder's role and competition levels analyzed.[29] Finally, being familiarized beforehand, 6- to 15-year-old Swiss competitive alpine skiers taking part in a physical fitness competition during the 2021 off-season conducted a biomechanical quantification of the performance of a low dynamic closed chain stabilization exercise addressing typical components of mechanisms leading to back gradual onset injuries in alpine ski racing.[170]

Studies included in Stage 6 recorded and analyzed injury data of WC athletes during nine WC seasons (2006–2015) and Austrian athletes of different competition levels for 17 years (2001–2017).[12,171] Furthermore, an injury prevention program was conducted targeting the specific injury patterns of youth competitive alpine skiers of the Swiss U16 category over 12 months in their real-world training setting while comparing their injury occurrence to age- and training-matched control groups.[172]

4 | DISCUSSION

This scoping review summarized and contextualized the current literature on alpine ski racing injury epidemiology, injury etiology, and injury prevention measures. Most of the studies comprised injury epidemiology and etiology (TRIPP stages 1 and 2). In contrast, little evidence included the development of preventive strategies (TRIPP stage 3), and very scarce literature was found on evaluation and implementation stages (TRIPP stages 4–6). Available preventive evidence targeted ski equipment, rules and regulations, course design, and snow preparation, mostly during the injury event phase.

4.1 | Context matters—Different settings need context-specific research

Our findings illustrate a wide distribution of contextual factors across studies, including competition level, gender, and country and federation size. Nevertheless, not all contexts were represented alike. We found that most studies were conducted in WC and EC settings, and almost no studies included FIS competition level participants. In particular, WC level was predominant in almost all TRIPP stages, whereas there was a promising and considerable body of evidence regarding youth athletes, especially on injury epidemiology data. It is of special interest that WC athletes reported higher injury rates than youth skiers. Likewise, such contexts also respond to different needs concerning their alpine skiing injury risk factors. Furthermore, most of the studies included a mixed sample of females and males. However, there were more single studies including only males ($n = 17$) than females ($n = 5$). These differences between different settings were also acknowledged within the countries and federations involved in the studies. Almost two-thirds of the studies included large and developed skiing countries that have developed state-funded sports systems, such as Switzerland and Austria.[186] Thus, we presented a broad outline of the importance of contextual factors and how influential they can be from a methodological perspective. In turn, all these different contexts and settings have different needs in terms of injury epidemiology, etiology, and prevention measures. For instance, it has been found

