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Risk management framework for competitive alpine skiing—co-developed with stakeholders

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ABSTRACT

Previous research has shown that stakeholders in the competitive alpine skiing communities consider risk management to be crucial in sports injury prevention. However, to date, there is a lack of a publicly available systematic and structured risk management approach for the competitive alpine skiing context. This work describes the codevelopment process of a risk management framework with stakeholders in the field of competitive alpine skiing. A panel of international experts invited through personal requests and with expertise in health protection and performance enhancement in competitive alpine skiing convened three times through online group meetings to co-develop a risk management framework through different activities. The underlying discussions focused on the fundamental questions of 'why', 'what', 'who', 'how' and 'for whom' and included the debate on specific examples from sports practice. The outcome after three meetings was a risk management framework. This framework includes a competitive alpine skiing-specific prevention wheel that integrates different stakeholder views relevant to different levels, their risk priorities, the main five domains and intervention areas identified from the literature, the graded and progressive timescale to intervene and the potential targets for risk management interventions. Moreover, the framework includes a decision-making tree, which operationalises the prevention wheel into a step-by-step sequence for risk management, including risk identification, risk assessment and risk mitigation. It should help stakeholders recognise their responsibilities and the potential actions they can take. Practical examples are provided to demonstrate how to apply the framework and to illustrate the complexity and dynamic interaction of the various factors in the competitive alpine skiing setting. The risk management framework developed lays a strong foundation for creating a safer environment for alpine skiers. It likewise contributes to providing overall awareness of the complexity and inter-relations of risks and prevention measures in the sport. By doing so, this framework has the potential to initiate further processes and on-field translation to sustainably and long-term improve athlete health and safety in competitive alpine skiing.

INTRODUCTION

Competitive alpine skiing is a sport characterised by high speeds and forces,[1–4] four main competition disciplines (Downhill, Super-G, Giant Slalom and Slalom),[5] demanding course settings and highly responsive equipment setups,[1–3 6 7] challenging environmental factors and terrains[1 6 8] and large physical and mental demands on athletes.[9] Injury rates in competitive alpine skiing are high, and severe injuries are frequent.[10–19] The most recent injury surveillance studies reported injury rates of 184.1 and 124.8 injuries per 100 athletes per entire season,[11 12] whereas more than 30% of the injuries are severe, leading to long-term absence from training and competition (more than 28 days).[11 12 14 20] Injuries occur throughout the entire season, accounting for both the competition and the preseason periods and across different competition levels.[11 12 20–23] Therefore, competitive alpine skiing can be considered a high-risk sport.[6 10 24]

A variety of potential measures may exist to mitigate these risks. Nevertheless, a recent review reported that only 20% of the literature addresses the development, implementation or evaluation of prevention measures within competitive alpine skiing, whereas as many as 80% is purely observational research.[25] Injuries and their prevention are complex and multifactorial;[26–29] thus, approaches such as complex systems and socioecological perspectives can be of interest.[26 30–32] Within such an environment, multiple factors (eg, athlete-, course-, equipment- and snow-related factors and context-dependent interactions between these factors) and stakeholders at multiple layers play a role in the event of an injury (eg, organisational, sociocultural and individual levels).[6 24 29 33 34] Stakeholders refer to the '*one who is involved in or affected by a course of action*',

encompassing athletes, coaches, medical staff, governing bodies representatives and policy makers.

In this context, stakeholders recently noted that their approaches to prevent injuries encompassed risk management strategies, where risk management was described as assessing, managing and sometimes accepting risk factors as part of safety-related decision-making.[29] This highlights how risk management is approached in the pursuit of finding a balance between risk and safety, a process strongly influenced by experience, communication and shared responsibilities among all stakeholders.[29] Additionally, current injury risk management models in sports illustrate organised and step-by-step elements, comprising risk identification, risk assessment, risk mitigation and risk communication.[35–38] However, to date, there is a lack of a publicly available systematic and structured approach that integrates risk management and shared responsibility for preventing injuries in the competitive alpine skiing context.

This study describes the process of codeveloping a corresponding risk management framework together with stakeholders and aims to present and exemplify it to a broader audience of stakeholders in the field of competitive alpine skiing.

METHODS

Participants

The lead authors (OBM, EV and JS) invited various stakeholders, based on personal contacts, from the competitive alpine skiing context to join a codevelopment panel. Despite two refusals and one withdrawal due to schedule incompatibilities and personal reasons, respectively, a panel of 12 international stakeholders (CB, VG, MA, DC, LE, MG, MJ, ML, GM, AO, KP and MS) was formed. They were selected based on their involvement in diverse academic and clinical disciplines across health protection and performance enhancement in elite sports and competitive alpine skiing.[6 23 24 39 40] All the panellists were researchers, epidemiologists, physiotherapists, sport and exercise physicians, on-snow coaches, off-snow coaches, former elite athletes, sport and exercise scientists, psychologists and biomechanists dealing with sports injury prevention and risk management and with expertise in competitive alpine skiing (online supplemental table 1). This ensured a diversity of expertise, backgrounds and perspectives. EV and JS served as senior investigators for the project.

Codevelopment process

Research team preparatory evidence input

The research team, including the lead authors (OBM, EV and JS) and two expert panel members (CB and VG), updated the literature review on sports injury prevention in competitive alpine skiing from Bonell Monsonís *et al*,[25] including additional articles published until 1 June 2024. This search yielded 52 new articles, resulting in 16 relevant studies after screening. Next, they summarised the literature findings and used concept mapping to connect the data.[41] Following a socioecological view at multiple levels (eg, individual, sociocultural and environmental) adapted for the complex and dynamic competitive alpine skiing context (figure 1),[26 42] a systems thinking map

