

**Preventing knee injuries in ski instructors – what
would an exercise program to reduce risk look
like? A scoping review**

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Table of Contents

Abstract	1
Introduction	2
Methods	5
Results	11
Discussion	32
Conclusion	45
References	47

Preventing knee injuries in ski instructors – what would an exercise program to reduce risk look like?

ABSTRACT

Objective: To determine what an exercise-based knee injury prevention program to reduce the risk of knee injuries for ski instructors would look like, and how it should best be implemented.

Methods: A scoping review of studies pertaining to skiing-related knee injuries and exercise-based knee injury prevention programs was conducted.

Results: 88 studies were reviewed, and the evidence charted and used to answer the research question. No studies were identified that specifically addressed the research question.

Conclusions: A successful exercise program to prevent knee injuries in ski instructors could include the following components: education regarding common mechanisms of knee injury while skiing; a variety of preseason exercises that are ideally continued through the season three times per week as part of a 20-minute warmup; neuromuscular; strength; single leg and eccentric exercises for hamstrings; quadriceps; hip; and core musculature; plyometric and landing exercises to minimize knee valgus. Exercises should ideally be led by a ski instructor trainer, be sport specific, employ visual feedback, and have an external focus for optimal motor learning.

Keywords: Ski Instructor, knee injury, exercise-based prevention

1. INTRODUCTION

Knee injury prevention programs (IPPs) have been effective at reducing injury risk in many sports (Lauersen et al., 2014). There is evidence supporting the use of pre-season training programs that incorporate strength, fitness and proprioceptive training in reducing sports injuries by up to two-thirds in a variety of sports (Lauersen et al., 2014). Several sports have successfully implemented IPPs and reduced the incidence of knee injuries such as the “FIFA 11” for football (Barengo et al., 2014) and similar programs for netball (Hopper et al., 2017) and basketball (Taylor et al. (2015). Considering this evidence, it would be of value to understand whether there is any research that exists that could be used to guide an exercise-based knee injury prevention for ski instructors.

Knee injuries are the most common injury sustained while skiing, with 30-60% of adult skiing injuries involving the knee (Viola et al., 1999). With regards to skiing-related knee injuries, a specific group of interest is ski instructors. A knee injury can be season and/or career ending for a ski instructor, much like that of an elite competitive skier. Only a small amount of data on knee injury rates specific to ski instructors has been published. Roberts (2013) stated 50% of ski instructors who participated in their research reported having a previous knee injury.

ACL injuries are of particular interest as they are frequently accompanied by injuries to other knee structures such as the medial collateral ligament and the medial meniscus (Posch et al., 2021), are much more costly (NZD\$50,000 per case including surgery, pre- and post-surgery care and rehabilitation) (ACC 2021), and result in the greatest time off work (ACC, 2022). By comparison, the lower extremity injury rate in competitive skiers has been reported as 1.54 per 1000 athlete days (Fu et al., 2019) and 1.8 per 1000 skier days for recreational skiers (Maier et al., 2020). With the incidence of anterior cruciate ligament (ACL) injury among ski instructors estimated at 4.4 injuries per 100,000 skier days (Viola et al., 1999) with ACL injuries accounting for 15-21% of all skiing injuries (Posch et al., 2021). In summary, ACL

injuries for ski instructors come with a large burden of injury with costs and time off work being very high.

Ski instructors are a unique category of snow sports professionals, spending considerably more time actively skiing than recreational skiers. Typically, they ski for six or more hours per day, usually more than 100 days per season (Personal communication with Cardrona Alpine Resort, 2021), conservatively totalling 600 hours per season, or close to the 1000 hours of skiing per year previously reported for professional ski instructors (Viola et al., 1999). A significant difference between elite competitive skiers and ski instructors is their age and overall physical conditioning. An elite skier, usually aged between 15 and 35 years, trains with expert coaches year-round, often only skiing for a few hours per day (Gilgien et al., 2018). In contrast, ski instructors have an average age of 36 (Roberts, 2013)-50 years (Professional Ski Instructors of North America, PSIA (2021)). Due to the amount of time skiing, their diverse age range and a lack of strength and conditioning incorporated into their training (PSIA, 2021), it follows that ski instructors appear to have a different injury risk compared to an elite competitive and recreational skiers.

In New Zealand there are approximately 2100 professional ski instructors (Personal communication with New Zealand Ski Instructors Association, 2021). Estimates suggest that on average, 2.5% of ski instructors are injured annually while at work, with knee injuries accounting for half of these injuries (ACC, 2021). Further afield, international data shows up to 25% of ski instructors have knee surgery during their careers (Warme et al., 1995). Within New Zealand, knee injuries covered by the Accident Compensation Corporation (ACC) cost an average of \$1,600 NZD per injury, with ACL injuries averaging \$37,000 NZD per injury (ACC 2021) and resulting in up to 148 days off work (Clark et al., 2020). It is, therefore, in the interest of ski resorts and insurance companies to reduce both the incidence and cost of knee injuries amongst ski instructors.

Most injury prevention research for skiing has focused on extrinsic factors such as signage, equipment or bindings (Hume et al., 2015). Other research for the prevention of knee injuries in skiers has focused solely on educational initiatives such as watching videos of knee injury mechanisms to reduce injury risk (Jørgensen et al., 1998). A systematic review by Hébert-Losier and Holmberg (2013) found no injury prevention recommendations that pertained to the exercise, training or physical fitness of recreational skiers. To date, only one study has been published which has specifically addressed reducing the risk of knee injuries in ski instructors. Ettlinger et al. (1995) had ski instructors and patrollers undergo educational training, showing videos of common injury mechanisms. Staff reduced their risk of a serious knee injury by 62% over three years.

With regards to program design, sport-specific exercise programs appear to be more effective at reducing injuries than general exercise programs (Mugele et al., 2018). This would suggest a sport-specific exercise-based IPP for ski instructors could be beneficial, and currently such a program has not been reported. A 2020 study with adolescent competitive skiers showed a 45% reduction in ACL injuries with a neuromuscular-focused exercise program both on snow while skiing, and off snow with dryland training (Westin et al., 2020).