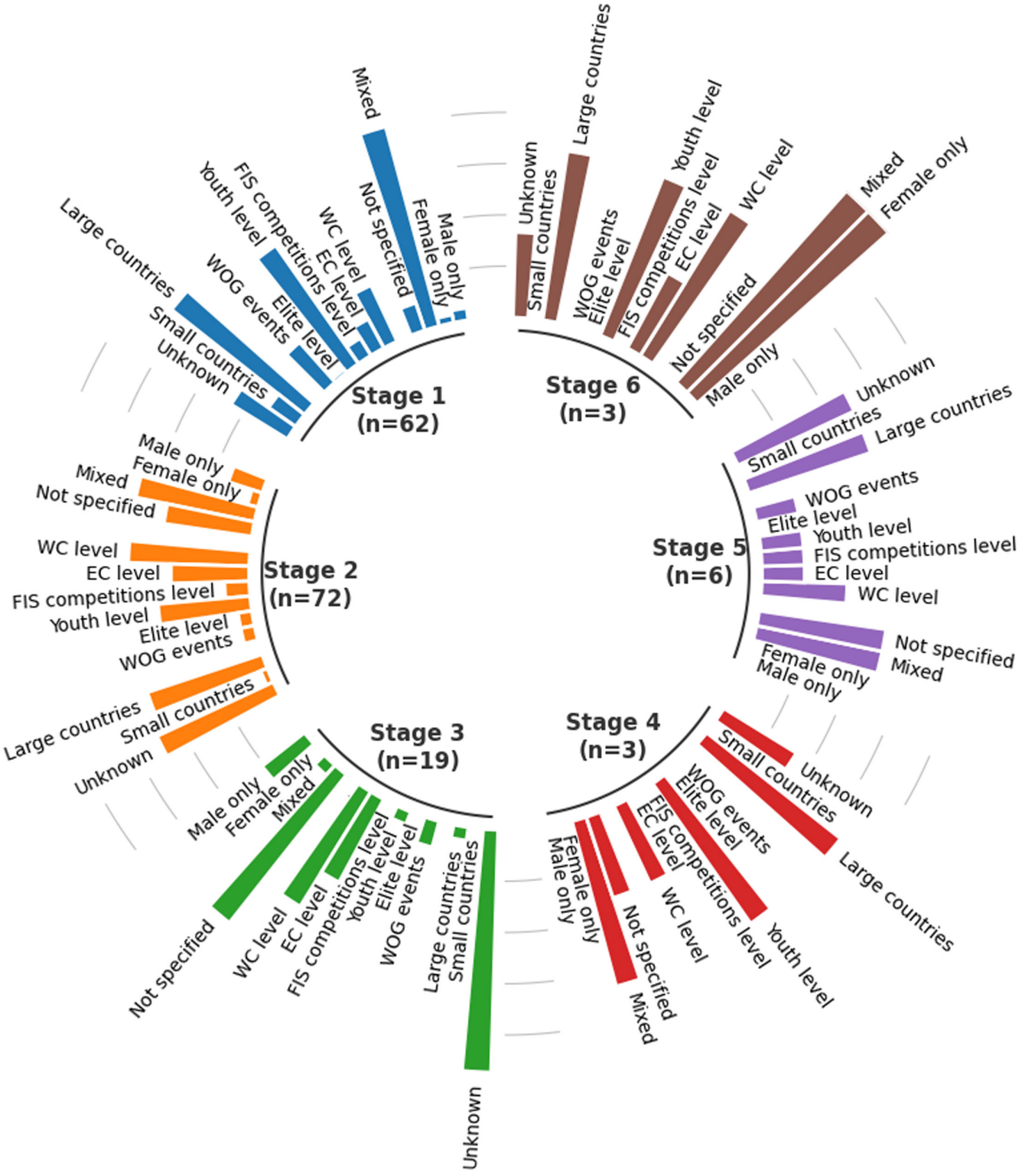

FIGURE 3 Classification of the included studies into the Translating Research into Injury Prevention Practice (TRIPP) framework focused on the contextual factors analyzed. Abbreviations: EC, European Cup; FIS, International Ski and Snowboarding Federation; WC, World Cup; WOG, Winter Olympic Games.

that injury profile and occurrence are gender-specific in the alpine ski racing context.[3,9] Therefore, complementary and context-driven research approaches are required according to their particularities, features and necessities, with a special focus on the youth.[187] To date, such context-specific differences have not been considered when designing injury prevention research within the alpine ski racing context.

TABLE 3 Classification of the included studies into the Translating Research into Injury Prevention Practice (TRIPP) framework focused on the contextual factors analyzed. The level of competition and country/federation numbers may not add up as a single study can include as many categories as provided.

