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Recommendations to improve ski area safety with obstacle padding

Marine Dorsemaine [a,b,c,*], Irving S. Scher [d,e], Tom Allen [f], Catherine Masson [a], Lenka L. Stepan [d], Pierre-Jean Arnoux [a,c]

[a] Aix Marseille Univ, Univ Gustave Eiffel, LBA, Marseille, France
[b] Domaines Skiables de France, Francin, France
[c] iLab-Spine: International Laboratory on Spine Imaging and Biomechanics, France
[d] Guidance Engineering and Applied Research, Seattle, WA, USA
[e] Mechanical Engineering, University of Washington, Seattle, WA, USA
[f] Department of Engineering, Manchester Metropolitan University, UK

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ABSTRACT

Objective: Fixed obstacles, such as trees, rocks and posts, are common within recreational ski areas. Collisions with fixed obstacles (CWO) can have severe consequences with significant physical, emotional and economic costs. Despite worldwide use of ski area padding, few studies have focused on padding and CWO. The snowsports safety community is now focusing on this topic to improve safety at recreational ski areas. The objectives of this white paper are to summarize the recent work conducted on ski area padding, to identify unsolved questions about CWOs and opportunities to improve safety.
Methods: A review of the current knowledge regarding CWOs and ski area padding was performed, combining scientific studies and experience from the authors and ski area safety professionals. This review covers: (i) the epidemiology of CWOs; (ii) the characteristics of CWOs; (iii) padding type and use; (iv) ski area safety professional practices; and, (v) padding performance and the limits for injury mitigation.
Results: Previous studies focused on epidemiology, padding practices and performance and provide motivation for further study in the areas of: (i) prevention of CWOs; (ii) padding practices to improve safety on the slopes; (iii) requirements for padding performance; and, (iv) technological advancement of padding materials and design.
Conclusions: There is a need for an international standard for ski area padding, to address the absence of padding performance requirements in most countries. Further research studies should also focus on providing guidance to ski areas on the best practices for choosing, applying, and maintaining ski area padding.

1. Introduction

Globally, skiing and snowboarding are popular winter sports, with most participation occurring on ski slopes at ski areas. Fear of injury, including being out of control and colliding with an obstacle may deter people from trying snowsports and reaping the associated health benefits [1,2]. Efforts are made by ski areas to reduce the likelihood of snowsports participants colliding with obstacles. Fixed objects located on or near ski slopes that are visible from uphill are called "obstacles" in the snowsports safety community. Objects that are not observable to attentive snowsports participants (in particular, skiers and snowboarders) from uphill are called "hazards." Obstacles are typically categorized as natural (mostly trees or rocks) or man-made (typically lifts, snowmaking equipment, or snow barriers). Because there is no universal term for areas that are designated for snowsports, we will use the expression "ski slopes" to include areas that may be called ski pistes, ski tracks, ski trails, ski runs or maintained trails; the ski slope itself (that is, the snow surface ground) and people on it are not included in the term "obstacles".

Collisions with obstacles (CWO) can result in severe injuries, effecting the head or torso in over 40% of cases [3]. To reduce the likelihood of a CWO, and the risk and severity of associated injuries, staff managing the safety of a ski area often warn participants about the presence of obstacles by mounting colored pads (also called mattresses) on them. Pads are typically mounted on the uphill side of obstacles. Inspecting and maintaining these pads is typically the role of ski patrollers, although practices can vary between ski areas.

In 2003, the frequent use of ski area padding in France led to the development of a national design standard by the Association Française

* Corresponding author. Laboratoire de Biomécanique Appliquée, Faculté de médecine secteur nord, Boulevard Pierre Dramard, Marseille, 13015, France.
E-mail address: marine.dorsemaine@univ-eiffel.fr (M. Dorsemaine).

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de Normalisation (AFNOR) [4]. Unfortunately, there is no evidence to suggest that the requirements of this standard were based on scientific studies nor that it led to improvements in padding performance. For these reasons (and because the standard was published solely in French), the AFNOR standard has not been adopted globally. Because little work on this topic had been conducted, the community of the International Society for Snowsports Safety (ISSS) (that includes engineers, scientists, medical professionals, and ski area professionals) initiated studies on the epidemiology, dynamics, and injury likelihood of CWOs. The ultimate goals of these combined research efforts are to reduce the number of CWOs and to decrease the severity of injuries in CWOs for recreational snowsports participants, by providing a better understanding of: (i) the situations that produce a CWO; (ii) the typical injury mechanisms; and, (iii) the capabilities and limitations of ski area padding systems throughout their life cycle.

The aims of this white paper are to relate to the reader the state-of-the-art in ski area padding and provide the information needed for researchers to further assess and improve ski area padding. To achieve these goals, the paper is divided into the following sections: (i) current situation: epidemiology and padding characteristics, practices and performances and (ii) perspectives for future work: prevention, practices, guidelines and standard.

2. Methods

This paper is based on the authors' research, including laboratory and on-slope testing and modeling, conference presentations, journal articles, and scientific discussions from the ISSS. These discussions included ski area safety professionals (e.g., ski patrollers and ski area safety managers) who provided information on their practices. An online search (Google) was conducted using the words “pad”, “padding”, “mattress” to identify padding manufacturers. Information was extracted from the websites of manufacturers located in France, US, Canada, Italy, Austria, and Serbia [5–19]. A narrative, rather than systematic, approach was chosen for the white paper, combining scientific studies with the authors’ experience and feedback from ski area safety professionals. Each author has conducted, presented, and published on topics related to recreational ski area padding and snowsports safety.

