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SYSTEMATIC REVIEW

Recreational Snow-Sports Injury Risk Factors and Countermeasures: A Meta-Analysis Review and Haddon Matrix Evaluation

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Abstract
Background Snow sports (alpine skiing/snowboarding) would benefit from easily implemented and cost-effective injury prevention countermeasures that are effective in reducing injury rate and severity.
Objective For snow sports, to identify risk factors and to quantify evidence for effectiveness of injury prevention countermeasures.
Methods Searches of electronic literature databases to February 2014 identified 98 articles focused on snow sports that met the inclusion criteria and were subsequently reviewed. Pooled odds ratios (ORs) with 90 % confidence intervals (CIs) and inferences (percentage likelihood of benefit/harm) were calculated using data from 55 studies using a spreadsheet for combining independent groups with a weighting factor based on quality rating scores for effects.
Results More experienced skiers and snowboarders are more likely to sustain an injury as a result of jumps, while beginners sustain injuries primarily as a result of falls. Key risk factors that countermeasure interventions should focus on include, beginner skiers (OR 2.72; 90 % CI 2.15–3.44, 99 % most likely harmful), beginner snowboarders (OR 2.66; 90 % CI 2.08–3.40, 99 % harmful), skiers/snowboarders who rent snow equipment (OR 2.58; 90 % CI 1.98–3.37, 99 % harmful) and poor visibility due to inclement weather (OR 2.69; 90 % CI 1.43–5.07, 97 % harmful). Effective countermeasures include helmets for skiers/snowboarders to prevent head injuries (OR 0.58; 90 % CI 0.51–0.66, 99 % most likely beneficial), and wrist guards for snowboarders to prevent wrist injuries (OR 0.33; 90 % CI 0.23–0.47, 99 % beneficial).
Discussion The review identified key risk factors for snow-sport injuries and evaluated the evidence for the effectiveness of existing injury prevention countermeasures in recreational (general public use of slopes, not racing) snow sports using a Haddon's matrix conceptual framework for injury causation (host/snow-sport participant, agent/mechanism and environment/community).
Conclusion Best evidence for the effectiveness of injury prevention countermeasures in recreational snow sports was for the use of helmets and wrist guards and to address low visibility issues via weather reports and signage.

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1 Introduction

Snow sports are a popular recreational activity; however, the incidence of injury can be high for both skiers and snowboarders [1, 2]. Targeted injury prevention countermeasures have the potential to help reduce the incidence and severity of recreational snow-sports injuries if they are based on an understanding of injury mechanisms and associated risk factors. Most research still focuses on the incidence and causes/mechanics of injuries rather than implementing preventive measures. Injuries result from a set of circumstances and pre-existing conditions that can be considered using Haddon's matrix [3], which provides a conceptual framework for injury causation. The temporal components of pre-event (primary injury prevention), event (secondary injury prevention) and post-event (tertiary injury prevention) phases were considered against human, agent and environmental factors. When considering recreational snow-sport injuries, the key question is "where will injury prevention interventions be most effective within this matrix"? In selecting injury prevention countermeasures there needs to be identification of the key problem hazards and resulting injuries; consideration of design change that ideally will not result in individuals having to take action each time the countermeasure is used; ensuring the countermeasure is accepted for use by the participants; ensuring there is a positive cost to benefit ratio; no unwanted side effects or misuse of the countermeasure; and the effects of the countermeasure can be measured. The effectiveness of common injury prevention countermeasures such as education and behaviour change programmes, environmental/equipment design changes, and regulation/legislation changes need to be evaluated.

2 Objective

This review aimed to identify key risk factors and evaluated the evidence for the effectiveness of injury prevention countermeasures in recreational snow sports using a Haddon's matrix [3] conceptual framework for injury causation (host/snow-sport participant, agent/mechanism and environment/community).

3 Methods

3.1 Literature Search Methodology

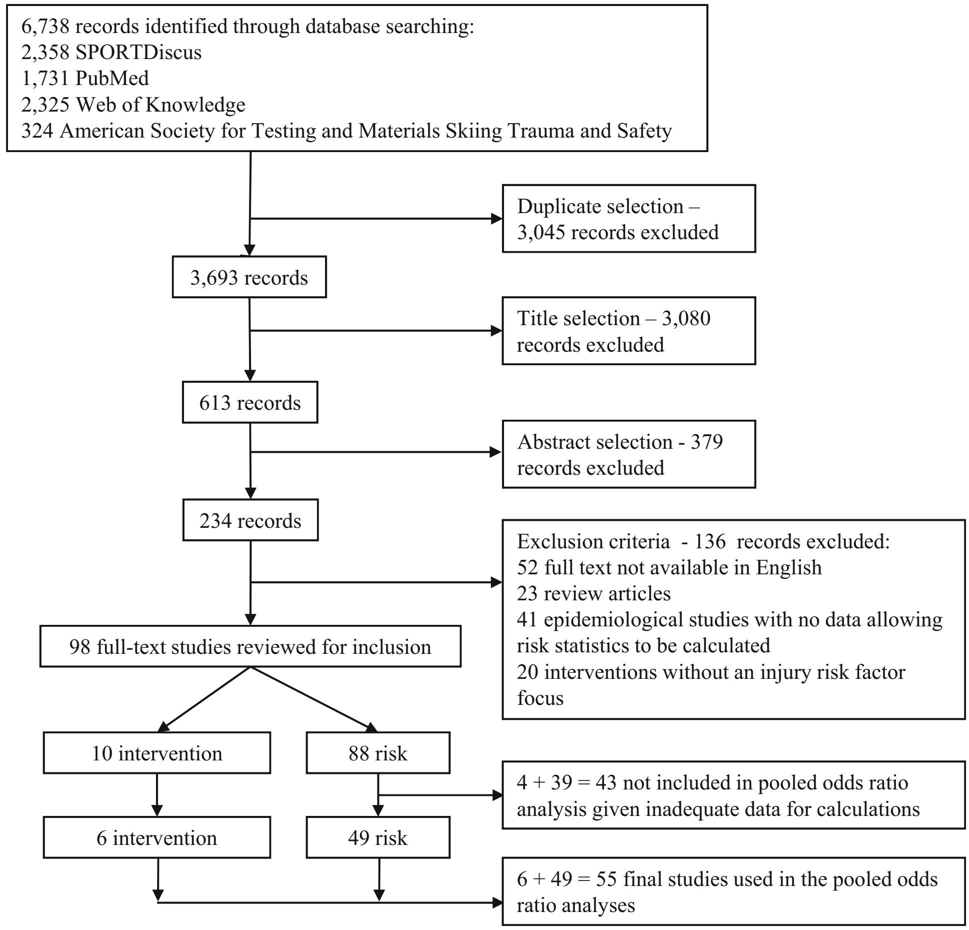
Cochrane Collaboration [4] review methodology (literature search, assessment of study quality, data collection of study characteristics, analysis and interpretation of results, recommendations for practice and further research) was used to evaluate the injury risk factors and effectiveness of injury prevention countermeasures in snow sports.