		Contextual factors												
		Gender				Level of competition						Country and/or federation		
Stage of the TRIPP framework	Total studies (n)	Male only [n (%)]	Female only [n (%)]	Mixed [n (%)]	Unknown [n (%)]	World Cup level [n (%)]	European Cup level [n (%)]	FIS competitions level [n (%)]	Youth level [n (%)]	Elite level [n (%)]	WOG events [n (%)]	Large countries and federations [n (%)]	Small countries and federations [n (%)]	Unknown [n (%)]
Stage 1	62	3 (4.8%)	2 (3.2%)	50 (80.6%)	7 (11.3%)	15 (24.2%)	8 (12.9%)	5 (8.0%)	35 (56.4%)	1 (1.6%)	13 (20.9%)	41 (66.1%)	8 (12.9%)	16 (25.8%)
Stage 2	72	10 (13.9%)	3 (4.2%)	34 (47.2%)	25 (34.7%)	34 (47.2%)	22 (30.5%)	7 (9.7%)	26 (36.1%)	4 (5.5%)	4 (5.5%)	34 (47.2%)	2 (2.8%)	36 (50.0%)
Stage 3	19	4 (21.1%)	0 (0.0%)	1 (5.3%)	14 (73.7%)	10 (52.6%)	7 (36.8%)	0 (0.0%)	1 (5.3%)	0 (0.0%)	2 (10.5%)	1 (5.3%)	0 (0.0%)	18 (94.7%)
Stage 4	3	0 (0.0%)	0 (0.0%)	2 (66.7%)	1 (33.3%)	1 (33.3%)	0 (0.0%)	0 (0.0%)	2 (66.7%)	0 (0.0%)	0 (0.0%)	2 (66.7%)	0 (0.0%)	1 (33.3%)
Stage 5	6	0 (0.0%)	0 (0.0%)	3 (50.0%)	3 (50.0%)	2 (33.3%)	1 (16.7%)	1 (16.7%)	1 (16.7%)	0 (0.0%)	1 (16.7%)	3 (50.0%)	0 (0.0%)	3 (50.0%)
Stage 6	3	0 (0.0%)	0 (0.0%)	3 (100%)	0 (0.0%)	2 (66.7%)	1 (33.3%)	0 (0.0%)	2 (66.7%)	0 (0.0%)	0 (0.0%)	2 (66.7%)	0 (0.0%)	1 (33.3%)

Abbreviations: FIS, International Ski and Snowboarding Federation; WOG, Winter Olympic Games.

4.2 | Improving the study methodology would improve the quality of injury prevention studies

We found substantial heterogeneity in the injury definitions, injury reporting methods, and terminology employed across study designs. While some of them did not provide key information, such as injury registration data and the study time of the season, in others, gender and country were not specified. Consequently, these differences across studies make direct comparisons challenging. Specifically, the most commonly used injury definition across studies concerns a time loss definition originally formulated in the football context.[180,181] We also encountered diversity in the injury collection and reporting methods employed. Some countries and federations have developed their own injury surveillance methods, such as Austria,[2,42,171] Canada,[49] Great Britain,[74,94] and Germany.[69] However, most new studies used validated tools such as the OSTRC questionnaire on health problems.[183,184] Additionally, different terminology was found regarding the duration of the season and the different time periods within the season. This was reflected by the use of nine different time spans while using different terms within the season, such as season, competitive or winter season, precompetitive or preseason, and off- or post-season. For example, 40% of the studies occurred during the competition season period alone, and the preseason period was only considered in 12% of the literature. As such, the need to include the off-season period has been recently emphasized, as there is a risk of underestimating injury occurrence, as well as injury risks and patterns that differ among season periods with a special focus on gradual onset injuries.[1,3,54] Furthermore, different terminology and criteria were used by researchers and federations concerning alpine skiers' competition levels, ranging from national performance-driven criteria (e.g., Austria and Switzerland),[2,42,54,116,130,171] and FIS points[40,96,97,98,101,117,128,145] to the WC Start List.[42] Again, the lack of consensus and such differences make comparing studies highly troublesome. Therefore, higher quality studies are needed to reach an agreement and find a consensus on homogenizing study methods within the alpine ski racing context.[188] Moreover, ensuring standardized methods and improving the quality of injury epidemiology studies is pivotal for apprising all other stages and being used in the subsequent TRIPP stages.[32,189]

4.3 | We should listen to stakeholders' voices to fulfill the needs from practice

There is a difference between the actual scientifically studied topics covered and the perceived areas of concern

TABLE 4 Studies of injury prevention in alpine ski racing, categorized by preventive intervention and intervention strategy following the modified and adapted Haddon matrix ($n = 31$).