3. Current situation

3.1. Epidemiology of CWOs

CWOs represent about 5% of ski patrol reports and rescues in the US and France [3,20]. According to previous research, the incidence of ski patrol reports for all incidents ranges from 0.43 to 2.50 per 1000 ski area visits [20]. Based on this range, the expected incidence of CWO is 0.022–0.13 per 1000 per ski area visits. Despite this low incidence, CWOs can have severe consequences (Table 1). Indeed, CWOs account for 13% of all traumatic brain injuries (TBI) and 48% of moderate or severe TBI [21]. CWO is also the first or second cause of traumatic death (>35% of accidents), with the most common obstacles being trees (60%), man-made objects (8%), and rocks (6%) [22,23]. Factors that increase the likelihood of a CWO include being male, an alpine skier, <26 yrs-old, and self-reporting as an advanced or professional skier [3]. This population is also known for skiing fast [24,25], with a risk-seeking behavior [26,27]. Recent work has shown that advanced participants travel at a mean (standard deviation) speed of 44.5 (11.3) km/h on wide-open, more difficult slopes (blue square in the US, equivalent to red slopes in Europe) [28]. In recent years, riding off-piste has become more popular. Off-piste areas tend to have more obstacles than groomed ski slopes, particularly natural ones such as exposed rocks and trees, increasing the risk of a CWO.

In summary, CWOs are rare but can cause severe injury. CWOs mainly involve a population that skis fast and takes risks, producing high-energy incidents with substantial emotional and economic costs for the participants, their families, and the ski areas. To the best of our knowledge, there are currently no epidemiological studies investigating the relationship between padding and CWO incidences/injuries.

3.2. Characteristics of obstacles and use of padding

Ungroomed areas (off-piste) between groomed ski slopes often contain obstacles (e.g. trees, rocks, trail signs, etc.). These ungroomed areas can reduce the speed of out-of-control participants before a CWO occurs, and in some cases, can prevent a CWO. After a loss of control at high speed, however, an off-piste CWO can still occur. Natural obstacles (e.g. rocks and trees) are rarely padded because they are typically considered an intrinsic element of ski areas and natural terrain. While man-made objects are often padded when located on the groomed slope, those found off-piste are rarely padded. It is impractical to pad all natural objects located near the ski slopes and doing so would change the character of snowsports. As a preventative measure, “Caution, trees don't move” signs are used in some places in the US to increase awareness of obstacles and reduce the likelihood of CWOs.

While efforts are made to limit the presence of obstacles on or near groomed slopes, particularly man-made ones, it is not always practical or possible to do so. To help draw attention to obstacles and warn participants of their presence, bright, contrasting-color (e.g. red, orange, or yellow) padding is often placed on on-slope, man-made objects within a ski area (e.g. tower lift, snow making equipment, etc.). It is uncommon for ski areas to pad an object with a color that blends in with the surrounding environment. Though each ski area may have its own practices for when and where to apply padding, there are no international standards nor universally agreed guidelines related to the use of ski area padding. According to interviews with ski area safety professionals, the decision to place a pad on an obstacle is typically based on: (i) the obstacle type (man-made or natural); (ii) the obstacle distance from the ski slope; (iii) the type of ski slope (groomed or ungroomed); and, (iv) the ski slope difficulty. In summary, there are no global, unified recommendations on the obstacles requiring padding and on the practices of applying padding.

3.3. Types of padding

Three main categories of padding can be found at ski areas: air padding, standard foam padding (typically between 5 and 30 cm thick)

Table 1
Summary of epidemiological studies related to CWOs.

Study	Country and years studied	Population	Frequency of CWOs (%)	Complementary information
Jenkins et al. [29]	US 1972–1982	Ski area medical offices N = 3536	8.7	
Lystad [30]	Norway 1982–1986	Ski area medical offices N = 883	6.9	
Dorsemaine et al. [3]	France 2014–2019	Ski area medical offices (Med) and Ski patrol rescues (SP) N = 88 351	Med: 3 SP: 1	
Shealy et al. [20]	US 2010–2011	Ski patrol rescues N = 13 145	4.5	
Bailly et al. [21]	France 2013–2015	TBI N = 366	All TBI: 13 M−S TBI[a]: 48	
Ruedl et al. [23]	Austria 2005–2010	Traumatic deaths N = 97	35	CWO: 2nd cause of death
Shealy et al. [22]	US 1991–2005	Traumatic deaths N = 562	≈74	CWO: 1st cause of death

[a] M−S TBI: Moderate or Severe Traumatic Brain Injury (TBI).

and thicker foam padding (often 30 cm thick or more). Air padding and thicker foam padding are only used in ski racing competitions, whereas standard foam padding is used on recreational ski slopes. Padding used for ski racing differs from that used on recreational ski slopes because of the differences in skier characteristics (such as speed and equipment). Ski racing padding is often larger, more difficult to install and remove, and requires more frequent maintenance and adjustment. There are publications on the efficacy of ski racing padding [31,32], but the relationship between the requirements for racing and recreational padding systems is currently unknown. Further work on padding related to both competitive and recreational snowsports could reduce injury likelihood and severity of both. The rest of this white paper focuses on standard foam padding for recreational ski slopes.