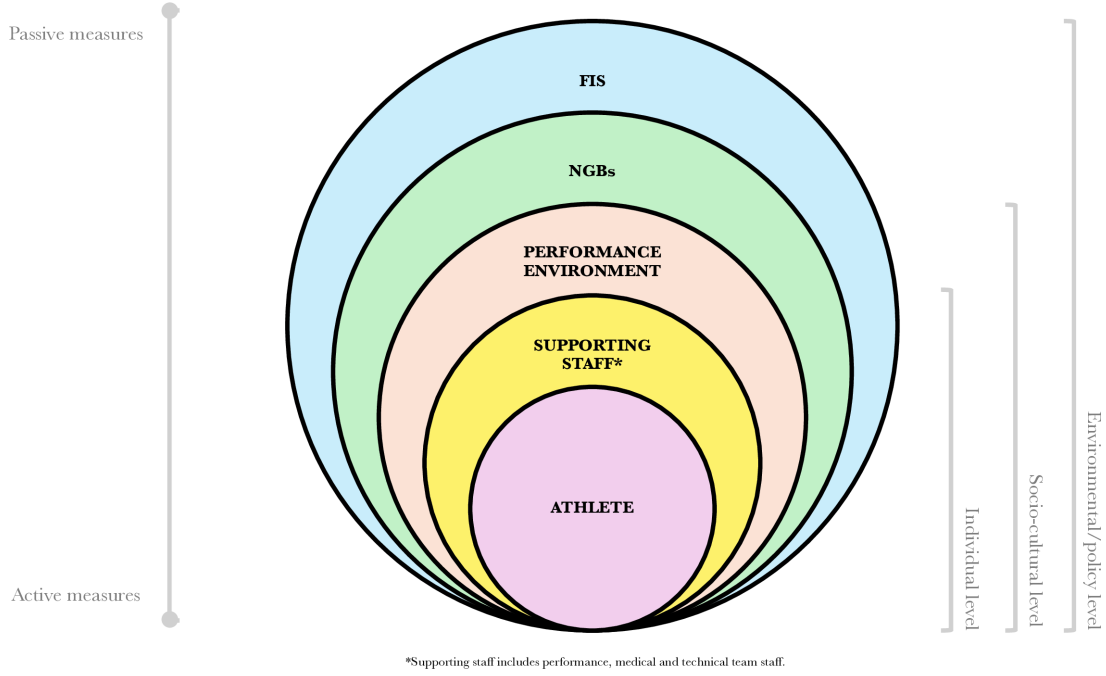

Figure 1 Socioecological view of risk management at multiple levels in competitive alpine skiing along with the passive–active intervention continuum. Adapted from Bolling *et al*,[26] Hendricks *et al*.[42] FIS, International Ski and Snowboarding Federation; NGBs, national governing bodies, including National Ski and Snowboarding Federations (NSSAs) and National Olympic Committees (NOC).

was created to illustrate interconnections among stakeholders (eg, skiers, coaches, team staff and governing bodies) and contextual factors affecting injury prevention (online supplemental figures 1-3),[26 30 34] serving as evidence input to this study. Hence, panel members were provided with a summary of the findings as preparatory material before the first meeting.

Working team codevelopment phase

The research team and the entire panel held three video conferences to develop a decision-making framework. The full codevelopment process is provided in figure 2.

Meeting 1

Based on the preparatory material, the stakeholder panel identified the main elements of the framework and their categorisation through four high-risk skiing scenarios from the 2023–2024 FIS Alpine Skiing World Cup, including women's and men's speed and technical races,[43 44] prompting discussions on contributing factors, their categories and modifiability. The lead author preselected high-risk scenarios in which a combination of multiple factors interact (eg, athlete, equipment, course and snow factors). These were used to explore and design ideas grounded in real-world competitive alpine skiing situations.[44 45] The collection of risk areas and stakeholders was led by scientific and empirical evidence, with a combination of the existing body of evidence, expertise and experience. Breakout groups, led by OBM, EV and CB, first facilitated idea generation inspired by the brainwriting method,[46] and feedback was collected via Miro,[47] followed by a whole group discussion. The stakeholders could add their thoughts and reflections up to 6 days after the meeting, both through the Miro board and a non-mandatory written form, an opportunity that four stakeholders took.

Meeting 2

The research team synthesised all the data from meeting 1. A preparatory task was sent to the panel, and all of them completed it. They were asked to organise and categorise into the different domains and intervention areas identified in meeting 1 and which stakeholders should be responsible or have access for each element identified and listed. Subsequently, all input collated from meeting 1 and preparatory tasks was presented. This meeting was intended to refine the framework's content and propose a risk management framework. After the meeting, three stakeholders took the opportunity to edit the notes or send their reflections through a written form.

Research team meeting

After collating all the stakeholders' perspectives, the lead authors met and debated how all the elements should be framed. Through two meetings and one round of feedback, the research team shaped the first draft of the proposed framework (eg, risk management wheel and decision-making tree). This was therefore circulated across the panel.

Meeting 3

Preparatory work aiming to revise the content and final adjustments and provide practical examples was sent to panel members, of which 10 stakeholders completed the tasks. The meeting attempted to review, discuss necessary revisions and agree on the proposed framework,