	Time window			
Intervention target	**Pre-event ($n = 10$; 34%)**	**Event ($n = 15$; 52%)**	**Post-event ($n = 0$; 0%)**	**Multiple time windows ($n = 4$; 14%)**
Athlete (alpine skier), ($n = 4$; 13%)	Physical fitness, training program ($n = 3$) • Neuromuscular warm-up in preseason ($n = 1$)[163] • Anti-rotation and rear-chain stabilization exercises ($n = 1$)[170] • The ISPAint program ($n = 1$)[172] Multicomponent ($n = 1$): • Athlete's education program on ACL injuries, and core stability and neuromuscular control exercises[166]	None	None	None.
Equipment, rules and regulations (sports activity), ($n = 10$; 32%)	Introduction of new equipment rules by FIS ($n = 4$)[12,18,156,171]	Equipment: skis ($n = 6$): • Less shaped skis (greater sidecut radius) ($n = 3$)[135,164,165] • Reduction standing height ($n = 2$)[159,185] • Long skis ($n = 2$)[164,185] • Reduction skis profile width ($n = 2$)[164,185] • Less aggressive ski behavior (greater sidecut radius) ($n = 1$)[164] • Reduction torsional stiffness ($n = 1$)[124]	None	None.
Course design and snow preparation (sports activity), ($n = 9$; 29%)	None	Changes in the course setting, equipment interventions, and steeper terrain ($n = 2$)[165,185] • To reduce high speeds: shortening vertical gate distance in SG and GS ($n = 2$)[161,162] • To reduce acting GRF peaks: increase gate offset in SL ($n = 1$)[133] Design and development of high-standard safety net systems by simulations ($n = 3$)[155,157,158]	None	Snow preparation techniques[a] ($n = 1$).[138]
Context (environment), ($n = 4$, 13%)	Establishment of safety culture: FIS Injury Surveillance System ($n = 1$)[21]	No competitions below −25/−27°C, including the combination of air temperature, wind speed (faster than 15 m/s), and ski racer's speed ($n = 2$)[100,160] No competitions above 2°C ($n = 1$)[160]	None	Physiotherapy treatments, including injury prevention, recovery, and rehabilitation ($n = 1$).[167]

TABLE 4 (Continued)

	Time window			
Intervention target	**Pre-event ($n = 10$; 34%)**	**Event ($n = 15$; 52%)**	**Post-event ($n = 0$; 0%)**	**Multiple time windows ($n = 4$; 14%)**
Multi-component/multiple interventions, ($n = 4$; 13%)	Athletes, coaches and supporting staff education on sports-related concussion[a] ($n = 1$)[168]	To reduce speed by increasing ski-snow friction force in SG and GS; and by increasing ski-snow friction force and air drag force in DH ($n = 1$)[110]	None	Regulations on safety-release of ski bindings; and planification and regulation on racing terrains and courses[a] ($n = 1$).[20] Changes in race schedule and organization adaptation[a]; same snow conditions from top to bottom[a]; injury screenings and minimum criteria for physical fitness[a]; less aggressive setup regarding the ski-plate-binding-boot system[a]; and implementation of jury decisions and race cancellations under poor visibility[a] ($n = 1$).[29]

Abbreviations: ACL, anterior cruciate ligament; DH, downhill; FIS, International Ski and Snowboarding Federation; GRF, ground reaction forces; GS, giant slalom; ISPAint, "Injury Screening and Prevention—Alpine Skiing" intervention; SL, slalom.

[a]Potential injury prevention intervention.