There are various pad shapes to match the different obstacles found at ski areas. These pads can usually be categorized as one of two types (Fig. 1):

- **Type A** – flat (cuboid) padding, which is the most common and can be placed on various objects (from small posts to large lift towers or snow barriers). The width of this type of padding is typically between 25 and 400 cm. Its thickness is typically between 5 and 10 cm in North America and between 6 and 30 cm in Europe. Type A padding can also be combined to create padding with a “U” shape or a “V” shape.
- **Type B** – padding with a shape adapted to a specific obstacle. It includes cylindrical, half-cylindrical or square padding. This padding type is mostly used on small posts or on the upper part of snow making equipment. For Type B padding, the obstacles can be up to 30 cm wide (outer diameter), with a padding wall thickness between 2.5 and 5 cm in North America and up to 15 cm in Europe.

Overall, padding is typically thicker in Europe than in North America (for both types of padding).

Ski area padding is typically made of a polymer foam. This foam is either closed- or open-cell with a cover often made of vinyl, polyurethane, or nylon. Closed-cell foam is typically much stiffer than its open-cell counterpart, as air cannot pass between cells during compression induced in impacts. To prevent water or moisture from entering the foam and then freezing, the covers used for open-cell foam pads are either welded (Europe) or stitched (US). Some closed-cell foam pads do not have a cover because the closed cellular structure prevents water from entering the foam. The cellular size and density of foam also varies between pads and manufacturers. Sometimes different foams are layered in one pad (sandwich construction), presumably to enhance overall performance.

3.4. Padding: practices

The following information is based on the experience of the authors and mostly reflects the practices in French and US ski areas, where most padding studies were conducted. Ski area padding is typically attached to obstacles during the winter season and otherwise stored indoors. Some ski areas leave padding in place all year, either to protect from a CWO during summer operations (such as mountain biking) or to avoid handling and storage issues. At many ski areas, padding is checked each morning by ski area safety professionals before the area opens. During this check, they will examine the pad's position on the obstacle and adjust when necessary. For example, the height of the pad may be adjusted based on changes in the snow level. In France, if ski area safety professionals notice that a pad cover is damaged (for example after a contact by a snow groomer or the sharp edge of snowsports equipment), they will make necessary repairs to allow the pad to remain in use. More substantial repairs of cuts or other damage to the covers are typically done at the end of the winter season using three possible solutions: (i) by placing a patch over the damaged region; (ii) by returning the pad to the manufacturer to replace the cover; or, (iii) by replacing the whole pad. These and other patching techniques may also be used by ski areas in other countries.

There are currently neither international standards nor universally agreed guidelines for the use and maintenance of ski area padding. In France and the US, ski patroller training courses may include instruction about how to transport padding, how to install it on obstacles, how to control and store it after the winter season, and on what types of padding are available and should be used [33]. Such training is recent but is becoming more common. There is still a need of complementary guidance regarding the best practices for ski area safety professionals.

3.5. Padding: performance to protect from injuries

As well as enhancing the visibility of obstacles, padding can provide energy attenuation during CWOs. The capabilities and limitations of padding for reducing injury severity has been experimentally investigated with crash testing and computer simulations. Using a partial Hybrid-III anthropomorphic testing device (ATD), a recent study [34]

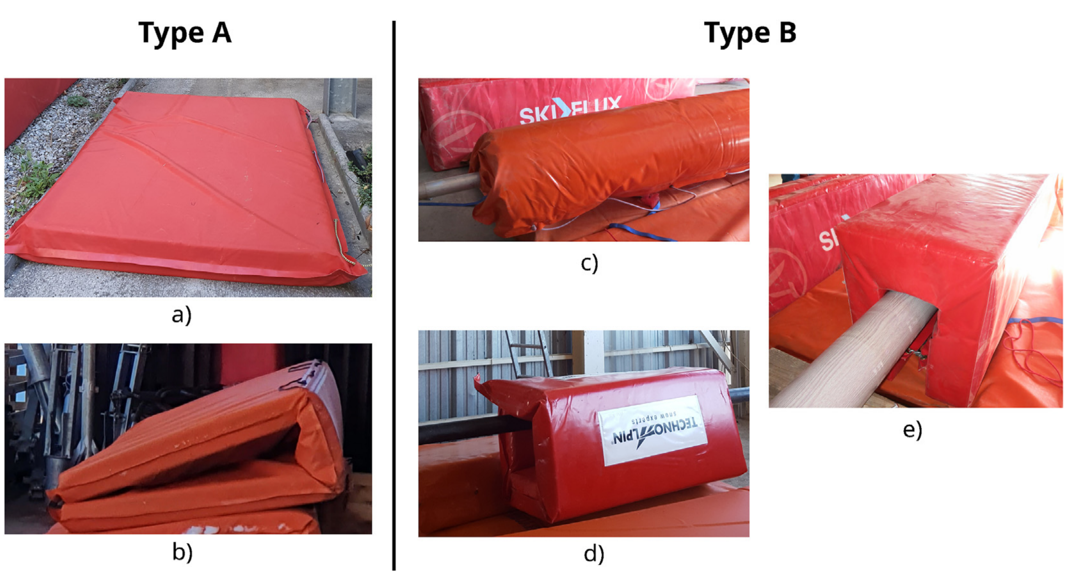

Fig. 1. Left: Type A padding with a) a rectangular shape, and b) a “U” shape, and Right: Type B padding with c) a cylindrical shape, d) a square shape and e) a “U” shape.

examined the effectiveness of ski area padding in reducing the likelihood of head and neck injury during a headfirst CWO. In this testing, the ATD impacted a padded wooden pole at 15 km/h (Fig. 2a). While the padding reduced linear head accelerations and Head Injury Criterion (HIC_{15}) scores below skull fracture and severe TBI thresholds [35], none of the examples tested significantly reduced the rotational head kinematics or the likelihood of severe cervical spine injury.