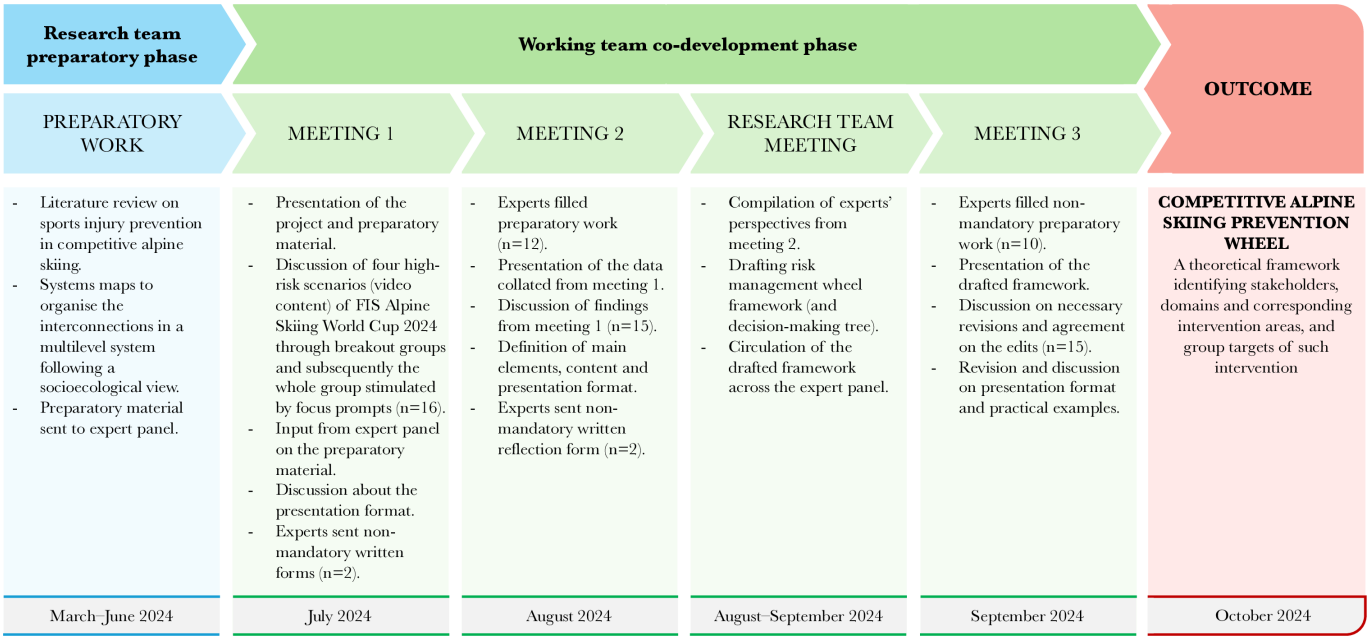

Figure 2 Development process of the competitive alpine skiing prevention wheel framework, composed of a preparatory phase carried out by the research team, followed by a codevelopment phase from the working team that led to the outcome of codeveloping the competitive alpine skiing prevention wheel. FIS, International Ski and Snowboarding Federation.

decision-making tree, its presentation format and practical examples provided.

The core author team (OBM, EV, VG, CB and JS) subsequently compiled a first complete draft and circulated it to the entire panel via email. All panel members were invited to review the manuscript and suggest edits until a final statement was agreed on.

Equity, diversity and inclusion statement

The working group included five women and 10 men from 11 different countries. Stakeholders actively participated in meetings to develop the risk management framework and were fully aware that the results were to be shared with the competitive alpine skiing community.

RESULTS

The codevelopment process: the build-up of the codevelopment phase

Meeting 1

The main areas, elements and factors across the multiple high-risk scenarios were identified. Different risk management models have been proposed and discussed. Although low-risk situations were not provided as supportive material, situations involving low-risk scenarios (eg, shadow or flat light) were considered and included in the discussion.

Meeting 2

The main areas, elements and factors identified in meeting 1 were framed into five domains (eg, organisational and contextual, snow and environmental, equipment, course design and athlete-related elements) that addressed their intervention areas, contributing factors and stakeholders' responsibilities and accessibility. Owing to the likeness and closeness with risk management approaches used in outdoor-related accident events, we opted for such a framework to organise all the described elements.[48–50]

Research team meeting

The risk management wheel framework and decision-making tree were first drafted, integrating stakeholders, domains and intervention areas, and group targets of such interventions.

Meeting 3

Revisions and edits to the framework led to the addition of the graded timeframe layer into both the risk management wheel and the decision-making tree. Likewise, such a graded timescale was therefore added within the decision-making tree, as was the graded risk categorisation.

The outcome: the competitive alpine skiing risk management wheel

The outcome after three rounds of group online meetings and codevelopment was the 'competitive alpine skiing prevention wheel' presented in figure 3. The wheel includes all identified relevant stakeholders, domains and corresponding intervention areas, risk priorities, different and graded timeframes and group targets of such interventions and operates via the interaction of the five integrated layers. Notably, mitigating a single corresponding factor (eg, risk) may involve multiple stakeholders, several intervention domains and various risk priorities and timeframes for different target groups. Thus, the risk management wheel should not create the illusion that each risk is associated with only one stakeholder responsibility, one domain, one risk importance, one timeframe and one action.

Stakeholders from a socioecological perspective

The outer ring integrates, in an exemplary way, all the identified stakeholders involved at all levels who can and should take responsibility or have access to risk management across the organisational, sociocultural and individual levels. Online supplemental figure 4 shows how the sport of competitive alpine skiing is framed and where each stakeholder group belongs to within the system.[29] Stakeholders may have different roles, tasks, levels of governance and points of leverage at which they can intervene within the complexity of competitive alpine skiing. At the organisational level, FIS and national governing bodies (NGBs) may be more prone to take passive measures towards a breadth of domains and group targets (eg, rules and regulations). A mixture of both active and passive strategies involves FIS, NGBs, coaches, health supporting staff and athletes as they all contribute to the sociocultural system of the sport from a political and social perspective (eg, governance, norms and values, sport culture and social structure). Athletes' beliefs, perceptions and attitudes towards active measures with a direct impact on themselves (eg, physical, mental, social and risk-taking behaviours) correspond to key aspects at the individual level.

Domains and corresponding intervention areas

The overarching domains and corresponding intervention areas that stakeholders influence and can modulate are shown in the middle ring (eg, organisational and contextual, snow and environment, equipment, course setting and athlete elements). We hierarchically organise the domains by their potential impact, modifiability and closeness to an event (eg, accident). Organisational and contextual elements are ranked on the upper end, as they outline the prevailing framework conditions (eg, most impactful) and their intervention areas and contributing factors indirectly affecting the accident. In contrast, the lower end corresponds to the intervention areas within athlete elements, directly describing the accident event. In this context, these are the most modifiable and least impactful factors. Moreover, a comprehensive compilation of contributing factors within each intervention, organised in alphabetical order, can be found in tables 1–5.