The impacts of knee injuries on professional ski instructors can be detrimental, and they need to be prevented. A tailored exercise program for this population has the potential to reduce knee injuries, prevent time off work and reduce healthcare costs, but what would this program look like and how could it be implemented? Based on existing evidence regarding successful exercise based IPPs in other sports, a similar program for ski instructors could be developed and would likely be beneficial, not just in terms of reducing lost time to participation in sport, but also in reducing time off work and the associated economic burden. Within the specific population of ski instructors, knee IPPs have yet to be reported. Exercise-based IPPs have been successful in preventing knee injuries in many other populations, with specific exercises, frameworks, and other elements of successful programs published

(Padua & Marshall, 2006). The goal of the current review is to map the current literature and determine recommendations for a future exercise-based IPPs for ski instructors.

There is a wide range of existing evidence that supports exercise-based injury prevention, but the lack of research in the specific field of knee injury prevention within the ski instructor population, indicates a scoping review is appropriate. The broad purpose of a scoping review is to examine the extent, range and nature of research in an area and to map this research and identify research gaps (Arksey & O'Malley, 2005). The mechanisms of knee injuries from skiing can be mapped, along with existing evidence for successful knee IPPs. This can be reviewed alongside the small amount of existing research in this field. The results of this review will add to the existing knowledge base and provide a foundation for the creation and implementation of an exercise-based knee injury prevention for ski instructors.

2. METHODS

A scoping review was chosen to clearly identify the research gap in this area and to best answer the research question. A scoping review uses a broad search of the literature required to collect and chart data. With this broad search, key themes and knowledge gaps can be identified (Arksey & O'Malley, 2005). A systematic review was not appropriate because of the lack of specific research in this area. The minimal research available therefore meant summarising the best research, as would be done in a systematic review was not possible. No quality assessment of the research was completed, in line with common scoping review processes (Arksey & O'Malley, 2005)

In keeping with the methodology developed by Arksey and O'Malley (2005), and further refined by Levac et al. (2010), this scoping review utilised a five-step approach. The five steps included:

1. Identify the research question
2. Identify relevant studies
3. Study Selection
4. Charting the data, and
5. Collating, summarizing, and reporting results.

For methodological quality and transparent reporting, this scoping review has followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for scoping reviews (PRISMA-ScR) (Tricco et al., 2018).

2.1. Identifying research questions

- 1) The overarching question for this review was: *What would an effective exercise program designed to reduce the risk of knee injuries in ski instructors include and how should the program be best implemented?* To answer this, three sub-questions were identified: What exercise programs currently exist to reduce the risk of knee injury for skiers?
- 2) What exercises could mitigate or avoid the consequences of the most common mechanisms of skiing knee injuries?
- 3) What are key elements of successful programs from other vocational or sports areas which reduce risk of knee injuries?

A scoping review is an appropriate way to answer these questions, and accordingly the original research question. Using this scoping review method, a broad literature search can be carried out in phases which is relevant given the current lack of research in this area.

2.2 Identifying Relevant Studies

Search Strategy

The literature search strategy, relevant to the three sub-questions were completed. Five databases were searched using a three-line search strategy: Cumulative Index to Nursing and Allied Health Literature (CINAHL Complete), EBSCO Health, MEDLINE, SPORTDiscus, and Scopus. Key words were chosen based on a broad search strategy and common synonyms. As recommended by

Search #	Research Subquestion	EBSCO Health	MEDLINE	Scopus
1	What exercise programs currently exist to reduce the risk of knee injury of skiers?	"Ski Instructor" +	"Exercise"	"Risk Reduction"
		"Knee injury" OR	"Program"	"Injury prevention"
		"Knee sprain"	"Training"	
			"Strengthening"	

we were initially screened by one researcher (MK), articles not excluded at this stage then had their abstracts screened. Articles that potentially satisfied inclusion criteria after title and abstract screening were identified, exported, and categorized within Endnote by MK for full text review. Duplicates were removed throughout the search process. Study identification and inclusion is summarised in table 2.

2	What are the most common mechanisms of injury for knee injuries while skiing?	"Knee injury"	"Exercise"	"Risk reduction"
		"Knee sprain"	"Program"	"Injury prevention"
			"Training"	
			"Strengthening"	
3	What are key elements of successful programmes from other vocational or sports areas which reduce risk of knee injuries?	"Knee injury"	"Exercise"	"Risk reduction"
		"Knee sprain"	"Program"	"Injury prevention"
			"Training"	
			"Strengthening"	

2.3. Study Selection

2.3.1 Identifying study selection criteria

Studies identified following each search had their titles, abstracts, and full text screened against the following eligibility criteria by MK: full text available; peer reviewed articles; published in English; specific to knee injuries; and inclusive of participants 16 years and older (as this represents the common

age-range of ski instructors). Furthermore, additional inclusion and exclusion criteria were identified relevant to the specific research sub-question. These additional criteria included:

- Sub-question #1 *Inclusion*: Relevant to skiing and exercise-based injury prevention.
- Sub-question #2 *Inclusion*: Published after 1991, when modern ski shapes became available, related to mechanism of knee injury while skiing. *Exclusion*: A focus on equipment-based injury prevention.
- Sub-question #3 *Inclusion*: Relevant to skiing and exercise-based injury prevention. *Exclusion*: Focused on a population under 16 years of age (as this is much younger than the age of ski instructors) and review articles.

Where the primary researcher (MK) was unsure about an article meeting the eligibility criteria, the whole research team met to decide via consensus.

Table 2. PRISMA table of articles identified from search strategy.

	SEARCH 1 (SUB-Q1)	SEARCH 2 (SUB-Q2)	SEARCH 3 (SUB-Q3)	TOTAL
IDENTIFICATION (SEARCH)	325	619	1957	2901
IDENTIFIED FROM OTHER SOURCES	1	0	12	13
AFTER DUPLICATE REMOVAL	273	386	326	985
AFTER SCREENING (TITLE)	88	118	163	396
ELIGIBILITY (ABSTRACT REVIEWED)	28	70	96	194
ELIGIBILITY (FULL TEXT REVIEWED)	12	17	59	88
TOTAL STUDIES INCLUDED				88

2.4. Charting the Data

2.4.1 Data extraction

Using the research question (and sub-questions) for guidance, the research team worked together to determine which details would be extracted and charted from the included studies. Throughout the research process, the data included and excluded was updated following discussions between the research team. This iterative process is recommended by Arksey and O'Malley (2005) and Levac et al. (2010). Data and qualitative content were sorted and included based on whether it answered the research question or sub-question or if it was useful towards the end goal of creating an exercise-based knee injury prevention for ski instructors. After an iterative charting process, the following details from the included studies were extracted and charted in addition to the authors, year of publication, study design and objective:

- Research sub-question #1 – *What exercise programs currently exist to reduce the risk of knee injury of skiers?* Study details (cohort, interventions (if any), conclusions and other notes of relevance.
- Research sub-question #2 - *What exercises could mitigate or avoid the consequences of the most common mechanisms of skiing knee injuries?* Study details (methods, interventions (if any), population demographics (human study or otherwise, age, gender, sample size, sport), conclusions, mechanisms of injury, exercises to address these mechanisms.
- Research sub-question #3 - *What are key elements of successful programs from other vocational or sports areas which reduce risk of knee injuries?* Population demographics (age, gender, sample size, sport), conclusions, recommendations for exercise-based knee injury prevention, and other notes of relevance.