Multibody computer simulations have been used to model over a thousand scenarios of a skier colliding with an unprotected obstacle under representative CWO conditions (initial skier speeds of 30, 45, and 60 km/h) [36]. The predictions of these simulations underlined the need to protect against both head and trunk injuries, as these body regions often impacted the obstacle at high speed (head: 30 ± 15 km/h, trunk: 24 ± 15 km/h). Based on these numerical results, two experimental studies were performed that included impacts with an EN 960 compliant headform [37] at 25 km/h on flat padding of varying thicknesses (mostly 10, 15, 20 and 30 cm) placed on a solid floor [38,39] (Fig. 2b). When the metallic headform was dropped from 3 m onto a 15 cm thick pad, the peak linear acceleration was 38 ± 3.9 g (mean ± standard deviation) [39]. This peak linear acceleration was three times lower than for similar impacts also performed from 3 m but on hard snow (138 ± 6.2 g) [40] and 27 times lower than when a Hybrid III headform (Humanetics) was dropped from 3 m onto a fixed steel anvil (1043 g) [41]. Padding thickness influenced performance, with 10 cm thick pads, as sometimes used, failing to reduce head accelerations below mild or severe TBI thresholds [39]. Similar head impacts on padding attached to poles more often exhibited foam densification or "bottoming out" (due to more concentrated loading around the pole) and linear accelerations above a mild TBI threshold.

In another study [42], multibody simulations were used to predict the ability of padding to protect against head and thoracic injuries. Over three-thousand simulations of CWOs were modeled with different skier size, initial speed (from 30 to 60 km/h), slope angle, obstacle shape, padding thickness, and distance between the skier and object that initiated the fall (Fig. 2c). These simulations indicated that padding has potential to reduce the risk of severe head injuries, particularly for impact speeds below 29 km/h. However, padding was unable to reduce head accelerations below injury threshold for higher-speed impacts (above 43 km/h). This study also highlighted the protection offered by thicker padding for impact speeds above 29 km/h, as already observed experimentally [34,38,39].

The performance of padding depends on more than just its thickness and the impact speed. The foam material, the impactor (mass and shape), and its positioning on an obstacle also influence the energy attenuation capacities of a pad and the related injury metrics [34,39]. Other parameters, such as the impact location, the outside temperature, its age, or cover type, have not shown significant influence on padding performance [39].

There is limited knowledge of the material property characteristics of the foams used in current padding (e.g., material type or density). This gap in knowledge prevents us from quantifying the influence of the material properties on the effectiveness of the pads and it makes comparisons between those of different manufacturers difficult. It is not possible currently to identify which pads may offer sufficient energy attenuation to reduce injury likelihoods across most reasonable impact conditions. When material property information is available on a manufacturers' catalogue, it is for new, unused padding and does not consider the potential for environmental effects (such as UV exposure or the temperature changes experienced by padding in ski areas). Other parameters are also yet to be considered, such as a cut on the cover or foam (or both), the object geometry under the pad (for example, a ladder on a lift tower that could create stress concentrations), and the surface friction. More work is needed to assess the protective capabilities and limitations of padding and the factors that influence its performance.

3.6. Current standards

The authors are aware of only one ski padding standard: *Pistes de ski—Fabrication des matelas pour dispositif de protection*, 2003, from AFNOR in France [4]. This is a design standard for ski padding covering impact performance, traction resistance of the cover and of the weld, and water absorption. There is no evidence to suggest that the tests in this standard are based on scientific research, particularly peer-reviewed, academic publications. The impact performance tests are conducted at room temperature with the padding laid flat on a solid floor. Two 30 kg impactors are used, a half-sphere with a diameter of 15 cm and a cylinder with a diameter of 20 cm, with respective impact energies of 100 and 440 J (corresponding to striking speeds of 9.3 and 19.5 km/h). Five impacts are performed on the same pad location with each impactor, with the last three from each set used to evaluate maximal accelerations. The main limitations of this standard are:

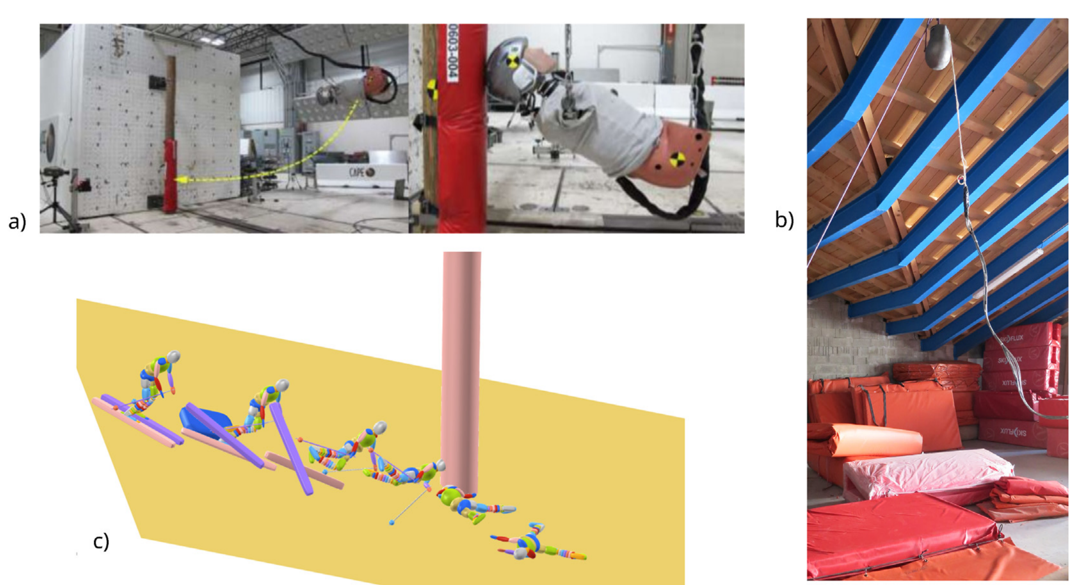

Fig. 2. Experimental tests performed with a) an ATD [34] and b) an isolated headform [39] and c) numerical simulation of a collision with an obstacle covered by a 20 cm thick padding [42].

- The impact conditions are not representative of critical impacts on ski padding, being a head or trunk impact, regarding the impactor mass, shape, and striking speed;
- The repetition of five tests at the same location may create a conditioning (e.g., plastic deformation to the structure of the underlying foam or rupturing cells in closed-cell foams) of the padding that is not representative of the situation on ski areas;
- The potential influence of temperature on padding behavior is not considered;
- Padding is only evaluated when laid flat on the floor with no test on the performances on an obstacle;
- The standard does not favor padding repair (cover replacement).

As such, there is a need for an international standard to provide minimal energy absorption abilities of padding used worldwide to make up for the absence of such specifications. This standard should also address the limitations of the current French standard.

4. Perspectives

The previous section emphasized recent work conducted to better understand the issues related to ski area CWO and padding. It also identified the missing elements related to this topic and the need of further studies to improve safety at ski areas. This section focuses on future work related to CWOs with the goal of improving skiing safety and reducing injury likelihood.

4.1. Prevention of CWOs

The first way to improve safety on slopes is to reduce the number of CWOs. While slope design is part of this process, it is not always possible to keep participants away from obstacles, particularly with changes in snow levels and conditions. Indeed, many participants actively seek to be near obstacles – for example, skiing in the trees and jumping off tree stumps or rocks. To reduce the risk of CWOs, ski areas may consider: (i) marking or making more apparent the presence of an obstacle; (ii) awareness campaigns to highlight that even high-skilled participants can sustain severe injury in a CWO; and, (iii) inform that padding is a last resort that cannot guarantee protection from severe injuries, even at typical skier speeds.

4.2. Evaluation of padding performance

Future studies should focus on improving the understanding of padding performance and the factors that affect it, such as aging, cuts and repairs, the position on large flat obstacles versus small ones (e.g. post), or the variations from different padding manufacturers. For that, the combination of full-scale testing with ATDs, the use of isolated impactors (partial ATDs, headforms, or rigid impactors as for helmet testing), and numerical modeling seem promising. ATD impacts would allow for: (i) impact simulations that represent actual accident conditions; (ii) consideration of multiple body impacts; and, (iii) data that can be used to determine injury risks. They could also fill the missing experimental data on the kinematics of CWOs and provide additional validation data for numerical models. Impact testing with isolated impactors is simpler, more accessible (for wide laboratory testing), can be more repeatable, favoring the analysis of padding behavior and performance. Future studies should evaluate the ability of padding to reduce head, neck, thoracic and spine injury risks.

There is a need of an international standard for ski area padding covering three main aspects: the impact energy attenuation capacities of padding, its waterproofness, and the cover resistance (when present). This standard should target the critical points of CWOs, being head and trunk injuries. For that, it is essential to not only have representative impact energies, but also representative impacting mass, size, and speed to consider the padding viscoelastic behavior. It should also evaluate padding in representative cold temperature and its performance when positioned on various obstacles, representative of its intended use. Relevant publications on TBI, helmets and other safety devices could inform the development of such an international standard. In response to ecological and recycling issues, an innovative aspect could be to facilitate padding repairs (described in section 4.4).

Providing the specifications for additional padding characteristics (e.g., padding design, foam material, foam density, and type of cells) by manufacturers would also be beneficial to objectively compare between products, manufacturers, and studies. It would also help to further develop fundamental knowledge on how padding can prevent injuries. In summary, there is a need for an international standard on recreational ski area padding and for additional scientific studies to better understand padding performance to protect from injuries and the parameters affecting this protection.

4.3. Technological evolutions

Given the research on foams used in body padding and helmets, we can also imagine future research on foam technologies for ski area padding. Such studies could focus on the choice of material, density, and cellular structure to improve the performance of padding to reduce the injury likelihood.