3.2 Search Parameters and Criteria

A search of the literature was conducted for snow-sport risk factors and mechanisms. The PubMed, CINAHL, Web of Science and SPORTDiscus databases, to February 2014, were searched for terms linked with the Boolean operators ('AND', 'OR', 'NOT'): 'ski*', 'snowboard*', 'injur*', 'risk', 'prevention'. Injury and prevention studies prior to the 1990s were considered relevant today as we learn from our historical approaches. However, due to changes in technology, some interventions surrounding equipment (bindings, braces, helmets) would hopefully have better effects the more recent the study. Given the limited number of studies for any risk factor, an inclusive approach was taken for the year of publication. Papers were selected based on title, then abstract and finally text. Manual searching of reference lists and the 'Cited by' tool on Google Scholar were used to identify additional articles. From volumes 6–19 of *Skiing Trauma and Safety* available for review, 324 articles were reviewed. These volumes from the American Society for Testing Materials (ASTM) series of conference proceedings articles were reviewed, given this is a specific conference series containing full papers focused on snow injury issues. Papers were excluded if their content (1) was unavailable in English; (2) was unavailable in full-text format; and (3) did not provide additional information for any of the identified sections and subsections of this review. Inclusion criteria for all articles were (1) reported data for risk factors on snow-sport injury rate or severity; or (2) reported data for interventions to reduce snow-sport injury. For subsequent analysis, exclusion criteria were (1) did not provide odds ratios (OR) or risk ratios (RRs) and/or other statistics allowing assessment of the effect factors on injury (or data to enable their calculation, e.g. cohort studies using only absolute and not relative injury rates); (2) data reported solely for other forms of snow sports, e.g. telemarking, Nordic skiing, ski boarding; (3) data reported only death rather than injury rate; and (4) data only compared injury risk between alpine skiing and snowboarding. In summary, articles were excluded if they were epidemiological studies with no injury risk focus, provided no data allowing risk statistics to be calculated, or were intervention studies without an injury risk factor focus or did not provide enough data for the OR analyses (Fig. 1 shows the flow of information through the systematic review).

A total of 6738 papers were identified, of which 3045 were duplicates. After selection for inclusion criteria and elimination based on exclusion criteria, 98 papers were left for inclusion into the final review (Fig. 1). Of the resulting 98 journal articles, 10 intervention studies (outlined in Table 1) and 88 papers [outlined in Table S1 of the electronic supplementary material (ESM)] detailing injury risk factors were reviewed, with six of the intervention studies and 49 of the other studies summarised for the pooled OR analyses. Although only the aforementioned papers were tabulated and used for pooled OR analyses, additional

Fig. 1 Flow of information through the systematic review



papers were kept and used for supporting evidence. For example, 23 snow-sport literature reviews were identified via online searching focusing on topics including helmet use [5], wrist-guard use [6], ski bindings [7], and alpine ski strength and conditioning [8]. Other groups of relevant articles included helmet use intervention or analysis [9–13] and injury mechanism analysis [14–16].

3.3 Assessment of Study Quality

Methodological quality evaluation is usually quantified using scales such as Delphi [17] or PEDro [18]; however, many of the criteria were not relevant in the current review. For example, none of the included studies in this review would meet 6/11 criteria of the Pedro Scale: (2) random allocation; (3) concealed allocation; (5) subject blinding; (6) therapist blinding; (7) assessor blinding; and (9) intention-to-treat analysis. Given the studies included would receive poor methodological scores as a reflection of a poor choice in quality scale rather than in the study design, two authors from the current study independently assessed each article using a 6-item custom methodological quality assessment scale, where 0 = clearly no and 1 = clearly yes. The six items included (1) study design (0 = prospective cohort or cross-sectional study, 1 = case control—randomised); (2) study samples (0 = no control or control not greater than 4:1, 1 = adequate); (3) participant characteristics (0 = not given, 1 = sex and age reported); (4) sport details (0 = not detailed, 1 = detailed); (5) outcome variables (0 = not appropriately defined or reported, 1 = appropriate and tabulated); and (6) statistical analyses included adjusted OR and/or RR adjusted for covariates (0 = no, 1 = yes). Covariates included age, sex, type of skier, weather condition, and self-reported experience level. The quality scores based on the paper selection criteria ranged from 1 to 6, and are shown in curved brackets in Table 1.

3.4 Data Extraction

For studies passing the quality criteria, data were extracted, including study name, snow-sport type, aim/focus, study design, participants' characteristics, methodological quality, interventions, outcome measures and injury risk factor statistics results (Table 1 shows the ten intervention studies [19–28], and Table S1 in the ESM shows 88 injury risk