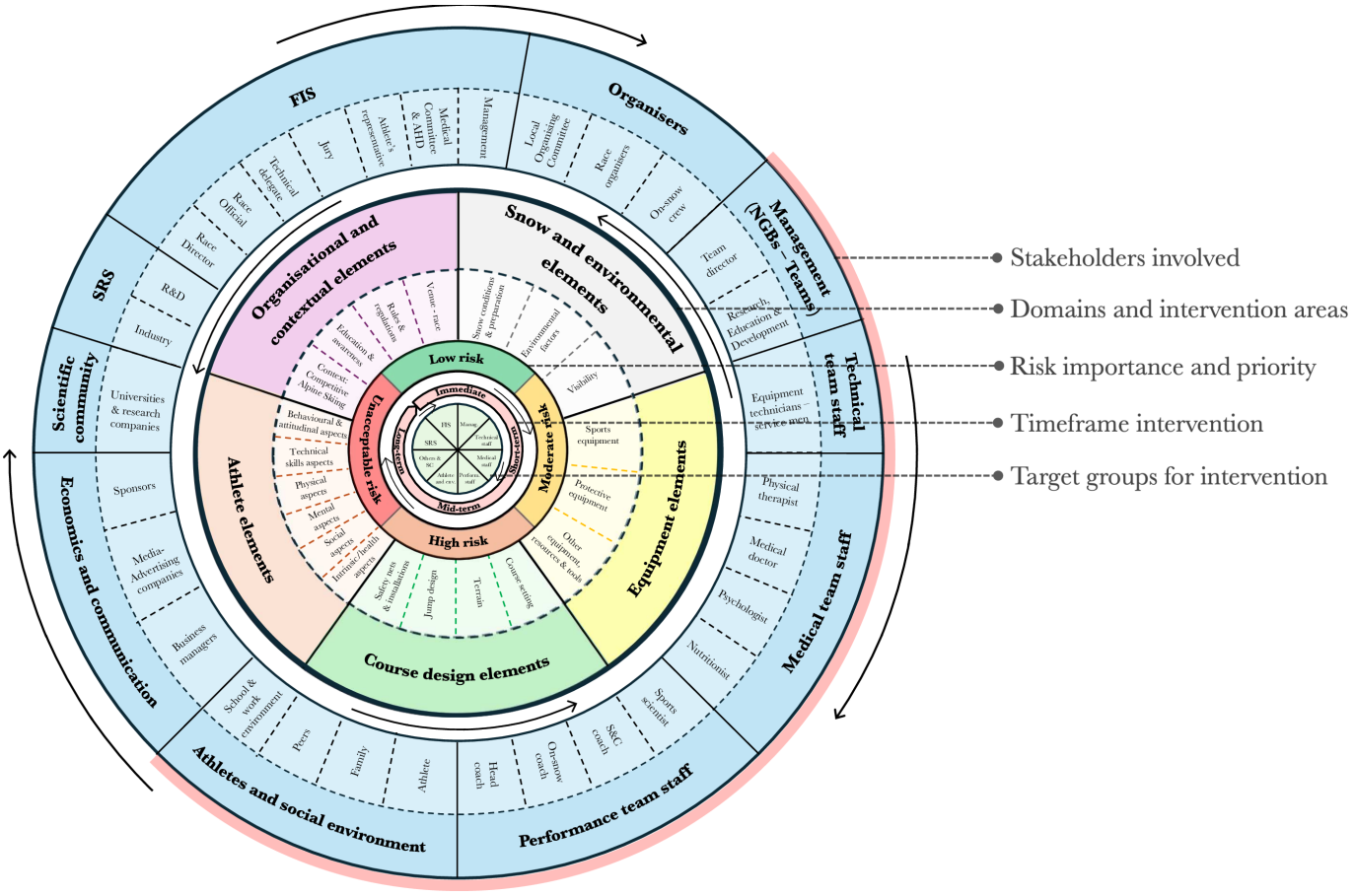

Figure 3 Competitive alpine skiing prevention wheel including identified relevant stakeholders, domains and corresponding intervention areas, risk priority, timeframe and target groups of such interventions. The stakeholder list does not claim to be complete but rather to present the big picture of competitive alpine skiing. Certain stakeholder groups and categories may not be interlinked and may sometimes be dependent. The red bold border highlights the stakeholder groups typically organised and closely related within NGBs, including National Ski and Snowboarding Associations (NSSAs) and National Olympic Committees (NOCs). AHD, Athlete Health Department; FIS, International Ski and Snowboard Federation; NGBs, national governing bodies; R&D, Research & Development; SC, Scientific Community; S&C coach, Strength and Conditioning coach; SRS, Ski Racing Suppliers.

Risk priorities and importance

Risk priority and importance against a specific scenario are defined as low, moderate, high and unacceptable risks. Despite the modifiability and impact of a corresponding factor (eg, specific risk), stakeholders may perceive the same risk differently. Assessing risk importance is a critical step in risk management.

Graded timeframes

The timeframe intervention in which domains and intervention areas by specific stakeholders can be approached to manage risks is presented gradually and progressively, from immediate to long-term interventions. Stakeholders may perceive time scales differently, and their perceptions of the time needed to modify a specific factor may also differ among stakeholders.

Target groups

The ultimate potential targets for risk management interventions can be found in the inner circle. Interventions may target multiple stakeholders at a time based on the rest of the circles of the risk management wheel.

Decision-making tree to illustrate the operationalisation of the competitive alpine skiing risk management wheel

To operationalise the competitive alpine skiing risk management wheel to a step-by-step sequence, we developed a decision-making tree that leads to several questions that may assist in decision-making (figure 4). By identifying and assessing risks and then taking action to mitigate them, stakeholders should pose the following questions throughout the subsequent five steps.

Step 1: problem definition

During the first stage of risk identification, to define whether a situation might be considered as a problem, the following key questions should be addressed:

- What is the impact on health and performance?

Based on stakeholders' perspective and experience, they should assess the likelihood of a specific scenario

Table 1 Intervention areas, contributing factors and stakeholders' responsibilities and accessibility for the organisational and contextual elements

Organisational and contextual elements		
Intervention area	**Contributing factor**	**Stakeholders' responsibility and accessibility**
Context: competitive alpine skiing	Course difficulty*	Coaches, FIS race directors, FIS technical delegates, LOC, race organisers
	Course length—duration of the race*	
	Event/participation format: competition level, men vs women, race vs training*	FIS, management
	Media (pressure): in- and off-race*	Athletes, FIS, LOC, management, media, psychologist
	Media commitments*	Athletes, business managers, FIS, LOC, management, sponsors
	Race calendar* ► time during the day (eg, for night races) ► time during the season (eg, spring) ► travel times/time zones crossed in the last few days ► back-to-back races	FIS, LOC, management, media, race organisers
	Resources for sports participation	Management, sponsors
	Resources for training	Athletes, FIS, management
	Social norms	FIS (society)
	Sports culture	FIS, management
Education and Awareness	Coaching practices and team dynamics	Coaches, management, scientific community
	Health perception education/awareness	Coaches, FIS, management, medical team staff, scientific community
	Mental readiness*	Coaches, medical team staff, scientific community
	Physical readiness*	
	Prevention knowledge education/awareness	Coaches, FIS, management, medical team staff, scientific community
	Risk management education/awareness* ► risk-taking behaviour/approach	
	Warm-up strategies*	Athletes, coaches, management, scientific community
Rules and regulations	Antidoping regulations	FIS, scientific community
	Competition regulations	
	Course difficulty*	
	Course regulations	
	Duration of the race*	FIS, LOC
	Equipment regulations	FIS, scientific community, ski racing suppliers
	ICR equipment regulations	FIS
	Insurance cover	Management
	Practice runs before competition*	Coaches, FIS, FIS race directors
	Protective gear regulations	FIS, scientific community, ski racing suppliers
	Qualification standards NSSA/FIS	FIS, management (NSSA)
	Race calendar (density of races)*	
	Recommendations from associations	Management (NSSA), ski racing suppliers
	Standards	FIS, ski racing suppliers
	Timings/in-race schedule*	FIS, LOC