A disruptive technology that offers potential to improve safety is auxetic (negative Poisson's ratio) materials. Auxetic open-cell foams have been proposed for padding [43,44] and have potential to improve the impact energy attenuation. More recent work has presented simple methods for making auxetic closed-cell foam [45–48] that could also bring benefits to ski area padding. Unfortunately, these auxetic materials and methods have not been thoroughly tested and implemented for padding application. A current barrier for using auxetic foams in ski area padding is the difficulty in producing it in sufficiently large dimensions.

Additively manufactured materials with specifically designed architectural structures have also been proposed for impact protection applications [44,49]. Mass producing such structured metamaterials in the required size for padding, such as via additive manufacturing or molding, would be more challenging than the established method of using foam. In the future, these new materials could be researched further and their commercial production advanced to improve the energy attenuation capabilities of ski area padding.

Another area for future development is the use of recyclable and recycled material for both the cover and foam to reduce environmental costs. This would require consideration of the entire life cycle of the padding, from its design to end-of-life recycling. The use of materials with small environmental impact should also be encouraged.

Padding is not just foam in many cases. Future studies should investigate the coupling between the foam, the cover, and the air trapped inside to optimize energy dissipation when pads are placed on both large and small obstacles. The adjustment of the padding on the obstacle is another key point for future research to optimize its performance, especially for obstacles with prominent edges such as a lift tower ladder or snow making equipment. A potential evolution could also come from ski racing, where padding is placed uphill of the obstacle (but without contact) rather than in direct contact with the obstacle. This position leaves residual space between the fully compressed padding and the obstacle. Another alternative could be to combine the use of padding on an obstacle with another uphill device (e.g. another pad or fence) to deflect the skier away from the obstacle. New designs and solutions to the CWO problem should be investigated in future studies.

4.4. Padding use

Related to the development of an international standard for ski area padding, it is essential to define best practices for ski area safety professionals. Such practices could form the basis of a universally agreed upon guideline document for ski area padding. This document could include information on:

- The choice of whether to protect an obstacle regarding the slope environment and define what obstacles fall under the responsibility of the ski area. For example, whether padding is needed for obstacles on or near the ski slopes (groomed, ungroomed), off-piste, between slopes, etc. The next step would include definitions of which obstacles should be protected and how (removed, marked, padded);
- The type of padding or performance suggested based on specific engineering principles. This section of the guidance document could refer to the (proposed) international standard for ski area padding to ensure only certified padding is used and that the padding is used in the manner for which it was certified;
- The proper padding position regarding the snow level, the skier trajectories, the adapted tightening, etc., with a discussion of how environmental conditions (e.g., fast, heavy snowfall) could affect ski area padding adjustments;
- The controls that should be done during the winter seasons;
- The management of padding, regarding repairs and replacement (due to aging or damage). In particular, encouraging ski areas to repair padding without performance reduction would be interesting for both economic and ecological reasons. If a pad needs to be replaced, foam and cover recycling should be promoted;
- The implementation of a traceability system of padding associated with a unique identification of each pad to improve padding management (repair, replacement, performance follow-up);
- The steps to take following an incident, to prevent recurrence.

Working groups composed of researchers and ski safety professionals are currently trying to identify the best practices for padding.

5. Conclusion

This white paper provides an overview of CWOs at ski areas and the ski area padding used, including the epidemiologic characterization of CWOs, studies examining padding performance, and ski area safety professional practices. Much remains to be done to improve ski area safety regarding padding issues. In particular, future research should focus on:

- Improving the understanding of parameters influence on padding performance such as pad aging, damage (cut), repairs (cover replacement), temperature influence and the coupling between the foam, the cover, and the air;
- Evaluating padding performance, specifically the capabilities of padding to protect from head, neck, trunk, and spine from injury when placed on different obstacles, including some with prominent edges;
- Evaluating the protection potential achieved by padding placed uphill of an obstacle, but without contacting the obstacle;
- Improving the energy attenuation capacity of padding using new foam and material technologies.

Based to the current work on ski area padding, the next step should be the promotion of an international standard for ski area padding design including requirements on:

- Impact performance evaluated in representative conditions of CWOs and focusing on protecting from head and trunk injuries;
- Padding waterproofness, to prevent water from entering the foam and freezing
- Permissible colors and requirements for carrying handles

Finally, a universally agreed guidance document should be defined for ski areas to help them on padding management regarding:

- The decision to place a pad on an obstacle and the choice of the appropriate type of padding;
- The proper position of the padding;
- The controls that should be done during the winter season;
- The general management of padding: repairs, replacement, storage, etc.