Table 1 Intervention studies ($n = 10$) that aimed to reduce snow-sport injury

References	Design, focus (quality rating)	Participant characteristics. Injury recording	Intervention detail	Injury reduction	Critique and recommendations for further interventions
Jorgensen et al. [23]	Prospective, randomised control, ski, educational bus video (5)	Recreational skiers, 243 video exposures, 520 controls. 1-week post-video exposure, self-reported injury. Total 8 ski days	Randomly selected buses screened educational video in the afternoon or evening of 18- to 24-h bus trips to ski resorts in the alps (for week-long skiing trip). Focus: how to get started in downhill skiing and injury prevention advice, including binding test and adjustment. Questionnaire 1 week post-intervention included control questions for key messages of the video	Intervention vs. control. Overall injury rate 16 vs. 23 %; RR 0.70; 95 % CI 0.39–1.22; $p < 0.05$. Injuries caused by falls 12.6 vs. 16.2 %; RR 0.78; 95 % CI 0.40–1.52; $p < 0.05$. Injuries caused by collision 6 vs. 12 %; RR 0.50; 95 % CI 0.20–1.23; $p < 0.05$. Beginner injury rate 5 vs. 44 %; RR 0.11; 95 % CI 0.05–0.26; $p = 0.002$. Experienced injury rate 17 vs. 21 %; RR 0.80; 95 % CI 0.45–1.43; $p = 0.30$	Bus video education resulted in less injuries, less collisions, less falls. Those less experienced benefited more from the video. Develop an educational video, and collaborate with tour companies to show the video on buses
Ettlinger et al. [21]	Prospective, randomised control, ski, video education programme for knee sprains (4)	Ski area, on-slope staff, 25 ski-area interventions (5 lost to follow-up), 22 ski-area controls. 2 years pre-intervention, 1 year post-intervention	1-h workshops for on-slope staff, injury mechanism video, guided discovery, develop risk profiles for knee injuries. Focus: avoiding high-risk behaviour, recognising potential dangerous situations, responding to such situations	Average normalised ACL sprains by educated staff, expected vs. actual: 26.6 vs. 10.6 (60 % decrease); $p < 0.005$. Control, expected vs. actual: 22 vs. 29	Guided discovery with video of near-injury and injury events significantly reduced the number of ACL injuries among on-slope staff (experienced skiers). Learn to identify and respond to potential injury events
Cusimano et al. [28]	Prospective, randomised control, ski and snowboard, video education programme (3)	11- to 12-year-old students ($n = 35$ intervention, $n = 34$ control). 4 school-supervised ski days	30-min teaching session with 20-min video 'A Little Respect: Think First!' and brochure (control = 30-min question and answer session about snow sports). Pre- and post-test assessing knowledge, behaviour and attitudes around snow-sport safety	Teaching group vs. control group: injury total (over 4 days) 2 (14.3/1000 ski days) vs. 4 (29.4 injuries/1000 ski days); RR 0.49; 95 % CI 0.04–3.39. All injuries minor	No clear effect. Education programme may reduce injuries. Video teaching session improved test scores
Danielsson et al. [19]	Pre-test, post-test, ski, binding adjustment, media campaign (3)	Swedish ski slopes. 1 season pre-intervention, 8 seasons post-intervention	Media campaign focus: importance of correct binding adjustment, offering free binding checks, retailers to use testing devices	From 1974/1975 season to 1981/1982 season, campaign estimated to decrease injuries by 4 %. 1974/1975 season, 12 % decrease in lower limb and 3 % decrease in upper-body injuries. Dropped ~20 % over 8 years, as did binding checking	Tendency to decrease injury risk initially following media campaign. Effectiveness declined with time. Indirect injury risk analysis method, results should be interpreted with caution

Table 1 continued

References	Design, focus (quality rating)	Participant characteristics. Injury recording	Intervention detail	Injury reduction	Critique and recommendations for further interventions
Ytterstad [22]	Prospective pre-post analysis, ski, education (3)	Harstad, Norway residents (n = 22,660). 5 years pre-intervention, 3 years post-intervention	Free texts (victims' stories), post-intervention injury data and recommendations for targeted intervention: promoting helmet use and binding/boot fitting; preventing collision injuries; preventing ski-lift injuries, sent to local resort with only downhill ski slopes	5-year baseline vs. 3-year intervention. Incidence/1000 person years: downhill skiing injury (exposure adjusted) 16.1 vs. 10.6, 0.85, CRR 95 % CI 0.66–1.10; p = 0.24. Downhill skiing hospital admittance 2.8 vs. 1.0	Free text handouts to ski club members can reduce injuries. Develop a ski club information handout system to promote key injury prevention messages
Laporte et al. [26]	Pre- and post-analysis, ski, simplification and media dissemination of binding international safety standards (2)	Four ski departments (North Alps, Haute Savoie, Savoie and Isere) for ACL risk assessment. 18 French skiing resort control groups (1597 skiers) and 204 equipment renters for measuring the impact of the campaign. One season post-intervention	30-s TV broadcast over 3 weeks on six French channels, and leaflet distribution. Focus: regular binding adjustment, ski renters fitting bindings. Ski renters were provided with written information. Focus: familiarise and abide by new regulations	ACL injuries risk incidence (MDBI): pre-2000 vs. post-2001, 3000 vs. 3314; $p < 0.05$. Overall injuries risk incidence (MDBI): pre-2000 vs. post-2001, 377 vs. 401; $p > 0.05$	Only a small decrease in injuries. Impossible to assess effectiveness of campaign
Hauser [20]	Prospective, randomised control, ski, binding adjustment and ski-pole design (4)	Recreational skiers, 460 bindings checked and adjusted, 143 bow ski poles (subgroup), 690 controls	Media recruitment, randomised. Bindings of the experimental group were checked and errors were assumed to correspond with the control group. Errors corrected prior to the ski season. Bow ski poles designed to protect the thumb from skiers thumb	Bindings intervention, all injuries RR 0.72; 95 % CI 0.42–1.23. Number of injuries, none: 1.09 (1.03–1.16); 1: 0.68 (0.52–0.89); 2: 1.64 (0.94–2.86); 3: 5.63 (1.98–16.06) >4: Ski pole intervention, skier's thumb 0.70 (0.17–2.80)	Well-informed binding adjustment showed a likely moderate effect at reducing overall injury rate. All should be encouraged to test their bindings regularly. Bow ski-pole design showed a possibly moderate effect to reduce 'skier's thumb'. Further research with a larger sample size is needed
Machold et al. [25]	Prospective, randomised control, snowboard, custom-designed wrist protector (5)	Austrian school children during school ski days, 342 protector, 379 control. Protected, 2483 half-days snowboarding; control, 3048 half-days snowboarding	Austrian students randomised to wear a custom-designed wrist protector or control (no protector or alternative design). Only moderate or severe injuries (fractures) were assessed. Intention-to-treat analysis to account for students who discarded protectors	C HR (95 % CI), severe injury of the wrist: wrist protector 0.13 (0.02–1.04), p = 0.054; experience 0.83 (0.70–0.99), p = 0.036; all severe injuries: wrist protector 0.23 (0.05–1.07). p = 0.061; experience 0.81 (0.68–0.96) p = 0.014	The specific wrist protector design used showed significant protective effect, although comfort and design with respect to retention needs to be considered