2.4.2 Data charting

The study details were summarized in three charts to make collating the evidence easier, and to answer the research questions. Within Table 4, studies were grouped based on how they contributed to answering the research questions. Groupings were based on studies that featured skiing, studies that were reviews, and studies that described how an exercised-based injury prevention should be implemented.

3. RESULTS

3.1 Selection of sources of evidence

Initially 2901 studies were identified from database searches. 1929 articles were removed due to being duplicates. A further 791 articles were removed after screening of the title and abstract. The remaining 194 articles had their full text screened and a further 106 articles were removed. An additional 13 studies, identified as relevant and included, were found through reference lists of included studies, from authors directly, and from contacting other researchers in this field. In total 88 studies were used for this scoping review. This selection process is described in Figure 1.

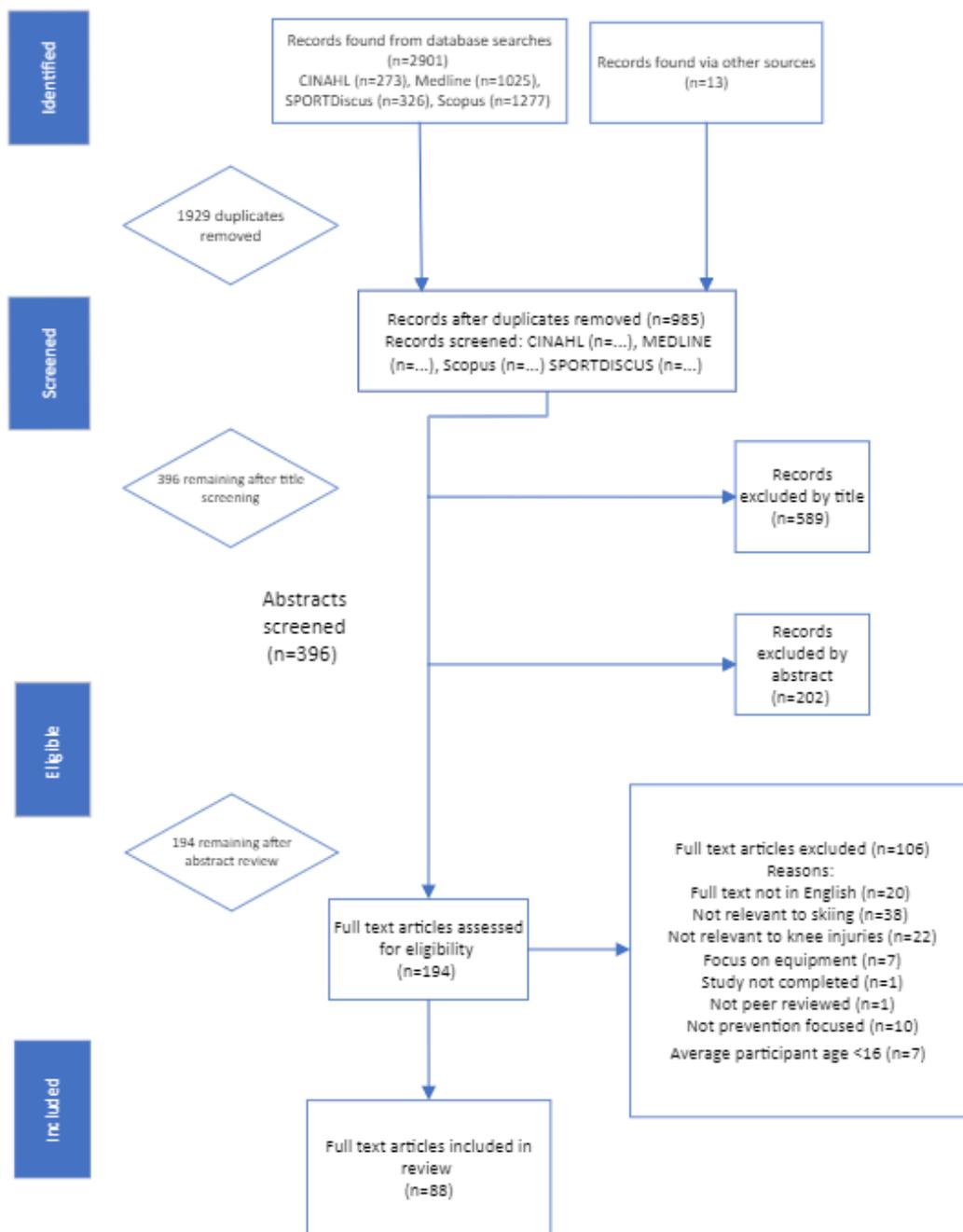


Figure 1. Flow diagram of articles identified and excluded following PRISMA guidelines.

3.2 Characteristics of sources of evidence

The 88 total studies included in this scoping review and their descriptive characteristics are shown in Tables 3-5. There were 12 studies identified as being existing research in this area. The other 76 related to mechanisms of knee injury while skiing or other exercise-based injury prevention research.

3.2.1 Ski Exercise Programs

12 studies were identified that contained relevant information on exercise-based IPPs for skiing. Five were experimental studies and have been summarized in Table 3. Seven were review articles. Overall, out of the 12 studies, eight generally recommended exercise as a method of injury prevention for skiers, whilst three looked at the effect of exercise on knee injury prevention (Roberts, 2013; Vitale et al., 2018; Westin et al., 2020), and two had ski instructors as part of their study population (Ettliger et al., 1995; Roberts, 2013).