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Declaration of competing interest

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References

[1] Burtscher M, Federolf PA, Nachbauer W, Kopp M. Potential health benefits from downhill skiing. Front Physiol 2019;9:1924. https://doi.org/10.3389/fphys.2018.01924.
[2] Mueller E, Gimpl M, Kirchner S, Kroell J, Jahnel R, Niebauer J, et al. Salzburg Skiing for the Elderly Study: influence of alpine skiing on aerobic capacity, strength, power, and balance. Scand J Med Sci Sports 2011;21:9–22. https://doi.org/10.1111/j.1600-0838.2011.01337.x.
[3] Dorsemaine M, Masson C, Laporte J-D, Jacot C, Martin J-L, Riveill S, et al. Collisions against obstacles in winter sport ski area. Wilderness Environ Med 2022;34:7–14. https://doi.org/10.1016/j.wem.2022.09.002.
[4] AFNOR. Pistes de ski - Fabrication des matelas pour dispositif de protection. 2003.
[5] Advertski. Protective Mattresses 2020. http://advertski.com/protective-mattresses/. [Accessed 27 March 2020].
[6] Alpina Sicherheitssysteme GmbH. Alpina Winterkatalog 2020:17. 2019-2020, https://epaper.digitri.com/15705330025882.dv#/1 [Accessed 27 March 2020].
[7] Alticoncept Equipement. Catalogue Alticoncept 2019:32–4. http://www.alticoncept-equipement.com/.
[8] Altitudes. Catalogue 2018:12–3. 2018-2019.
[9] Apple Athletic. Skiing. Apple Athletic 2020. https://appleathletic.com/products/skiing. [Accessed 27 March 2020].
[10] Eurogripp. Products. Eurogripp 2020. http://eurogripp.com/prodotti_ing.html. [Accessed 27 March 2020].
[11] FallLine. Pads. FallLine 2020. https://www.fallline.com/ski-industry/pads/. [Accessed 27 March 2020].
[12] Inter-Mtn. Winter Catalogue 2019 2020. http://www.inter-mtn.com/pdf/WinterNP/Catalogue.html#p=1. [Accessed 26 March 2020].
[13] Liski. FOAM RUBBER MATTRESSES 2020. https://www.liski.it/en/categorie_prodotto/foam-rubber-mattresses/. [Accessed 26 March 2020].
[14] MBS. Catalogue safety - racing - Fun. 2019-2020 2019.
[15] Fahrzeubau Meingast. Collision protection padding. Meingast Fahrzeugbau 2020. http://www.meingast.at/en/winter-service/collision%20protection%20padding. [Accessed 27 March 2020].
[16] Moore Manufactoring. Tower and Post Pads 2020. http://www.mooremfg.com/tower_and_post_pads.htm. [Accessed 27 March 2020].
[17] Securisport. Protection equipments. SÉCURI-SPORT 2020. https://www.securisport.com/en/protection-equipments. [Accessed 27 March 2020].
[18] Tube Pro. Winter catalogue. 2018. 2018.
[19] TYYNY. Catalogue Mountain. 2020.
[20] Shealy JE, Ettlinger C, Scher I, Johnson R. 2010/2011 NSAA 10-year interval injury study. In: Johnson RJ, Shealy JE, Greenwald RM, editors. Skiing trauma and safety: 20th volume. West Conshohocken, PA: ASTM International; 2014. p. 1–19. https://doi.org/10.1520/STP158220140002.
[21] Bailly N, Afquir S, Laporte J-D, Melot A, Savary D, Seigneuret E, et al. Analysis of injury mechanisms in head injuries in skiers and snowboarders. Med Sci Sports Exerc 2017;49:1–10. https://doi.org/10.1249/MSS.0000000000001078.
[22] Shealy JE, Johnson R, Ettlinger C. On piste fatalities in recreational snow sports in the U.S. In: Johnson R, Shealy J, Yamagishi T, editors. Skiing trauma and safety: sixteenth volume. West Conshohocken, PA: ASTM International; 2006. p. 27–34. https://doi.org/10.1520/STP39643S.
[23] Ruedl G, Bilek H, Ebner H, Gabl K, Kopp M, Burtscher M. Fatalities on Austrian ski slopes during a 5-year period. Wilderness Environ Med 2011;22:326–8. https://doi.org/10.1016/j.wem.2011.06.008.
[24] Bailly N, Abouchiche S, Masson C, Donnadieu T, Arnoux P-J. Recorded speed on alpine slopes: how to interpret Skier's perception of their speed? In: Scher IS, Greenwald RM, Petrone N, editors. Snow sports trauma and safety. Springer International Publishing; 2017. p. 163–74.