Table 1 continued

References	Design, focus (quality rating)	Participant characteristics. Injury recording	Intervention detail	Injury reduction	Critique and recommendations for further interventions
Ronning et al. [24]	Prospective, randomised control, snowboard, custom wrist protector (5)	Recreational snowboarders >9 years, protector 2515, control 2514 recreational. Single ski day	Demonstration of wrist brace prior to recruitment. D-ring wrist brace (Smith & Nephew, Nesbru, Norway). Block randomisation to keep number of control and protected at pistes even. No prior injury. Participation on multiple days possible—each observation considered independently. Intention-to-treat analysis	Wrist brace vs. control: wrist injuries 0.32 vs. 1.15 %, $p = 0.001$; C RR (95 % CI) 0.28 (0.13–0.59); all injuries 33 % vs. 51 % C RR, $p = 0.05$	Wearing braces decreased the risk of wrist injuries. Promote the purchase of wrist guards, and hiring of wrist guards, or sponsor wrist-guard free use
Slaney and Weinstein [27]	Pre-post analysis, snowboard, compulsory wrist-guard policy (2)	Secondary school students (12–16 years) in single-school snow-sport programme. 315 pre-policy (4 years), 267 post-policy (3 years)	Single school with a 10-day snow-sport programme. Introduced compulsory wrist-guard policy	Post-policy vs. pre-policy wrist fracture: 0.95 vs. 0.37 %, $p = 0.38$; C RR (95 % CI) 0.39 (0.06–2.73)	Compulsory wrist-brace-wearing policy showed a possible large effect on reducing wrist fractures. However, the efficacy of implementing such policies outside of a school environment is unknown

C crude, *HR* hazard ratio, *RR* risk ratio, *ACL* anterior cruciate ligament, *MDBI* mean days between injuries, *CI* confidence interval, *CRR* crude risk ratio

factor studies used in the review—noting that only six of the intervention studies and only 49 of the injury risk factor studies had sufficient data to be included in the pooled OR analyses). There was a large range in sample size, injury risk factors investigated, definition of injury risk factor categories (e.g. such as types of slope conditions of hard and icy, soft and powdery, or slushy) and injury risk factor statistics (e.g. RRs, ORs, Pearson correlations) utilised throughout the risk factor studies. For example, skiing ability was assessed using readiness for risk and speed measured using a self-reported visual analogue scale (1 for minimum speed or minimum risk, and 10 for maximum speed or risk) [29] or by participant self-reported categorical ability (beginner–intermediate, intermediate, intermediate–expert) [30]. This large variation in definition of outcomes and factors between studies made combined analysis difficult for some risk factors. For example, head injury was defined as serious (e.g. severe traumatic brain injury with intracranial bleeding with edema) in some papers, whilst a head/face injury was less severe (e.g. minor facial injury including a fractured nose) in other papers. The diagnosis of injuries in studies may have been provided by a range of medical personnel such as paramedics or physicians. Most studies did not adjust for covariates. A good exception was the conditional inference trees analysis by Hasler et al. [29], who identified non-helmet-wearing snowboarders on icy slopes as being at risk.

3.5 Analysis and Interpretation of Results

For individual studies, the relative frequencies for injury (relative risk, OR) were tabulated with 90 % confidence intervals (CIs). For example, relative risk or RR was calculated as the relative risk of injury for no helmet versus helmet as 25/10 = 2.5 if 10 % of helmet users and 25 % of non-helmet users were injured. The hazard ratio (HR) is similar, but is the instantaneous RR. The OR was calculated as (25/75)/(10/90) = 3.0. RRs and HRs are mostly reported for cohort studies to compare the incidence of injury between groups. ORs are mostly reported for case-control studies to compare the frequency of exposure to the risk factor or countermeasure in injured and non-injured participants. The OR is approximately the same as the RR or HR in value and meaning when frequencies are less than 10 % [31]. Pooled ORs with 90 % CIs and inferences (percentage likelihood of benefit/harm) were calculated using a spreadsheet for combining independent groups with a weighting factor based on quality rating scores for effects. The likelihood that an effect was substantially harmful, trivial or beneficial was given in plain-language terms using the following scale: 0.0–0.5 %, most unlikely; 0.6–5.0 %, very unlikely; 5.1–25.0 %, unlikely; 25.1–75.0 %, possible; 75.1–95.0 %, likely; 95.1–99.5 %, very likely; 99.6–100 %, most likely [31]. Values are reported with 90 % CIs to express the uncertainty in the true effect.

A Haddon matrix approach was used to summarise the identified injury risk factors and injury prevention countermeasures likely to be effective in reducing injury incidence or severity (Table 3).

4 Results

A wide range of risk factors have been investigated in a number of studies, including modifiable factors such as helmet use [10, 30, 32–36], wrist-guard use [6, 37–40], ability [41, 42], alcohol use [43, 44] and terrain conditions [45–48]. Non-modifiable factors such as age [49–51], sex [52–55] and weather [29, 56, 57] have also been examined. In contrast to studies investigating a large number of risk factors with little depth, less frequently studies have gone into more depth focusing on a single factor such as physical condition [58] or ski binding factors [59–61]. Of the ten intervention studies (Table 1), six focused on education programmes [19, 21–23, 26, 28], three on wrist-brace interventions [24, 25, 27], and one on a ski-binding adjustment intervention [20]. Data from six of the intervention studies and 49 of the risk factor studies could be used in the pooled OR analyses.