3.2.1.1 Summary of experimental studies

The experimental studies all indicated that knee injuries in skiing could be reduced, either by education (Ettliger et al., 1995; Jørgensen et al., 1998; Roberts, 2013; Westin et al., 2020), exercise (Vitale et al., 2018), or both (Roberts, 2013; Westin et al., 2020). There were fewer knee injuries in intervention groups than control groups for the four studies measuring injuries. In one study knee injuries were not monitored (Vitale et al., 2018) but there were improvements in outcome measures indicative of knee injury risk.

Table 3. Research sub-question – What exercise programs currently exist to reduce the risk of knee injury for skiers?

Author/Date	Study details	Interventions	Findings/Conclusion	Other relevant information
Ettlinger et al. (1995)	<p><u>Objective:</u> determine whether an injury awareness training program for ski patrollers and instructors, reduces in-season serious skiing knee injuries.</p> <p><u>Study design:</u> non-randomized controlled trial.</p> <p><u>Intervention group:</u> on-slope staff (ski patrollers and instructors) at 20 ski resorts (precise cohort number unknown).</p> <p><u>Control group:</u> on-slope staff (ski patrollers and instructors) at 25 ski resorts (precise cohort number unknown).</p>	<p>Data collected during one complete season (end of October to start of April).</p> <p><u>Intervention group:</u> completion of a two-session injury awareness training program (utilizing tools such as using video-footage of common skiing injuries and self-reflection tasks) to educate participants on common mechanisms of skiing knee injuries.</p> <p><u>Control group:</u> no training program was provided</p>	<p>Anterior cruciate ligament incidence (primary variable) over three seasons. 62% reduction in incidence of ACL injury in the intervention group. No change for the control group.</p> <p>Concluded that skiing knee injury awareness training was a valuable tool to use to significantly reduce ACL injuries in ski patrollers and instructors.</p>	<p>Precise participant numbers not reported (likely unknown)</p> <p>Most frequently cited paper found in the review of literature for the current scoping review.</p>
Jørgensen et al. (1998)	<p><u>Objective:</u> test the effect of an instructional ski video on the behaviour and injuries of downhill skiers.</p> <p><u>Study design:</u> prospective randomized intervention study.</p> <p><u>Intervention group:</u> 243 skiers.</p> <p><u>Control group:</u> 520 skiers (skiing at the same areas over the same two-week period but traveling on different buses. Comparable control groups for age, sex, and skiing experience.)</p>	<p>Data collected at the end of the ski week on the return bus journey.</p> <p><u>Intervention group:</u> watched a 45-minute instructional video focused on how to get started in downhill skiing and advice on injury prevention, especially the significance, testing and adjustment of bindings</p> <p><u>Control group:</u> travelled as usual with no instructional video.</p>	<p>An instructional ski video can change the behaviour of downhill skiers and reduce the injury risk and consequences significantly.</p> <p>21.3 injured/1000 skier days in video group. 30.6 injured/1000 skier days in control group. (P<0.05).</p>	<p>Beginner and experienced skiers. Highest injury reduction rate in beginner skiers. Injury reduction in experienced skiers was not statistically significant (P=0.30)</p> <p>Intervention was based mostly on equipment, not on exercise.</p>
Roberts (2013)	<p><u>Objective:</u> determine if injury rates are reduced following a program of corrective joint stability exercise and dietary counselling.</p> <p><u>Study design:</u> Prospective Cohort Study</p> <p><u>Intervention group:</u> 5 volunteers in each area (lift attendant, ski instructor, ski patroller) were recruited at each of five resorts (n=75)</p> <p><u>Control group:</u> all patrols, lift ops, and instructors for the current season at 5 participating resorts and all workers in the same departments at 4 control resorts which did not use the program</p>	<p>Data collected during one season.</p> <p>Intervention at the beginning of the season. Injury rates tabulated before and after the education program.</p> <p><u>Intervention group:</u> 30-minute educational programs about hydration, diet, and functional awareness at the beginning of the season.</p> <p>Functional movement awareness was termed a 'proprioception workshop.' Simple proprioceptive drills to help increase stability at the lumbar spine, hip, knee, and shoulder were presented and participants were encouraged to utilize the drills regularly.</p>	<p>Workers showed poor stability at the lumbar spine, knee, and shoulder. 50% of ski instructors reported a previous knee injury. 43% of instructors reported not being active outside of work.</p> <p>Overall reduction in injury claims at participating resorts (P<0.04), supported by an increase in injuries at the control resorts.</p> <p>Provision of educational programs encouraging hydration, diet to stabilize BG, and functional-movement awareness was effective in reducing worksite injuries.</p>	<p>Overall injury reduction.</p> <p>Not specifically knee injury. Functional movement stability was assessed at the beginning of the study but not reassessed at the end.</p> <p>Not possible to determine whether the hydration and diet education or the functional movement component was more effective.</p>