[25] Ruedl G, Brunner F, Woldrich T, Faulhaber M, Kopp M, Nachbauer W, et al. Factors associated with the ability to estimate actual speeds in recreational alpine skiers. Wilderness Environ Med 2013;24:118–23. https://doi.org/10.1016/j.wem.2012.11.021.
[26] Ruedl G, Abart M, Ledochowski L, Burtscher M, Kopp M. Self reported risk taking and risk compensation in skiers and snowboarders are associated with sensation seeking. Accid Anal Prev 2012;48:292–6. https://doi.org/10.1016/j.aap.2012.01.031.
[27] Ruedl G, Burtscher M, Wolf M, Ledochowski L, Bauer R, Benedetto K-P, et al. Are self-reported risk-taking behavior and helmet use associated with injury causes among skiers and snowboarders? Scand J Med Sci Sports 2015;25:125–30. https://doi.org/10.1111/sms.12139.
[28] Stepan L. Skier and snowboarder speeds at US ski areas. J Sci Med Sport Plus submitted ISSS volume.
[29] Jenkins R, Johnson RJ, Pope MH. Collision injuries in downhill skiing. In: Johnson R, Mote C, editors. Skiing trauma and safety: fifth international symposium. West Conshohocken, PA: ASTM International; 1985. p. 358–66. https://doi.org/10.1520/STP46651S.
[30] Lystad H. Collision injuries in alpine skiing. In: Johnson R, Mote C, Binet M-H, editors. Skiing trauma and safety: seventh international symposium. West Conshohocken, PA: ASTM International; 1989. p. 69–74. https://doi.org/10.1520/STP19455S.
[31] Petrone N. The effect of impact speed, construction, and layout of different ski safety barriers on peak decelerations and penetration values of a solid dummy during full scale impacts. In: Johnson RJ, Shealy JE, Greenwald RM, Scher IS, editors. Skiing trauma and safety, 19. West Conshohocken: Astm International; 2012. p. 153–70. 1553.
[32] Petrone N, Ceolin F, Morandin T. Full scale impact testing of ski safety barriers using an instrumented anthropomorphic dummy. In: Sabo A, Kafka P, Litzenberger S, Sabo C, editors. Engineering of sport 8: engineering emotion - 8th conference of the. International sports engineering association (isea), 2. Amsterdam: Elsevier Science Bv; 2010. p. 2593–8.
[33] Domaines Skiables de France. Pisteur-Secouriste 1er degré. Support pédagogique à l'usage des candidats à l'examen BREVET NATIONAL PISTEUR-SECOURISTE 1er DEGRÉ. 2018.
[34] Scher IS, Stepan L, Shealy JE, Hoover RW. Examining ski area padding for head and neck injury mitigation. J Sci Med Sport 2021;24:1010–4. https://doi.org/10.1016/j.jsams.2020.04.019.
[35] Mertz H, Irwin A, Prasad P. Biomechanical and scaling bases for frontal and side impact injury assessment reference values. Stapp Car Crash Journal 2003;47:155–88.
[36] Dorsemaine M, Llari M, Riveill S, Laporte J-D, Jacot C, Masson C, et al. Collisions against obstacles while skiing: typology of victims and impact conditions. Sci Sports 2023. https://doi.org/10.1016/j.scispo.2022.07.010.
[37] AFNOR. Fausses têtes à utiliser lors des essais de casques de protection. 2006.
[38] Dorsemaine M, Bailly N, Riveill S, Faucheur T, Perretier C, Masson C, et al. About some factors influencing safety mattress performances in head impact collisions: a pilot study. J Sci Med Sport 2021;24:1067–107. https://doi.org/10.1016/j.jsams.2021.02.015.
[39] Dorsemaine M, Masson C, Riveill S, Arnoux P-J. Mattress performances according to impact conditions and cycle of use. J Sci Med Sport Plus Accepted. In Press.
[40] Bailly N, Llari M, Donnadieu T, Masson C, Arnoux PJ. Head impact in a snowboarding accident. Scand J Med Sci Sports 2017;27:964–74. https://doi.org/10.1111/sms.12699.
[41] Cripton PA, Dressler DM, Stuart CA, Dennison CR, Richards D. Bicycle helmets are highly effective at preventing head injury during head impact: head-form accelerations and injury criteria for helmeted and unhelmeted impacts. Accid Anal Prev 2014;70:1–7. https://doi.org/10.1016/j.aap.2014.02.016.
[42] Dorsemaine M. Enjeux de sécurité des matelas de protection dans nos stations de ski. Aix-Marseille Université; 2022.
[43] Allen T, Duncan O, Foster L, Senior T, Zampieri D, Edeh V, et al. Auxetic foam for snow-sport safety devices. In: Scher IS, Greenwald RM, Petrone N, editors. Snow sports trauma and safety. Cham: Springer International Publishing; 2017. p. 145–59. https://doi.org/10.1007/978-3-319-52755-0_12.
[44] Duncan O, Shepherd T, Moroney C, Foster L, Venkatraman PD, Winwood K, et al. Review of auxetic materials for sports applications: expanding options in comfort and protection. Appl Sci-Basel 2018;8:941. https://doi.org/10.3390/app8060941.
[45] Duncan O, Alderson A, Allen T. Fabrication, characterisation and analytical modelling of gradient auxetic closed cell foam. Smart Mater Struct 2021. https://doi.org/10.1088/1361-665X/abdc06.
[46] Duncan O, Leslie G, Moyle S, Sawtell D, Allen T. Developments on auxetic closed cell foam pressure vessel fabrications. Smart Mater Struct 2022;31:074002. https://doi.org/10.1088/1361-665X/ac6ea2.
[47] Fan D, Li M, Qiu J, Xing. H, Jiang Z, Tang T. A novel method for preparing auxetic foam from closed-cell polymer foam based on steam penetration and condensation (SPC) process. ACS Appl Mater Interfaces 2018;10. https://doi.org/10.1021/acsami.8b02332.
[48] Fan D, Shi Z, Li N, Qiu J, Xing H, Jiang Z, et al. Novel method for preparing a high-performance auxetic foam directly from polymer resin by a one-pot CO2 foaming process. ACS Appl Mater Interfaces 2020;12:48040–8. https://doi.org/10.1021/acsami.0c15383.
[49] Shepherd T, Winwood K, Venkatraman P, Alderson A, Allen T. Validation of a finite element modeling process for auxetic structures under impact. Phys Status Solidi B-Basic Solid State Phys 2020;257:1900197. https://doi.org/10.1002/pssb.201900197.