from stakeholders' standpoint. Such discrepancy between priorities in research and priorities in sport practice highlights a large gap in injury prevention research in alpine ski racing. For instance, based on the current research on injury etiology, more than half of the studies investigated athlete-related risk factors, whereas only 10% covered snow-related factors. Conversely, Kiers et al.[29] investigated and updated the stakeholders' priorities of perceived key injury risk factor categories in alpine ski racing based on a framework from Spörri et al.[4] Hence, based on stakeholders' perspectives, the most important risk factor entailed snow conditions, and three more snow-related aspects were rated within the top 10 features.[29] Additionally, equipment- and course setting-related aspects were rated on top of athlete-related factors, which include fatigue, physical aspects, and athletes' race preparation and crash behavior. Thus, the available literature on injury risk factors does not agree with what alpine ski racing stakeholders perceived as the highest priority among all risk factors. Concurrently, in the same study by Kiers et al.,[29] they assessed the stakeholders' top three risk factor ratings and differences based on their competition level and active roles, pointing out the role of contextual factors within this field. On the one hand, stakeholders' perceptions vastly differed between the WC, EC, and FIS competition settings. On the other hand, stakeholders' perspectives also depended on their active roles (e.g., athlete, coach, team medical staff, ski racing supplier, and FIS representatives), showing different results based on their priorities. Therefore, these results suggest that stakeholders' perspectives and perceptions should be considered when responding to their needs. To date, there is no research based on stakeholder perceptions in alpine ski racing. For this reason, including more qualitative research would contribute to bridging the gap between the current research and the actual end-users' needs.[30,188,190,191] Accordingly, such a call to action has been previously suggested in the Sports Medicine field to involve all stakeholders in the development of more comprehensive athlete-centered health research.[30,190]

4.4 | More research is needed on the development, implementation, and evaluation of injury prevention strategies

Only 20% of the current evidence included studies that developed, implemented or evaluated alpine ski racing injury prevention measures. Additionally, most evidence was encountered during the injury episode, whereas we found few interventions encompassing the pre- and post-injury event. Preventive interventions mainly involved equipment, rules and regulations, course design,

and snow-related measures, whereas only 16% of them included athlete-related strategies. Such a shortage of athlete preventive interventions did not concur with the available literature on risk factors, which primarily focused on athlete-related factors. Likewise, we found approximately 30% of snow-related interventions, while they were only addressed in 10% of the studies on injury etiology. Nevertheless, we have found consistency in the literature on the risk factors and preventive strategies related to equipment, rules and regulations, and course design. Consequently, one could argue that such a lack of preventive measures might be due to the discrepancies between injury etiology and injury preventive measures research and the existing gap between the current research and the stakeholders' priorities. For this reason, in line with previous literature, recognizing all stakeholders' needs regarding their injury risk factor priorities might represent a feasible starting point to address this scarcity of injury preventive measures.[4,29,32] Listening to alpine ski racing stakeholders' voices and targeting specific levels (e.g., competition levels and countries and federations) would contribute to the development of effective prevention measures and their further successful implementation. Therefore, it would lead to injury prevention research that fulfills end-user needs and priorities.[32,192]

4.5 | Strengths and limitations

This scoping review aimed to summarize the available literature on alpine ski racing injury epidemiology, injury etiology, and injury prevention measures. Our broad research question and comprehensive search strategy resulted in a thorough mapping of the current state-of-the-art evidence on injuries and their prevention in alpine ski racing. Using two conceptual frameworks helped us contextualize and summarize the available evidence. This, in turn, contributed to providing an accurate representation and understanding of the present evidence base. We pursued a rigorous and transparent approach throughout the entire process. We engaged a large research team with broad knowledge and diverse expertise in the field at every stage of the process to improve the quality of the decision-making, as advocated by the current perspectives on scoping methodologies.[193] Likewise, we acknowledge that we encountered some limitations. On the one hand, the screening of full-text studies was carried out by a single researcher, yet another researcher supported the final decisions, indicating a resource limitation. On the other hand, no health sciences librarian was involved in designing and conducting our scoping review, which may lead to researcher bias during the study selection process.

Scoping reviews rarely formally evaluate the methodological quality of included studies. Although we did not conduct a proper methodological assessment, we did extract sufficient data on the included study methods to claim that there is a need for higher quality studies within the field. The studies contributing data were heterogeneous in study designs and methods, as well as in terms of injury data, injury etiology, injury prevention strategies, and implementation data. In addition, not all studies included key data such as the competition level, country or federation and period within the season. Altogether, standardized injury collection and reporting methods, as well as better methodological designs, might have improved insight into the findings. Eventually, the impact of this approach also contributed to identifying the knowledge gaps on injury prevention within the alpine ski racing context.