		<u>Control group:</u> no intervention		
Vitale et al. (2018)	<p><u>Objective:</u> evaluate the effects of an 8-week NMT program focused on core stability, plyometric, and body weight strengthening on dynamic postural control and vertical jump performance</p> <p><u>Study design:</u> randomized controlled trial</p> <p><u>Intervention group:</u> 12 male skiers randomly selected from Italian ski teams</p> <p><u>Control group:</u> 12 male skiers randomly selected from Italian ski teams.</p> <p>Both groups had comparable demographics, with no differences in age, height, weight, weekly skiing, or training volume. Average age: 18</p>	<p>Pre- and post-testing at baseline and at 8 weeks of YBT, CMJ and DJ.</p> <p><u>Intervention group:</u> neuromuscular warm-up exercises progressing through three phases of difficulty. Focus was on the quality of movement and emphasis on core stability, hip control, and proper knee alignment. 30 minutes 2x/week</p> <p><u>Control group:</u> standard warm up exercises. Light aerobic exercise and dynamic stretching</p>	<p>YBT showed significant improvement in the intervention group but not the control group. No significant differences (improvements or declines) of CMJ and DJ for either group.</p> <p>A NMT program incorporated into the warmup of elite skiers may be effective at improving LE joint awareness and improve postural control</p> <p>Conclusion: NMT to improve proprioception, LE joint biomechanics and dynamic balance could improve YBTs and therefore reduce injury risk.</p>	<p>Because poor YBT performances has been associated with an elevated risk of noncontact lower extremity injuries, this study informs professionals on the need to develop sport-specific neuromuscular training programs to decrease the overall LE injury risk in elite junior skiers.</p> <p>>75% compliance</p>
Westin et al. (2020)	<p><u>Objective:</u> study whether a specific prevention program could reduce or prevent the number of ACL injuries in competitive adolescent alpine skiers.</p> <p><u>Study design:</u> prospective cohort design.</p> <p><u>Intervention group:</u> 308 alpine skiers who attended a ski high school between 2011 and 2013</p> <p><u>Control group:</u> 456 alpine skiers who attended a ski high school between 2006 and 2011</p> <p>Both groups had comparable demographics with no significant differences in age, skiing experience, previous LE, or ACL injuries. Average age: 17.</p>	<p>ACL injuries and re-injuries were counted during the study period of 21 months.</p> <p><u>Intervention:</u> ACL injury prevention video, watched every 3 or 4 weeks, pre- and in-season. 3 indoor exercises: one leg hop for distance, square hop test, single leg squat. Implemented by coaches. Overall focus on equal performance on both sides.</p> <p>3 outdoor/on-snow exercises: Shuffle, back & forth, turns with lifted inner ski.</p> <p><u>Control:</u> No intervention</p>	<p><u>Intervention seasons:</u> 12 skiers sustained 12 ACL injuries (prevalence of 3.7%, injury incidence of 0.26/100months).</p> <p><u>Control seasons:</u> 33 skiers sustained 35 ACL injuries (prevalence of 8.1%, injury incidence of 0.48/100 months).</p> <p>ACL injuries in the intervention group were reduced by 45% ($p=0.03$)</p> <p>Focus on being able to perform these exercises equally well on the right and left may have resulted in reduced left knee ACL injuries (not noted as statistically significant)</p>	<p>Historical controls</p> <p>Only 42% compliance</p>

Abbreviations: YBT- Y-balance test, CMJ – Counter movement jump, DJ – Drop jump, LE – Lower extremity

3.2.2.2 Summary of review articles

From the seven review articles, minimal research specific to skiing injury programs was identified/reported, with five studies concluding that more research on exercise-based injury prevention for skiers was needed (Davey et al., 2019; Hébert-Losier & Holmberg, 2013; Johnson et al., 2009; Koehle et al., 2002; Swedberg et al., 2016).

3.2.3 Injury Mechanism

Seventeen studies were found that identified mechanisms of knee injury while skiing. Twelve of these were experimental studies and have been summarized in Table 4. Five were review articles. Two studies (one experimental, one review) mentioned ski instructors, but did not specifically study them. Rossi et al. (2003) hypothesized that ski instructors spend a significant amount of time skiing below their ability level stating that data from instructors may not be applicable to recreational skiers or ski racers. Ruedl et al. (2009) classified ski instructors, as well as ski racers as 'expert' skiers. In their study there were fewer expert skiers injured.

3.2.3.1 Summary of experimental studies

Seventeen studies were found that identified mechanisms of knee injury while skiing. Five studies were focused on alpine ski racers, one on freestyle skiers, and five were lab studies using models, cadavers, or pig knees (Table 4). The remaining focused on general 'alpine skiers' or recreational skiers.

The most common causes of knee injury identified were: backwards fall (9), 'boot induced' (5), knee hyperflexion (4), knee valgus + external rotation (especially when landing) (4), knee hyperextension (4), and 'phantom foot' (4). Several other mechanisms were identified such as the 'slip-catch' mechanism, which mostly is only seen in high level alpine ski racing, and not as relevant to ski instructors, along with some generic mechanisms such as loss of balance.

Table 4. Research sub-question – What exercises could mitigate or avoid the consequences of the most common mechanisms of skiing knee injuries?

Author/ Date	Study details	Findings/Conclusion	Injury mechanisms	Relevance to injury prevention exercises
Aune et al. (1995)	<u>Objective:</u> examine motion pattern & muscle activity during jumping & landing in downhill skiing to estimate the muscular involvement during the jump-landing-backward fall ACL injury. <u>Study design:</u> case study (n=2) <u>Participants:</u> 2 professional ski racers <u>Methods:</u> EMG activity of gastrocnemius, biceps femoris, rectus femoris & vastus medialis recorded during 3 runs by 2 skiers during a ski jump + landing on a racecourse. Compared to muscle activity in a control jump from an 85cm table.	Knee flexors recruited before knee extensors. Peak activity reached simultaneously at landing. As the landing was stabilized knee extensor activity persisted during eccentric work while knee flexors relaxed. Questionable evidence that an ACL rupture by a backwards fall is caused by quadriceps contraction.	Backward fall ACL injury is likely caused by a combination of boot top-induced anterior shear, forceful knee hyperflexion and the absence of a significant protecting hamstring force.	Recovery from knee hyperflexion. Hamstring recruitment & strengthening training.
Bere et al. (2011)	<u>Objective:</u> describe the skiing situation leading to ACL injuries in the WC alpine skiing based on a technical video analysis. <u>Study design:</u> observational study <u>Participants:</u> WC alpine skiers with ACL injuries, observed on video by ten experts to describe factors contributing to the injury <u>Methods:</u> 20 ACL injuries observed. Experts described the following factors: skier technique, skier strategy, equipment, speed and course setting, visibility, snow conditions and any other factors	Main contributors to injury: skier technique, skier strategy, visibility, snow conditions. Skier technique & strategy: Slip catch – 10 cases, Landing back-weighted – 4 cases, Dynamic snowplough – 3 cases Visibility & snow conditions: bumps, large jump, ice, flat light *Slip catch and dynamic snowplough noted as being different than mechanisms impacting recreational skiers.	Three mechanisms identified: Slip Catch – Skier out of balance backwards + inwards, unable to maintain balance on outside ski, unable to absorb terrain. Dynamic Snowplough – Too much pressure on inside edges & inside ski, unable to respond to changes in snow. Landing back-weighted – Poor jumping technique, leaning back at take-off & landing on tails of skis.	Foot-Foot weight shifting exercises. Training on uneven surfaces. Jumping technique training + landing training.
Bere et al. (2014)	<u>Objective:</u> describe the injury situations in World Cup alpine skiing <u>Study design:</u> descriptive laboratory study <u>Participants:</u> WC alpine skiers injured while racing between 2006-2009. <u>Methods:</u> 69 injuries & 124 runs of matched controls analysed by 5 experts to evaluate the skiing situation, skier behaviour & snow conditions.	Most injuries occurred while turning or landing from a jump 19/23 knee injuries occurred while skiing, not as the result of a fall 46% of injuries occurred in the final quarter of the race	Most knee injuries are a result of loss of balance and inability to control the ski and stabilize the knee properly.	Exercises to avoid tibial internal rotation + valgus movements. Dynamic ski exercises relevant.
Fu et al. (2019)	<u>Objective:</u> to understand the force inside the knee joints while landing in three landing positions (neutral, backward, forward landing) of a jump in freestyle skiing. <u>Study design:</u> observational study <u>Participants:</u> 3D computer knee models	Neutral landing - greatest peak stress on medial meniscus but stress on the ACL, PCL, MCL, and LCL were at their least. Forward Landing – high likelihood of medial meniscus + MCL damage.	Skiers with weak posterior thigh muscles should avoid forward landing to reduce the possibility of PCL or MCL injury.	Encourage landing with neutral tibia position. Strengthen hamstrings.