Continued

Table 1 Continued

Organisational and contextual elements		
Intervention area	**Contributing factor**	**Stakeholders' responsibility and accessibility**
Venue—race	Access to venue location	FIS, LOC
	Accommodation/hotel	Coaches, FIS, management (team director)
	Advertising banners placement	Advertising companies/media, FIS race directors, FIS race organisers, Jury, LOC
	Bib draw	FIS, LOC, media
	Camera-men placement on the hill/course	FIS race directors, jury, LOC, media/advertising companies, race organisers
	Chair lift time	FIS, LOC
	Coaches and slip crew training, education and placement on the hill/course	Coaches, FIS race directors, jury, LOC, on-snow crew (slippers), race organisers
	Communication information flow (eg, how, when and through whom alpine skiers are informed about track conditions, accidents, breaks after accidents and changes)	Coaches, FIS, jury, LOC, management, medical-performance-technical team staff
	Design of the finish area	FIS race directors, jury, LOC, race organisers
	Duration of the race*	
	Emergency action plan: rescue, extraction plan, standards	FIS race directors, FIS team medicals, LOC, race organisers
	Event/participation format: competition level, men vs women, race vs training*	FIS, FIS race director, jury, LOC, race organisers
	Hospitality area before the race and accessibility	FIS, LOC
	Indoor and outdoor warm-up areas and resources (eg, shelter)	FIS, FIS race directors, jury, LOC, race organisers
	Jury decisions/decision-making process (eg, communication with alpine skiers after the course is set)	Athletes' representatives, coaches, FIS race directors, jury, race organisers, scientific community
	Medical team personnel placement and on-hill communication	FIS, LOC, medical team staff
	Medical centres and resources on site, treatment standards	LOC
	Practice runs before competition*	Athletes, coaches, FIS race directors, LOC
	Ski patrol placement on the hill/course	FIS, on-snow crew, LOC
	Timings/in-race schedule*	FIS, LOC, race organisers

*Contributing factors included in multiple intervention areas and domains.
FIS, International Ski and Snowboard Federation; ICR, international competition rules; LOC, local organising committee; NSSA, National Ski and Snowboarding Association.

having a potential impact on athletes' health and performance following a 5-point Likert scale.

► How important is it?

The appraisal of risk importance and priority should be acknowledged to make the first decision. The importance of a specific scenario or topic by the stakeholder group is defined, ranging from low, moderate, high and unacceptable risk. In addition, risk priority may vary based on stakeholder perceptions and perspectives. When a risk is deemed unacceptable, two options are possible. First, further steps might not be needed, and instant action might be considered (red-dashed arrow, figure 4). Second, unacceptable risks might be subject to proper evaluation in further steps.

► What is the problem temporality?

Risk temporality should be considered at this stage. It is important to distinguish risk importance from action timeframes, as risk importance in isolation should not dictate the reach or timeframe of planned action. Examples of questions could include: 'Is this a short-term or long-term problem? 'and 'Will this problem persist in the future?'.

Altogether, answering these questions would lead to defining a specific scenario as problematic or not. Thereby, this key decision would potentially bring stakeholders to the next step of the process or, otherwise, to decide not to take further action. Hence, no action is needed if a specific scenario or topic is not viewed as a problem.

Table 2 Intervention areas, contributing factors, stakeholders' responsibility and accessibility for snow and environmental elements

Snow and environmental elements		
Intervention area	**Contributing factor**	**Stakeholders' responsibility and accessibility**
Snow conditions and preparation	Changing snow conditions	FIS race directors, jury, LOC, race organisers
	Course maintenance (race line, spill zones, finish area) ► snow accumulation close to racers' ideal lines	FIS race directors, jury, LOC, on-snow crew, race organisers
	Snow conditions (eg, cold, icy, hard, warm, wet, soft, slippery, natural, man-made)	FIS race directors, jury, LOC, race organisers
	Snow preparation on the race track (eg, water injected)	
	Snow preparation in relevant areas: course, spill-zone, finish area (eg, water injected)	
	Time during the season (eg, spring)*	FIS, FIS race directors
Environmental factors	Altitude	Coaches, FIS race directors, jury, LOC, management, medical team staff, performance team staff, race organisers
	Event/participation format: competition level, men vs women, race vs training*	FIS
	Temperatures (air) (eg, hot and cold)	FIS, jury, race organiser
	Time during the season (eg, spring)*	FIS, FIS race directors
	Weather conditions (eg, snowfall, rainfall)*	FIS race directors, jury, race organisers
	Wind/wind gust	
Visibility	Changing light conditions ► flat light, shadow, limited or no contrast	FIS race directors, jury, race organisers
	Fog	
	Weather conditions (eg, snowfall, rainfall)*	

*Contributing factors included in multiple intervention areas and domains.
FIS, International Ski and Snowboard Federation; LOC, local organising committee.

Step 2: stakeholder groups' accessibility and reach and action feasibility

Accessibility and, consequently, responsibilities from stakeholders are identified in the last step of risk identification. If that specific scenario or topic is not or might not be entirely within the range of one specific group, this model also considers other stakeholder groups' contributions. Furthermore, identifying whether actual preventive measures are already in place can have an impact on the next steps, as it can accelerate or slow down the decision-making process.

Step 3: identification of the domains and intervention areas and the target group

Through the first step of assessing a risk, areas that the identified stakeholders can influence or modulate are identified. These may vary across stakeholder groups, and they are greatly influenced by the guiding question from step 1. Moreover, the target group is selected such that the planned action should be tailored to the affected target group.

Step 4: impact and investment – action timeframe and resources

This second section of risk assessment refers to the timeframe required to modify the corresponding factors and the resources available or potentially needed to act. The time windows include a graded scale for immediate ('now'), short-, mid- and long-term actions. When there are not enough resources to act, strategies to obtain resources should be identified, and other stakeholder groups' contributions might be considered.

Step 5: taking action

To mitigate risks, planned action is taken based on all the previous reasoning (risk priority, stakeholders, factors, timeframe and resources) towards the target group(s) identified for such intervention(s).