Table 2 provides a summary of the derived injury ORs and 90 % CIs for host/participant, agent/mechanism, and environment/community risk factors from the 55 studies (note that some studies contributed data to more than one risk factor, therefore the total number of studies does not add up to 55 in Table S2 of the ESM, or Fig. 2). Figure 2 of the pooled ORs (OR = crude OR; LRA OR = linear regression adjusted OR) can be interpreted as clear evidence for the benefit of a countermeasure or factor if the average and CI is below 1.0 (e.g. wrist-brace use for preventing wrist injuries). Conversely, there is a clear negative risk of injury if the countermeasure or risk factor is above 1.0. Table 3 provides a summary of host/snow participant, agent/mechanism and environment/community snow-sport risk factors, the potentially modifiable risk factors and those where there is evidence from the scientific literature for effective injury prevention countermeasures targeted at the risk factors. Key risk factors to focus on for countermeasure interventions include beginner skiers and snowboarders, participants who rent skis and snowboards, female participants, knee injuries in females, snowboarders, and poor visibility. Countermeasures shown to be effective included injury prevention education for all injuries for skiers and snowboarders; helmets for both ski and snowboarding for head and neck injuries; wrist guards for ski and snowboarding for wrist injuries; and knee braces for knee injuries in skiers.

5 Discussion

Many studies detailed snow-sports injury characteristics and injury risk factors from epidemiological studies; however, there was limited evidence for effectiveness of injury prevention countermeasures from randomised controlled trials or studies evaluating the cost-to-benefit ratio of countermeasure interventions. Some important host factors (e.g. age and sex), and environmental factors (e.g. weather) are unalterable. Interventions should focus on affecting modifiable factors such as education, protective equipment (in particular wrist guards and helmets), equipment design/set-up and limiting the snow-sport participant's exposure to poor run conditions and jump planning.

5.1 Effects of Skiing/Snowboarding Experience

For both snowboarding [50, 55, 62–68] and skiing [41, 50, 55, 62, 64, 67–78], self-rated beginners were far more likely to sustain an injury than individuals who were of self-reported intermediate or advanced ability [55]. More experienced skiers and snowboarders were more likely to sustain an injury as the result of jumps, while beginners sustained injuries primarily as a result of falls [42]. Analysis of two decades of injury data in France showed that injury risk slowly increased up until 2005 when a reversal in injury risk occurred [67]. This reversal in trend was attributed primarily to a decrease in snowboarding injury risk. Beginners contributed to most of the number of recorded injuries, with the first 4 days of exposure being the most precarious.

5.2 Effectiveness of Education Interventions

The effectiveness of education interventions was unclear, based on the CI; however, education interventions were rated as 65 % possibly beneficial, using the classification system of Hopkins [31]. This result is probably due to the diverse nature of the education campaigns and target populations. Due to the limited number of studies, it remains unclear what the best format and content is for the education sessions for particular target groups of participants (e.g. based on age, sex or skiing/snowboarding ability).

Screening of a 45-min educational video on long-haul bus trips specifically to ski slopes was effective in reducing injury risk, collisions and falls, particularly in beginners [23]. Key messages covered in this video were basic skills

Table 2 Summary of the effect sizes for the pooled injury odds ratios and 90 % CLs for host/participant, agent/mechanism and environment/community factors

Risk factor (n = number of contributing studies)	Pooled odds ratio	Lower 90 % CL	Upper 90 % CL	Inference—clinical	True value of the effect statistic (% likelihood)						Practical implications to focus injury prevention
					Substantially beneficial (%)		Trivial (%)		Substantially harmful (%)		
Skill beginner, all injuries, skier, n = 16	2.72	2.15	3.44	Most likely harmful	0.00	Most unlikely	0.00	Most unlikely	100.00	Most likely	Beginner skiers
Skill beginner, all injuries, snowboarder, n = 8	2.66	2.08	3.40	Most likely harmful	0.00	Most unlikely	0.00	Most unlikely	100.00	Most likely	Beginner snowboarders
Lessons, all injuries, skier and snowboarder, n = 5	1.18	0.96	1.45	Likely trivial	0.04	Most unlikely	78.29	Likely	21.68	Unlikely	–
Education, all injuries, skier and snowboarder, n = 3	0.67	0.38	1.17	Unclear; more data needed	66.03	Possibly	31.47	Possibly	2.50	Very unlikely	Education for all injuries for skiers and snowboarders
Sex (F vs. M), all injuries, skier, n = 7	1.21	1.02	1.42	Likely trivial	0.00	Most unlikely	77.22	Likely	22.78	Unlikely	–
Sex (F vs. M), all injuries, snowboarder, n = 8	1.02	0.81	1.29	Likely trivial	2.16	Very unlikely	93.48	Likely	4.36	Very unlikely	–
Sex (F vs. M), head, skier and snowboarder, n = 3	0.72	0.65	0.79	Likely beneficial	88.33	Likely	11.67	Unlikely	0.00	Most unlikely	Females
Sex (F vs. M), knee, skier and snowboarder, n = 7	2.77	2.01	3.81	Most likely harmful	0.00	Most unlikely	0.00	Most unlikely	100.00	Most likely	Female knee injury
Helmet, all injuries, skier and snowboarder, n = 6	0.74	0.57	0.97	Possibly beneficial	58.66	Possibly	41.31	Possibly	0.03	Most unlikely	Helmets for ski and snowboarding for all injuries
Helmet, head, skier and snowboarder, n = 6	0.58	0.51	0.66	Very likely beneficial	99.99	Most likely	0.01	Most unlikely	0.00	Most unlikely	Helmets for ski and snowboarding for head injuries
Helmet, neck, skier and snowboarder, n = 3	0.82	0.64	1.04	Possibly beneficial	34.06	Possibly	65.86	Possibly	0.08	Most unlikely	Helmets for neck injuries
Wrist guard, all injuries, skier and snowboarder, n = 3	0.66	0.27	1.61	Unclear; more data needed	61.53	Possibly	27.85	Possibly	10.62	Unlikely	Wrist guards for ski and snowboarding for all injuries
Wrist guard, wrist, snowboarder, n = 8	0.33	0.23	0.47	Most likely beneficial	99.99	Most likely	0.01	Most unlikely	0.00	Most unlikely	Wrist guards for snowboarders
Knee brace, knee, skier, n = 2	0.21	0.11	0.43	Most likely beneficial	99.89	Most likely	0.11	Most unlikely	0.00	Most unlikely	Knee braces for skiers
Bindings check (<1 year), lower limb, skier and snowboarder, n = 4	1.09	0.86	1.38	Very likely trivial	0.69	Very unlikely	88.08	Likely	11.22	Unlikely	–
Rented, all injuries, skier and snowboarder, n = 6	2.58	1.98	3.37	Most likely harmful	0.00	Most unlikely	0.00	Most unlikely	100.00	Most likely	Rental ski and snowboard participants
Visibility (poor vs. good), all injuries, skier and snowboarder, n = 3	2.69	1.43	5.07	Very likely harmful	0.06	Most unlikely	2.85	Very unlikely	97.09	Very likely	Visibility when poor