	<u>Methods:</u> 3D Knee model created based on one male athlete from the national aerial team. Kinematic models based on video analysis recreated with three different successful landings. Stress distributions curves for knee ligaments, menisci, and tibial plateau.	Posterior Landing – ACL injury most likely. Tibial rotation on landing – increased risk of ACL injury	Skiers that have weak anterior thigh muscles should avoid backward landings to reduce the risk of ACL injury.	Strengthen quadriceps.
Hame et al. (2002)	<u>Objective:</u> record the forces generated in the anterior cruciate ligament with application of tibial torque to cadaveric knees in different positions. <u>Study design:</u> controlled laboratory study <u>Participants:</u> 37 fresh-frozen cadaveric knees hyperflexion. <u>Methods:</u> knees were instrumented with a tibial load cell that measured resultant force in the ACL while internal and external tibial torques were applied to the tibia at full extension, 90° of flexion, full flexion, and forced hyperflexion.	At each knee flexion position, mean force generated by internal tibial torque was higher than the mean generated by external tibial torque. Mean forces generated by tibial torque at 90° of flexion were low. During flexion-extension without tibial torque applied mean forces were highest when the knee was hyperflexed.	Application of internal tibial torque to a fully extended or fully flexed knee is the most dangerous loading condition for injury from twisting falls during skiing. Hyperflexion + tibial internal rotation (trying to recover from a jump) Full extension + tibial internal rotation (crossing ski tips while falling forwards).	Knee flexion/extension control exercises. Exercises to avoid tibial internal rotation. General strengthening.
Heinrich et al. (2018)	<u>Objective:</u> to evaluate the effect of varied landing height on peak ACL force during jump landing & to compare the effect of landing height with the effect of the landing position varied by the trunk lean of the skier. <u>Study design:</u> quasi-experimental research design <u>Participants:</u> A 25-degree-of-freedom sagittal plane musculoskeletal model of an alpine skier. <u>Methods:</u> alpine skier model used to simulate different jump landings, with varying landing height and trunk lean of the skier, and their corresponding effects on peak ACL force.	Peak ACL force increased with jump height and backward lean of the skier. Peak ACL force was about eight times more sensitive to trunk lean than landing height. Decreased sensitivity of the landing height was based on the lower effects on the knee muscle forces and the shear component of the knee joint reaction force.	Increased backward lean causes increased ACL peak force. Trunk backward lean is associated with increased plantar flexion and quadriceps force.	Landing position training. Focus on avoiding trunk backward lean of the skier, and consequently on proper jump preparation and technique.
Koyanagi et al. (2006)	<u>Objective:</u> establish a safer form of skiing for the prevention of injury to the ACL. <u>Study design:</u> quasi-experimental research design <u>Participants:</u> 10 healthy women <u>Methods:</u> participants were placed on a force plate on an artificial slope. Muscle activity was recorded by EMG, joint moments were analysed & extrusion of the lower leg by the boot was measured using a force sensor sheet. Participants assumed forward and backward bending postures with a single leg by changing their centre of gravity.	Forwards bending – Increased extension moment of hips & ankles, increased hamstring activity. Backwards bending – Increased flexion moment of hip, extension moment of knee, pressure of boot & quadriceps contraction. Muscular activity of the hamstrings was decreased. The dependency on the hamstrings increased in forward bending in a skiing posture on a slope with slight knee flexion.	Internal force exerted by the quadriceps + passive extrusion of the lower leg by the boot, may contribute to ACL injury in a backward bending posture while skiing. Forward bending advantageous for the prevention of ACL injury. In a backward bending skiing posture, the extension moment of the knee produced by quadriceps contraction also increased hamstring imbalance.	Focus on trunk flexion and slight knee flexion Exercises to strengthen hamstrings.
Ruedl et al. (2009)	<u>Objective:</u> investigate the distribution of injury mechanisms and the related frequencies of ACL injuries in female skiers. <u>Study design:</u> questionnaire	The forward twisting fall most reported ACL injury mechanism (51%) followed by the backward fall with body rotation (29%).	In order of most to least frequent: Forward fall with rotation – catching an edge	Fore/aft Balance exercises. Rotation control exercises.