Practical examples

The following practical examples are intended to illustrate the complexity and dynamic nature of the competitive alpine skiing setting and to show how to employ the risk management framework (eg, the 'wheel' and 'decision tree') for the purpose of athlete health protection. Three selected examples of load management, lacerations and cut-resistant underwear development, as well as course design, are currently hot topics in the competitive alpine skiing community.[1 25 29 39 40 51–54] However, the framework does not provide solutions to the selected practical examples. The following scenarios may not be considered

Table 3 Intervention areas, contributing factors and stakeholders' responsibilities and accessibility for the equipment elements

Equipment elements		
Intervention area	**Contributing factor**	**Stakeholders' responsibility and accessibility**
Sports equipment	Aggressivity of the equipment (ski-snow interaction)	Athletes, coaches, equipment technicians—service men, FIS, ski racing suppliers
	Binding adjustment (release)	
	Boot	
	Ski edges	
	Ski preparation	
	Ski-plate-boot-binding system	
Protective equipment	Airbag	Athletes, FIS, medical team staff, scientific community, ski racing suppliers
	Air fences (eg, finish area, obstacle protection) *	FIS race directors, jury, LOC, race organisers
	Back protector	Athletes, athletes' representatives, coaches, FIS, scientific community, ski racing suppliers
	Carbon shin protectors (eg, underneath the suit and boot)	
	Cut-resistant clothing	
	Forearm protector	
	Goggles and lenses	
	Helmet	
	Shin protector	
	Slalom poles	
Other equipment: resources, emergency equipment and other tools	Emergency action plan: rescue, extraction plan, standards, communication process on the hill	FIS medical team, LOC, race organiser, ski racing suppliers
	Warm-up garment	Athletes, coaches, management

*Contributing factors included in multiple intervention areas and domains.
FIS, International Ski and Snowboard Federation; LOC, local organising committee.

isolated scenarios; rather, they may coexist and may be interactive in nature.

Load management

Several factors can contribute to increasing or reducing athletes' load, such as tight competition schedules, challenging snow conditions, specific equipment and setup factors and excessive physical and/or mental loads associated with sports participation in general.[24 25 51 52 55] Accordingly, approaches to and the management of athletes' internal and external loads may vary depending on stakeholder perspectives, roles and resource accessibility (online supplemental figure 5).[29 56] While most stakeholders may influence organisational, contextual and athlete-related elements in terms of immediate to long-term actions, the approaches and the perceived priorities for taking action may differ.[24 51 57] For example, FIS and athletes may approach load management differently (online supplemental figure 6). On the one hand, FIS can modulate elements at the framework/regulation level, including organisational and contextual elements, as well as equipment rules. Given FIS's scope of action, they may view load management as a low- to moderate-risk problem, and given the nature of their actions, further potential actions may take place both in the mid- and long-term periods. On the other hand, athletes may believe that load management is a moderate- or even a high-risk problem. Their reach relies on all athlete factors, with special attention given to biopsychosocial factors and behavioural elements of training and competition.[58 59]

Lacerations and development of cut-resistant underwear

The industry (eg, ski racing suppliers (SRS)) constantly invests in developing equipment to increase performance, whereas equipment technicians (eg, ski) work towards more performance-enhancing and aggressive (eg, direct in force transmission) skis to help their skiers achieve their performance goals. One potential way to optimise the system ski-plate-binding and boot force transmission is tuning of maximally sharp ski edges; the latter, however, can also play a major role in the causation of cut injuries (or laceration). Recent efforts against lacerations have been conducted at different levels within the competitive alpine skiing community to increase athlete safety through, for instance, the development of cut-resistant underwear.[60] In this effort, different stakeholders such as FIS, National Ski and Snowboarding Federations and SRS may contribute to its development and implementation with mid- and long-term actions towards different target

Table 4 Intervention areas, contributing factors and stakeholders' responsibilities and accessibility for the course design elements

Course design elements		
Intervention area	**Contributing factor**	**Stakeholders' responsibility and accessibility**
Course setting	Blind gates	Coaches, FIS race directors, jury, race organisers
	Course difficulty*	Coaches, FIS race directors, jury, LOC, race organisers
	Course length—duration of the race*	Coaches, FIS race directors, jury, race organisers
	Gate placement: horizontal offset & vertical distance	
	Physical load of a run/race*	
	Predictability of the course (vs course variation)	
	Rollers and compressions*	
	Speed (eg, high and uncontrolled, low)	
	Turns in context of the terrain and radius of the turn (eg, sharp)	
Terrain	Course difficulty*	Coaches, FIS race directors, jury, LOC, race organisers
	Course length—duration of the race*	Coaches, FIS race directors, jury, race organisers
	Physical load of a run/race*	
	Rollers and compressions*	
Jump design	Height, length, trajectory and landing impact of jumps	Coaches, FIS race directors, jury, LOC, race organisers
	Jump landing (eg, flat, blind, turn, bumpy)	
	Jump take-off	
	Landing in turns or before turns and compressions	
Safety nets and installations (race and training events)	A-net position, quantity, layers and tightness ► positioning relative to course design (anticipated impact scenarios) ► high net standards also during training and lower-level competitions	Coaches, FIS race directors, jury, LOC, race organisers, scientific community
	Air fences (eg, finish area, obstacle protection)*	Coaches, FIS race directors, jury, race organisers
	B-net position, quantity, height, rows ► positioning relative to course design (anticipated impact scenarios) ► high net standards also during training and lower-level competitions	Coaches, FIS race directors, jury, LOC, race organisers, scientific community
	Nets angle (A- and B-nets) ► high net standards also during training and lower-level competitions	
	Obstacle protectors (eg, advertising banners, TV-tower constructions, timing equipment, slipping-crew-waiting-area, trees)	
	Planning spill zones relative to course design	Coaches, FIS race directors, jury, LOC, race organisers

*Contributing factors included in multiple intervention areas and domains.
FIS, International Ski and Snowboard Federation; LOC, local organising committee.

groups. Their actions may focus on innovation, product development and equipment regulations, making the wearing of cut-resistant underwear feasible and compulsory. However, there may also be athlete-related elements that need to be considered, such as increasing awareness and usage compliance in training, for example, where the competition rules do not apply.