F female, *M* male, *CL* confidence limit

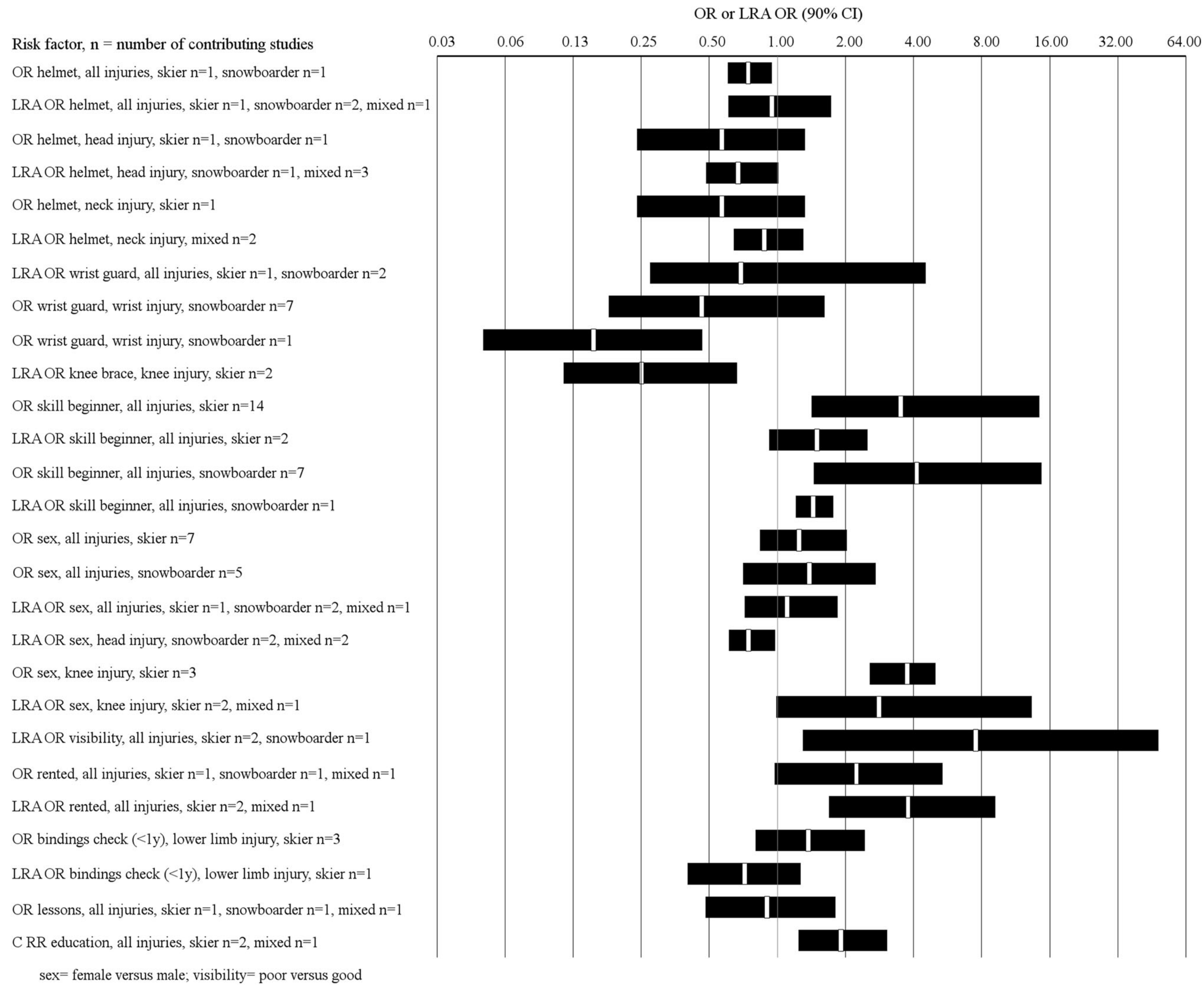


Fig. 2 Forest plot of effect sizes with 90 % CIs for the risk factors for snow sports. The number of studies contributing to the results for each variable are shown as '*n*'. The average odds ratio (*white bar*) and average 90 % CI (*black bar*) for each risk factor or countermeasure from the pooled odds ratios reported in the studies are shown. An OR <1 indicates a preventive factor. *OR* crude odds ratio, *LRA OR* linear regression analysis odds ratio, *C RR* crude risk ratio, *sex* female vs. male, *visibility* poor vs. good, *CIs* confidence intervals

and safety requirements, including binding checking and helmet use. Screening occurred during an 18- to 24-h bus trip in the afternoon or evening. A 1-h group education workshop was beneficial for more experienced individuals (on-slope employees) and showed a clear benefit in reducing the injury rate [21]. The workshop used video-directed discussions, including identifying and responding to possible hazard situations, and participants developing risk factor identification for anterior cruciate ligament injury. The nature of the education programme and the target audience appear to be keys to the success of the education programme. Injury risk initially decreased following a media campaign, however effectiveness declined with time [19]. Providing past injury information as well as technique and safety tips to ski club members by way of paper handouts and leaflets clearly reduced hospital ski injury admittance [22]. However, a 30-min teaching session with a 20-min educational video 'A Little Respect: Think First!' and brochure, followed by a test, were ineffective in reducing the risk of injury in 11- to 12-year-old school children over 4 school-supervised ski days [28]. The video focused on the alpine responsibility code, proper helmet use and clothing attire, trail and terrain sign interpretation, and emergency procedures in the event of an injury. Although there was a trend for a reduction in injury, the ineffective result was probably due to the inadequate sample size [28].