	<p>Participants: 65 ACL injured female skiers, including instructors</p> <p>Methods: conducted in two Austrian ski clinics used to recruit volunteers. Data on injury mechanisms (causes & types of falls), demographic data, skiing ability, equipment, snow conditions, difficulty of the ski slope, & weather collected by questionnaire within 2 days after injury.</p>	<p>No significant differences regarding age, height, weight, BMI, & skiing skills</p> <p>58% of forward twisting falls occurred on grippy snow. No significant differences with weather & slope difficulty.</p>	<p>Backward fall with rotation</p> <p>Backward fall without rotation</p> <p>Forward fall without rotation</p>	
<p>Shea et al. (2014)</p>	<p>Objective: identify the most common knee injury mechanisms in recreational downhill skiers and to assess injury frequencies across several demographics</p> <p>Study design: descriptive epidemiology study</p> <p>Participants: 541 patients with acute knee injuries, all skill levels</p> <p>Methods: questionnaire administered by ski patrol. Skill level identified as well as knee injury mechanism. Patients selected 1 of 6 injury classifications; age, sex, height, weight, years of experience, ability level, & ski binding release.</p>	<p>Overall injury distribution: valgus–external rotation (32.9%), phantom foot (22.5%), hyperextension (19.0%), boot induced (7.8%), collision (2.2%), & other (15.6%).</p> <p>The phantom foot mechanism was most common in ages 30-40 years.</p> <p>Children & adults showed no significant difference in injury mechanism distribution.</p> <p>“Advanced” skiers had a higher prevalence of valgus–external rotation.</p> <p>Bindings released for 19.3% of adults.</p> <p>60.0% of respondents female.</p>	<p>Valgus external rotation most common, especially in advanced skiers (such as ski instructors)</p> <p>Phantom-foot – second most common and most common in skiers aged 30-40 (such as ski instructors)</p> <p>Hyperextension – third most common</p> <p>Boot induced – fourth most common</p>	<p>Greatest focus on exercises to counter a valgus external rotation movement.</p>
<p>Speer et al. (1995)</p>	<p>Objective: demonstrate the uniqueness of the injury mechanism for acute complete tears of the anterior cruciate ligament in recreational alpine skiers by using patterns of osseous injury as detected by MRI.</p> <p>Study design: observational study</p> <p>Participants: 42 recreational skiers who had an acute complete ACL tear from skiing (average age 32, 22 male, 20 female)</p> <p>Methods: all patients completed a survey about injury mechanism, ability, & ski release. MRI performed an average of 9 days post-injury. MRIs reviewed to assess the presence of osseous abnormalities. Lesion size & location noted.</p>	<p>17 (40%) - Osseous injury to lateral femoral condyle; over terminal sulcus in 15 of these.</p> <p>4 (10%) - bone bruise on medial femoral condyle; all at extreme posterior margin.</p> <p>34 (81 %) - bone bruise on lateral tibial plateau; 33 at extreme posterior margin & 27 of these at the posterolateral tibial rim.</p> <p>1 chondral injury.</p> <p>12 (29%) - bone bruise on the medial tibial plateau; all on the posterior margin.</p>	<p>Based on the bone bruising patterns, most skiing-related ACL tears occur with more knee flexion than non-skiing ACL tears.</p> <p>Increased knee flexion – most commonly from a backwards fall, ski then acts as a lever causing rapid rotation of tibia.</p> <p>External rotation of tibia on femur most common.</p>	<p>Exercises to move COM forwards</p> <p>Exercises to strengthen hip external rotators and abductors.</p>
<p>Yeow et al. (2011)</p>	<p>Objective: to apply simulated ski-landing impacts to knee specimens, and to examine the joint force/ kinematic responses and their correlations with the impact force.</p> <p>Study design: experimental study</p> <p>Participants: 10 human cadaveric knees (male, average age 60)</p> <p>Methods: cadaveric knee specimens with intact ACL’s positioned in 70° knee flexion & placed under axial and rotational loads simulating a ski landing. Joint forces & kinematics recorded.</p>	<p>Positive correlations observed for axial impact force with anterior tibial force, medial tibial force, anterior tibial translation, internal tibial rotation, and valgus joint rotation.</p> <p>Axial impact force more strongly correlated with anterior tibial force, anterior tibial</p>	<p>Increased axial landing force with anterior tibial force, anterior tibial translation & internal tibial rotation most likely to cause failure of the ACL.</p>	<p>Reduce landing impact forces.</p> <p>Exercises to counter tibial internal rotation.</p>

		translation & internal tibial rotation than medial tibial force or valgus joint rotation.	
Yeow et al. (2010)	<p><u>Objective:</u> investigate the direct contribution of axial impact compressive load to anterior tibial load during simulated ski landing impact of intact knee joints without quadriceps activation</p> <p><u>Study design:</u> experimental study</p> <p><u>Participants:</u> 12 pig hind legs</p> <p><u>Methods:</u> pig hind legs, randomly assigned to non-impact control group (n=4) or impact group (n=8) loaded at high knee flexion angle (70°) to simulate a ski landing. MRI used to measure tibial plateau angle. Histology used to observe cartilage damage.</p>	<p>Axial impact compressive load directly contributes to anterior tibial load causing increased ACL stress and cartilage damage during ski landing.</p> <p>Anterior tibial loading from axial impact compressive loading, together with anterior tibial loading from the quadriceps, can act synergistically to elevate risk of ACL failure & cartilage damage during ski landing.</p>	<p>High knee flexion at the time of landing may contribute to a greater likelihood of ACL injury or cartilage damage.</p> <p>Landing technique.</p>

Abbreviations: ACL – Anterior Cruciate Ligament, COM – Centre of Mass, LCL – Lateral Collateral Ligament, MCL – Medial Collateral Ligament, PCL – Posterior Cruciate Ligament, WC – World Cup

3.2.3.2 Summary of review articles

Five review articles were found that discussed mechanisms of knee injury while skiing. All reviews focused on human participants, three on all skier abilities (Jannelli et al., 2019; Pressman & Johnson, 2003; Rossi et al., 2003) and two specifically on alpine ski racers (Fischer et al., 1996; Tarka et al., 2019). Mechanisms discussed were similar to those in the experimental studies: forced hyperextension (3), the 'phantom foot' mechanism (3), trying to recover from an uncontrolled situation/loss of balance (2), boot induced (2), a backwards landing, or backwards fall with hyperflexion and internal rotation (2), loss of balance (1), backwards snowplough (1), forward fall (1). Other related causes discussed were fatigue (1), decreased core strength (1) and poor drop jump training (1).

3.2.4 Other sports examples

A total of 59 studies were identified with relevant examples of exercise-based injury prevention exercises, programs, or methods. Twenty-six were experimental studies, 33 were review studies. For conciseness, only experimental studies were broken down and detailed, review studies were thoroughly reviewed but not summarised in the tables below.

3.2.4.1 Summary of experimental studies

Twenty-six experimental studies were identified and are summarized in Table 5. Two of these studies were skiing-based; 19 were focused on the types of exercises included in a program for knee injury prevention in another sport; and five were focused on how the exercises were implemented or other aspects of a successful program. The most common recommendations for exercise program components were: neuromuscular training (15), landing techniques (14), hamstring strengthening (10), plyometrics (9), pre-season programs (6), core strengthening (7), multifaceted programs (5) exercises

addressing knee valgus (2), eccentric strengthening (2), implicit learning (2), external focus (2) and coach-led (2).