Course design

As part of competitions, responsibilities for course design are typically shared between FIS (eg, Race Directors), head and on-snow coaches, race organisers and the scientific community (online supplemental figure 7).[29] While FIS can intervene within organisational and contextual elements, especially concerning contextual factors and modelling or creating rules, guidelines and regulations on snow preparation and course setting, on-snow coaches are responsible for setting the course during competition (except for Downhill), and LOCs, race organisers and on-snow crews take care of snow preparation and further snow conditions during racing. Moreover, the scientific community is continually exploring new ways to increase athlete safety in terms of course setting, terrain, jump design and safety nets and installations. Actions by FIS, organisers, management and the scientific community may take longer (eg, mid- to long-term), whereas on-snow coaches may need to act immediately when

Table 5 Intervention areas, contributing factors and stakeholders' responsibilities and accessibility for athlete elements

Athlete elements		
Intervention area	**Contributing factor**	**Stakeholders' responsibility and accessibility**
Intrinsic—health aspects	Age/sex/gendered environmental factors	Athletes
	Anthropometry	
	Current minor injury	Athletes, medical team staff, performance team staff
	Jet lag	Athletes, FIS, management, medical team staff, performance team staff
	Nutrition	Athletes, FIS, LOC, management, medical team staff, performance team staff, scientific community
	Preinjuries or current injuries	Athletes, FIS, management, medical team staff, performance team staff
	Previous or current illness	
	Skier experience (eg, good and bad)	
Social aspects	Cultural context	Athletes
	Media (pressure)*	Athletes, business managers, sponsors, management, media, ski racing suppliers, sponsors (individual and team)
	Media commitments*	
	Skier's personal life and stressors	Athletes, family, management, peers, school and work environment
	Team pressure and team dynamics	Management, performance team staff
Mental aspects	Anxiety from bad experiences	Management, coaches, family, management, medical team staff (psychologist, physiotherapist)
	Fear of reinjury	
	Focus/concentration during the race	
	Mental health and mental disorders	
	Mental load management	Management, FIS, management, medical team staff (psychologist, physiotherapist), performance team staff
	Mental readiness*	Athletes, coaches, family, management, medical team staff (psychologist, physiotherapist)
	Social media activity	Athletes, business managers, management, media/advertising companies, sponsors (individual and team)
Physical aspects	Aerobic and anaerobic power and capacity	Athletes, management, medical team staff, performance team staff, scientific community
	Balance, coordination and agility	
	Fatigue	
	Joint mobility and muscle flexibility	
	Physical fitness/robustness	
	Physical readiness: aerobic power, strength and power, structural tolerance, performance and perceived fatigability*	
	Training and competition load management	
Technical skills aspects	General alpine skiing-specific skills: skiing level and adaptability related to discipline and course setting	Athletes, management, performance team staff
	Situational alpine skiing-specific skills (eg, jumps, compression, rollers, changing visibility, fall behaviour)	
	Specific pre-event activation skills: warm-up, practice runs*	
Behavioural and attitudinal aspects	Course inspection before race/training	Athletes, jury, management, on-snow coaches
	Risk-taking behaviour/approach	Athletes, FIS, management, medical team staff (psychologist, physiotherapist), performance team staff (on-snow coaches), scientific community

*Contributing factors included in multiple intervention areas and domains.
FIS, International Ski and Snowboard Federation; LOC, local organising committee.

setting the course for a specific race, although there is a long-term plan in place for course setters during the season. Moreover, it is important to consider that every athlete may cope with a certain course set differently (online supplemental figure 8), where experience (good or bad), previous injuries and health, prevention and risk management education and awareness play pivotal roles.[29] This may include not only athlete elements but also how athletes interact with the snow, environment and course design, as well as how each athlete deals

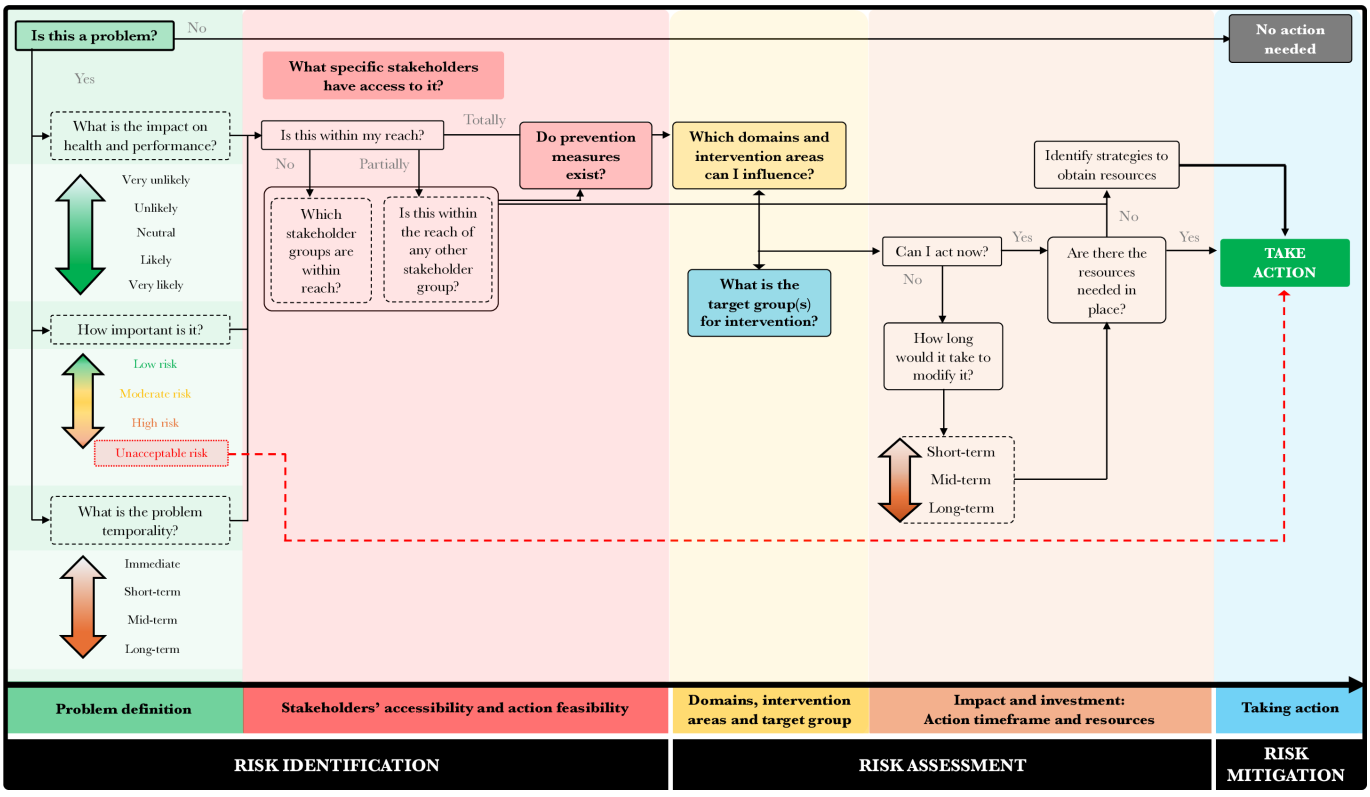

Figure 4 Decision-making tree for operationalising the competitive alpine skiing risk management wheel to a concrete step-by-step sequence, including three major steps: (1) risk identification through acknowledging problem definition, its feasibility and stakeholders' access and reach; (2) risk assessment by identifying domains and intervention areas, action timeframe and resources and (3) risk mitigation when taking action based on the previous reasoning throughout the decision-making process.

with the interaction and cumulative effect between snow conditions, visibility and the course set contingent on their prior experience and training.