Three studies investigated the effect of taking lessons on injury risk. Two studies produced unclear results; however, Langran and Selvaraj [42] found lessons were associated with an increased risk of injuries not only in those injured on

Table 3 Summary of host/snow participant, agent/mechanism and environment/community snow-sport risk factors, the potentially modifiable risk factors, and those for which there is evidence from the scientific literature for effective injury prevention countermeasures targeted at the risk factors

Host/snow participant
Behaviour
Abstinence from alcohol[a]/alcohol intoxication[a]
Abstinence from drugs[a]
Readiness for risk[a]
Readiness for speed[a]
Risk-taking behaviour; judgement and recklessness[a]
Use of appropriate equipment[a,b]
Lessons[a]
Ability/experience
Seasons of experience in snowsports[a]
Self-reported ability (beginner, intermediate, expert)[a]
Body–motor control
Physical conditioning[a]
Duration of warm-up before the first ride[c]
Weight[a]
Body composition[c]
Nutrition and hydration[c]
Fitness[a]
Psychomotor skill development[c]
General health
Age[a,d]
Sex[a,d]
History of injury[a,d]
Knowledge
Knowledge about snow-sport safety and injury mechanisms[a,b]
Knowledge of trail details and safety rules[a,b]
Knowledge of injury prevention strategies[b]
Agent/mechanism
Behaviour
Protector use (e.g. spine protector, knee brace)[a]
Wrist guard worn[a,b]
Helmet worn[a]
Other protective equipment worn[a]
Equipment ownership[a]
Seasonal checking of ski/snowboard equipment by specialist[a]
Snow-sport type[a]
Injury and treatment
Effectiveness of treatment[a]
Severity of injury[a,d]
Protectors
Equipment design[a]
Age of equipment[a]
Binding release type[a]
Binding release check[b]
Storage of equipment[a]
Environment/community
Behaviour
Proximity to other participants[a]
Experience of aggressive behaviour of other participants[a]
Injury and treatment
First-aid[c]
Help-seeking behaviour[c]
Access/transport to hospital care[c]
Quality/affordability of health care[c]
Weather and terrain
Snow/slopes and weather[a]
Slope conditions (hard/icy, soft/powdery, slushy)[a]
Snow conditions (fresh snow, old snow, artificial snow)[a]
Accessibility to trails[c]
Terrain bans or access (barriers, signage)[a]
Terrain[a]
Trail grooming[a]
Jump planning[a]
Weather and visibility (sunny/good visibility, cloudy/bad visibility)[a,d]
Temperature[a]
Protectors
Protective mats[c]
Noise[c]

[a] Factors derived from literature

[b] Factors included in intervention studies

[c] Factors not yet addressed in studies

[d] Unalterable factors

their first day of skiing or snowboarding but also in all individuals injured. Increased risk-taking as a result of confidence after having taken lessons may increase injury risk.

5.3 Effects of Equipment

The use of rented equipment was clearly harmful (OR 2.37; 90 % CI 1.84–3.05); however, it was not clear from the studies whether it was the equipment per se, its maintenance, or the people who used rental equipment that resulted in rental equipment being a risk factor. A number of factors were likely contributing to this result; primarily the age (children) of the skier or snowboarder, skill level (beginner) and knowledge of the equipment. The studies with adjusted ORs were performed on children [79], who usually have less experience and also have reduced coordination when compared with adults [49], or on individuals who were injured on their first day on the slope [42]. Beginners were most likely more at risk of injury, having less specific strength, coordination and skill than more experienced skiers and snowboarders [51, 64].

Pooled ORs for having bindings checked within the last year showed a likely trivial effect. Individual analysis of a study of 572 injured and 576 uninjured control recreational downhill skiers indicated that bindings checked within the last year showed a 63 % possibly beneficial effect and a 35 % trivial effect [60]. Similar results were reported for a randomised intervention where the intervention population had bindings tested and properly adjusted prior to the start of the season (60 % possibly beneficial, 39 % trivial) [20]. Later studies, 1996–1997 season [64] and 2002–2003 season [80], showed binding checks to be possibly harmful. No details about who performed the binding checks were given for the 1996–1997 season [64]. While injuries reported during the 2002–2003 season included time since the last professional binding check, no details were given as to whether calibration machines were used. Boulter et al. [60] distinguished between how binding checks were performed, test apparatus and with skier characteristics or without characteristics, and found the risk increased slightly when the testing method was less specific. In France when the recommended binding settings were lowered using the French Association Francoise de Normalisation (AFNOR) settings for females, knee injuries did reduce.

The evidence supports that helmets were clearly beneficial for reducing the risk of head injuries in skiers and snowboarders [30, 81–85], and possibly useful in the reduction of neck and other injuries [29, 86–88]. A clear effect of sex was found for head injuries, with males more likely to sustain head injuries than females [83, 84, 89]. Whether males have increased risk-taking behaviour or less helmet usage is unclear. Non-helmet users were 2.3 times more likely to die from a head injury than helmet users [90]. Resistance to helmet use includes the perception there is no need to wear one and that they were uncomfortable [91]. Reduced ability to hear and see the surroundings were also given as reasons for non-use of helmets.

Snowboarders sustained upper extremity injuries, particularly wrist fractures [92]. Use of a customised wrist brace in a group of Austrian school children when snowboarding showed a clear effect for reducing wrist fractures [25]. Comfort of the brace was noted as a hindrance to retention of the intervention. Use of a wrist brace showed a definite reduction in wrist injuries for snowboarders in a population of recreational snowboarders; however, presentation of the use of a wrist brace prior to recruitment and randomisation introduced a selection bias only for individuals willing to try using a wrist brace [24]. The design of the wrist guard is important [93, 94]. A compulsory wrist-brace-wearing policy implemented with secondary-school students (12–16 years) in a single-school snow-sport programme showed a possible large effect on reducing wrist fractures [27]; however, the efficacy of implementing such policies outside of a school environment is unknown. Wrist guards may increase the risk of elbow, upper arm and shoulder injuries whilst reducing the risk of hand, wrist and forearm injuries [38]. This is potentially due to impact forces being transmitted up the kinetic chain of the limb.

Females were at greater risk of knee injuries for both skiing and snowboarding [54, 56, 87, 95–97]. Knee braces for skiers were most likely beneficial and use should be encouraged [95, 98]; however, the practical issues of hygiene and fit of braces used in a rental setting need to be addressed.