4.6 | What do we still not know? Future directions

Future research on alpine ski racing needs to focus on all stages of the TRIPP framework. Although much is known about injury epidemiology and etiology in such a context, further research is needed to better inform about the problem and understand the mechanisms of injury and other associated factors. Injury epidemiology studies should include high-quality injury surveillance studies, including valid and reliable methodological tools for the other stages. Such methodological improvement would address the methodological heterogeneities and inconsistencies in terminology and develop consensus on the injury definition and reporting methods within the alpine ski racing field. Likewise, multidisciplinary approaches in injury etiology are needed, such as biomechanical, clinical, and behavioral research. A better understanding of injury epidemiology and etiology will assist in developing injury prevention strategies. Hence, more research is needed to target the development, implementation, and evaluation of injury prevention measures. Listening to alpine skiers' and stakeholders' voices can contribute to identifying potential solutions and developing appropriate preventive measures. Arguably, identifying the contextual factors throughout all stages of injury prevention may lead to the eventual design, implementation and evaluation of effective and context-driven preventive strategies. Addressing all these knowledge gaps can provide insights for practitioners and policymakers to develop evidence-based injury prevention strategies and policies for alpine ski racing to create a safer sports environment involving athletes, coaches, and other stakeholders.

5 | CONCLUSIONS

This scoping review, that is one of the first of its kind, mapped out the available literature on injury prevention within the alpine ski racing context. Most literature involves injury epidemiology and etiology studies, including a wide spectrum from the WC to youth athletes; however, mainly large countries have a long tradition of alpine skiing culture. Few studies exist on preventative measure development, implementation, and evaluation. Additionally, the diversity of contextual factors identified in the current literature represents a challenge to evidence-based guidance for injury prevention in alpine ski racing. The limitations described in the literature (e.g., lack of definitions, small and diverse sample groups, heterogeneous methodological approaches and settings, and limited literature on injury prevention development, implementation, and evaluation) provide a road map for designing future injury prevention studies aimed at addressing key gaps identified in the alpine ski racing literature. Therefore, a more comprehensive context-driven approach throughout all stages of injury prevention would benefit the ultimate implementation of effective preventive strategies.

6 | PERSPECTIVES

Our findings provide an in-depth and comprehensive overview of the current literature on sports injury prevention in the alpine ski racing context. The core messages of this scoping review can be broken down into three highlights. First, most of the available literature describes injury epidemiology and etiology, and there is a lack of research on the subsequent stages of injury prevention in alpine ski racing (e.g., the development, evaluation, and implementation of specific countermeasures). Second, current studies on the topic of injury prevention in alpine ski racing are heterogeneous and inconsistent regarding definitions used, methodological approaches, study quality, and settings (e.g., competition levels, gender, time within the season, and countries and federations size). Third, injury prevention studies in youth skiers still represent a minority in the published literature, and this population should be targeted more specifically. Hereafter, future investigations toward increasing safety in alpine ski racing requires high-quality studies using standardized definitions and methods across all stages of the injury prevention cycle, focusing on the athlete, the equipment, the competition context and the environmental factors. Additionally, qualitative approaches may contribute to exploring and further understanding athletes' and other stakeholders' perspectives and perceptions on injury prevention, which could support the identification and development of potential preventive measures within this context. Yet, we know a lot about little and little about a lot across all the areas associated with injury prevention in alpine ski racing.

AUTHOR CONTRIBUTIONS

Oriol Bonell Monsonís, Jörg Spörri, and Evert Verhagen were responsible for the conception of the study. Oriol Bonell Monsonís executed the search strategy. Oriol Bonell Monsonís and Marit Warsen independently reviewed the records. Oriol Bonell Monsonís extracted data with the supervision of Evert Verhagen. Oriol Bonell Monsonís was responsible for the first draft of the manuscript. All authors contributed to the interpretation of the findings, critical revision of the manuscript, reviewed and approved the final manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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