DISCUSSION

In this study, researchers and stakeholders from the competitive alpine skiing context codeveloped a holistic risk management framework. The described codevelopment process included multiple phases, rethinking and revision among the research group and the expert panel. The risk management wheel describes stakeholder-driven solutions in competitive alpine skiing and operates via the interaction of five integrated layers. Moreover, it provides answers to the critical questions of why, what, who, how and to whom risk management may be important. The codeveloped decision-making tree operationalises the prevention wheel to a step-by-step sequence.

The complexity and multifactorial nature of the setting towards multifaceted approaches

In the recent literature, stakeholders described that their risk management approaches entail three different behaviours: assessing, managing and sometimes accepting risk factors as part of safety-related decision-making.[29] Within the competitive alpine skiing setting, multiple factors and stakeholders play a part in injury causation and injury prevention.[6 24 34] In this context, the proposed competitive alpine skiing risk management wheel embraces the complexity and dynamism of the setting by following a socioecological perspective of risk management at different levels.[25 26 29 52] Similarly, we developed a decision-making tree to make even more thoughtful and less arbitrary decisions in practice. Accordingly, this decision-making tree defines a step-wise process from a specific standpoint to make (or not) decisions in front of a specific scenario or topic. The fundamental concept of the framework remains consistent, while it aligns with the risk management principles in sports,[29 35–38 61] with a special focus on risk identification and risk assessment using an integrated approach across different stakeholders in the field, emphasising communication and the identification of action steps. Thus, it promotes structured reasoning to guide thinking and decision-making processes to be translated into actionable steps in risk management, rather than providing direct solutions concerning what preventive or risk management measures should be designed, developed or implemented. However, its specific contents may require constant monitoring, iteration and updating to align with evolving trends and demands in the sport and shifts in the contextual conditions (eg, estimation, weight and cumulative effect of the interaction of contributing factors). Recognising this need for adaptability underscores the tool's practical value and ensures its continued relevance in dynamic environments.

What is it for and for whom? Practical implications

The proposed competitive alpine skiing-specific risk management framework aims to raise all stakeholders' awareness of their responsibilities and empower them to identify and potentially act on their areas of influence. With a particular emphasis on risk identification and assessment,[29 35 37 61] this framework is intended to improve athletes' health and safety, as it may stimulate prevention efforts across intervention areas and stakeholders at multiple levels. It does not introduce risk mitigation strategies to reduce the level of individual, sociocultural or organisational risk resulting from specific contributing factors. However, it emphasises the importance of a multifaceted approach that encourages shared responsibilities and identifies stakeholder actions through risk identification and risk assessment to ensure that stakeholders across different levels in the system are aware of their contribution to the field. Therefore, the framework also yields a step-by-step decision-making process for risk management, potentially educating and raising awareness of stakeholders' reach and impact in this complex risk-prevention measure matrix in competitive alpine skiing. Yet, future dissemination strategies should ensure that all involved stakeholders are aware of the framework and can apply it in their corresponding context.

Future directions towards creating a positive safety culture

Despite the performance-driven mindset in which (at least in the short term) the *fastest* and not the *safest* athlete may win,[29] the creation of a safety culture in competitive alpine skiing seems reasonably promising.[62] Leadership at both the organisational level (eg, FIS and NGBs) and the practical context of sports (eg, coaches, team staff and experienced athletes) plays critical roles in the development and fostering of a safe culture within the competitive alpine skiing setting. In this connection, we understand our current risk management framework as a potential starting point for improving the health of competitive alpine skiers. For example, this work can contribute to future proactive or reactive risk management tools to identify and weigh injury risk factors and to further implement risk mitigation solutions. We, however, acknowledge that future efforts are needed to develop risk assessment methods at multiple levels across various intervention areas to promote a safer environment while preserving the actual competitive environment.[63]

Strengths and limitations

A strength of our study is the underlying codevelopment process incorporating the experience and knowledge of risk management from a panel of international stakeholders who contributed their unique perspectives and backgrounds.[64] Throughout the process we used participatory and interactive methods, which can enhance creativity and foster dialogue in group work.[65] Nonetheless, our approach did not follow any standardised cocreation process protocol or a Delphi process with a subsequent implementation stage.[66 67] This might have impacted our results with an over-representation of stakeholders' perspectives; however, we engaged all stakeholders and gathered all their perspectives and feedback during the process. Although we aimed for a diverse group, we acknowledge that the panel might not represent all the diversity of competitive alpine skiing, as all the stakeholder groups were not sufficiently represented (eg, current athletes, technical team staff, organisers, economics and communication and SRS representatives). Additionally, although we did not include low-risk scenarios as part of the supportive material, we believe that this might not have affected the outcome of the framework, as potential low-risk situations were also considered throughout the codevelopment process. Rather than making recommendations, the aim of this conceptual framework is to be developed by stakeholders in competitive alpine skiing and used on an ongoing basis. It does not consider any concrete or tangible endpoints after action has been taken, nor any evaluation process to assess its adoption and implementation. Future research should address an empirical validation step to demonstrate the applicability of the framework, for example, by testing it with all stakeholders represented in the framework across real-world case study analyses. However, the involved stakeholders codeveloped an evidence-informed and context-specific framework that can assist in decision-making in competitive alpine skiing. The proposed framework should be interpreted with caution, given its specificity in the competitive alpine skiing context.

CONCLUSIONS

The competitive alpine skiing-specific risk management framework, developed in collaboration with stakeholders, provides a practical foundation for creating a safer environment for alpine skiers to perform. By addressing the complexity and multifactorial nature of risk management, this framework aims to promote the health and safety of athletes in real-world contexts. From both research and sports practical perspectives, it offers a structured approach to guide thinking, decision-making and actionable steps in risk management. The framework combines all identified relevant stakeholders, intervention areas, their components, risk prioritisation, various timeframes and the ultimate goals for implementation. We believe it has the potential to improve risk management practices by fostering collaboration and shared decision-making processes among all involved parties.

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