5.4 Effects of Weather and Terrain

Inclement weather is clearly harmful, increasing the risk of injury substantially. Visibility and condition of the snow appear to be key factors contributing to the increased risk of injury [29, 56, 99]. Increasing the size and frequency of signage to improve visibility during inclement weather periods may help decrease injury incidence. The average reaction time, from the time a sign comes into view to the time needed to respond to avoid an obstacle, is 1056 ms in clear visibility; therefore, during adverse weather conditions there is a need to allow for greater times for reacting to signage before obstacles [100].

Inappropriate trail design and grooming can increase the incidence of injuries at alpine ski areas at certain trail sites [99]. Other risk factors such as jump planning and type of terrain need further investigations using epidemiology risk factor analyses so that ORs can be determined. Experimental studies have indicated that the design of the landing surface is important for reducing injury risk [45, 48].

5.5 Priorities for Countermeasure Interventions

Based on the strength of the evidence from the effect size analysis, priorities for countermeasure interventions could be as follows:

- *Signage.* Increase the size and frequency of signage to improve visibility during poor weather periods. The average reaction time from the time a sign comes into view to the time needed to respond to avoid an obstacle is $\sim$1000 ms in clear visibility; therefore, in adverse weather conditions there needs to be allowance for greater times for reacting to signage before obstacles. There is a need for consistent signage, incorporating the science behind what signage influences behaviour.
- *Weather reports.* Increase the frequency of mountain reports, including snow conditions, and include how to check mountain reports and how to interpret the reports in educational programmes for beginners. To avoid ski-field operators 'talking up' the weather and snow

conditions to entice participants onto the field, this information needs to be independent of the ski-field operators.

- *Trail grooming.* Increase grooming hours during periods of fresh snowfall, no recent snowfall, or icy conditions. Groom during the day to maintain slope integrity. There is a need for regulation or competency requirements for ski-field groomers.
- *Terrain park design.* The design of terrain parks should be considered. Filtering systems could be developed where more challenging obstacles (e.g. a big jump) are placed at the start of a terrain park to filter out those without the necessary skill to use the park.
- *Education.* Develop educational videos, targeted at beginners, for screening on tour buses and at key rental locations. Video length should be considered, with short but catchy messages for rental locations and more detailed explanations for bus videos. Key messages to include in videos targeting beginners would be safety rules and key safety protocols (helmets, wrist guards in snowboarders, knee braces for skiers), important skills, hazard awareness (collisions with other people and rocks and trees), understanding the weather and snow conditions and how these can affect speed, stopping ability and visibility issues which change the impact of hazards. Create partnerships with tour companies that transport participants to the ski areas by bus, so that TV messages on snow-sport injury prevention messages can be played on the buses. Develop workshops for more experienced skiers and snowboarders, using videos of injurious or near-injurious events to promote thought and discussion of key things to be aware of and how to respond to different, potentially injurious situations. All on-slope personnel should attend these workshops regularly (i.e. every 2 years, with a first-aid refresher). Lesson instructors should be required to remind beginner skiers not to take risks with their newly acquired skills that exceed their ability. Beginner participants should be encouraged to build up speed and technical aspects slowly. All lessons should be undertaken with helmets worn; this often happens with children but needs to be across the board, with instructors setting the example. The Norwegian expression is “if you don’t wear a helmet you have already had a head injury!”
- *Rental equipment.* Target information to equipment renters regarding helmet and wrist-guard use, appropriate equipment fitting, awareness and key injury prevention skills. Possible options could include compulsory reading of information before equipment is provided, free fitting/bindings check and helmet/wrist/knee braces, and educational videos at rental facilities.
- *Digital assets.* Use digital assets such as cellphones, websites and TV screens mounted at ski-area facilities to provide information on injury prevention. For example, mount TV screens in rental facilities so that while participants are waiting in line to get their snow equipment, they can view the short key messages on injury prevention regarding the use of helmets and wrist guards, the ski slope rules, and techniques on how to stop safely, etc. Mount TV screens in other areas where queues form, such as in food venues and on chair-lift facilities.
- *Protectors.* Helmet use should be a key feature in education campaigns, with a focus on appealing to the male population. Free helmets with all rentals should be considered to ensure that those at higher risk of injury (i.e. beginners) are well protected. Free wrist braces should be available for snowboarders to use. This would encourage those willing to utilise wrist guards to do so. As the design of wrist guards is important, careful selection of guards is needed. Design must consider how to increase user compliance by addressing comfort, ease of cleaning, and effectiveness at reducing injury. Interventions regarding knee brace use should be targeted at females. Written and video information should note the higher risk in females and that the use of knee braces is an effective preventative measure. As the design and type of knee brace is a determinant of its injury prevention effectiveness, education messages about considering the use of professionally fitted knee braces could be provided. The evidence suggests that the more precise and specific the binding adjustments are to the individual, the more likely the binding adjustments will prevent injury. In France when the recommended binding settings were lowered using the French AFNOR settings for females, knee injuries were reduced. The issue of time pressures for technicians in adjusting bindings in rental outlets needs to be addressed so that correct binding adjustments are made rather than reverting to a ‘thump the heel of the boot and if it releases then all is OK’ adjustment. Public education could drive shop practices. The use of the more sensitive and specific torque calibration machines should be considered.

In analysis of the countermeasures reported in the studies from 1981 to 2013, no adjustment was made for the historical and sociocultural context in which these studies occurred. For example, an education campaign that was conducted nearly 20 years ago with a video in a bus may not have the same impact on a cohort carrying their own personal entertainment devices via their phones in 2014. Placing digital information screens on slopes will require these devices to operate at temperatures that can be

<30 °C. Consideration of educational or warning signage becoming an object hazard would also be required. Technology and equipment changes may result in different effect sizes for injury risk; therefore, an implementation plan for countermeasure interventions for skiers and snowboarders needs to consider the current sociocultural and technological context.

6 Conclusions

Snow sports would benefit from easily implemented and cost-effective injury prevention countermeasures that are effective in reducing injury rate and severity. The best evidence for effectiveness of injury prevention countermeasures for recreational snow sports was for use of helmets for skiers/snowboarders to prevent head injuries, and wrist guards for snowboarders to prevent wrist injuries. Key risk factors that injury prevention countermeasures should focus on include beginner skiers and snowboarders, skiers/snowboarders who rent snow equipment and poor visibility due to inclement weather.

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