Table 5 – Exercise-based knee injury prevention programs from other sports.

Author/Date	Study Details	Population	Findings/Conclusions	Recommendations for exercise-based knee injury prevention	Notes
Skiing related studies					
Koller et al. (2015)	<p><u>Objective:</u> test the hypothesis that recreational alpine skiing is associated with pronounced eccentric muscle fatigue.</p> <p><u>Study design:</u> observational study</p> <p><u>Methods:</u> isokinetic strength testing 1 day before, 1 hour & 1 day after skiing for 4 hours.</p>	<p>Skiers</p> <p>24 healthy & fit, recreational level</p> <p>M & F</p>	<p>Eccentric strength in quadricep and hamstring muscles detected at 1- & 24-hours post-skiing.</p>	<p>Additional eccentric training recommended in conditioning programs for recreational skiers.</p> <p>Quadriceps and hamstring muscles recommended but especially hamstrings and the non-dominant leg.</p>	<p>Intermediate skiers</p>
Vitale et al. (2018)	<p><u>Objective:</u> evaluate the effects of an 8-week NMT program focused on core stability, plyometric, and body weight strengthening on dynamic postural control and vertical jump performance</p> <p><u>Study design:</u> RCT</p> <p><u>Methods:</u> 12 skiers in intervention group, 12 skiers in control group. Pre- and post-testing at baseline and at 8 weeks of YBT, CMJ and DJ.</p> <p><u>Intervention group:</u> neuromuscular warm-up exercises progressing through three phases of difficulty.</p> <p><u>Control group:</u> standard warm up exercises. Light aerobic exercise and dynamic stretching</p>	<p>Elite Junior Skiing Athletes</p> <p>Av age 18</p> <p>M</p>	<p>YBT showed significant improvement in the intervention group but not the control group. No significant differences (improvements or declines) of CMJ and DJ for either group.</p> <p>A NMT program incorporated into the warmup of elite skiers may be effective at improving LE joint awareness and improve postural control</p> <p>Conclusion: NMT to improve proprioception, LE joint biomechanics and dynamic balance could improve YBTs and therefore reduce injury risk.</p>	<p>NM warm-up exercises progressing through three phases of difficulty. Focus on the quality of movement and emphasis on core stability, hip control, and proper knee alignment.</p> <p>30 minutes 2x/week</p> <p>Exercises in the warm-up routine: Core stability & plyometric exercises in 3 phases.</p> <p>Exercises progressed were: plank, side bridge, one leg hip lift, split squat, front lunges, 2-legged calf raises, abdominal crunches, lateral jump & hold, back hyperextension on ground, tuck jump with soft landing.</p>	<p>>75% compliance</p>
Exercises from other sports					
Achenbach et al. (2018)	<p><u>Objective:</u> show how an injury-prevention programme effectively reduces severe knee injury in adolescent team handball players.</p> <p><u>Study design:</u> RCT</p> <p><u>Methods:</u> 23 adolescent handball teams. 13 randomly allocated to intervention group (168</p>	<p>Adolescent handball players</p> <p>Age 15-19</p> <p>M & F</p>	<p>The primary outcome parameter 'severe knee injury' occurred significantly more often in the control group (incidence 0.33/1000h) than in the</p>	<p>4 modules of exercises shown to prevent lower limb injuries</p> <p>1: Strength exercises (plank, side plank, Nordic hamstring)</p> <p>2: Plyometric exercises (multidirectional single leg jumps)</p>	

	players), 10 into control group (111 players). Handball exposure & sustained injuries documented for both groups. Primary outcome: incidence of knee injury. <u>Intervention group</u> : participated in an injury-prevention program for one season. <u>Control group</u> : usual training		intervention group (injury incidence 0.04/1000h) ($p=0.019$)	3: Jump and landing exercises ('ice-skater, jump jump run) 4: Proprioceptive exercises (one leg, eyes closed destabilise partner) Volume: 15 mins 2-3/week preseason, 15 mins 1/week in-season When: 10-12 weeks preseason, then full season	
Begalle et al. (2012)	<u>Objective</u> : quantify and compare quadriceps with hamstrings coactivation EMG ratios during commonly used closed kinetic chain exercises. <u>Study design</u> : cross-sectional study <u>Methods</u> : participants completed 9 separate closed chain therapeutic exercises in a randomized order. <u>Outcome measures</u> : surface EMG activity of VM, VL, MH & BF muscles. Q:H coactivation ratio computed as sum of average quadriceps (VM, VL)/ average hamstring (MH, BF)	Healthy, physically active volunteers Av age: 22 M & F	Smaller Q:H ratios during the SL deadlift than SL squat. Largest Q:H ratios observed during transverse-lunge, lateral-lunge), & forward-lunge exercises. (All $P < 0.001$). Most balanced (smallest) coactivation ratios observed during SL deadlift, lateral-hop, transverse-hop, & lateral band-walk exercises. These exercises potentially could facilitate balanced activation in ACL injury-prevention programs.	Recommended exercises based on Q:H balance: SL dead lift, lateral hop, transverse hop & lateral band walk. Not recommended: Lunge exercises (high Q:H ratios).	
Caraffa et al. (1996)	<u>Objective</u> : to assess the ability of a proprioceptive training program to reduce the incidence of ACL injury in soccer players. <u>Study design</u> : prospective controlled study with 40 soccer teams (600 players) <u>Methods</u> : 20 teams received special proprioceptive training over 3 seasons, 20 did not. <u>Intervention</u> : 5 phases of proprioceptive training, increasing in difficulty. <u>Control group</u> : training as usual	Soccer Semi-professional or amateur Age not specified M	10 ACL injuries in the intervention group (0.15 injuries/team/season) 70 in the control group (1.15 injuries/team/season) Significantly different ($P < 0.001$)	Following a neuromuscular facilitation technique: Proprioceptive training using a wobble board and step-up progression. 5 phases, each progressively more difficult. Volume: Daily during pre-season, at least 20 mins/day. Recommended to continue during season 3x/week.	ACL injury only recorded
Gilchrist et al. (2008)	<u>Objective</u> : examine whether the use of an alternative warm-up to enhance NM & proprioceptive control can reduce ACL injuries, specifically noncontact ACL injuries, in NCAA Division I female soccer athletes <u>Study Design</u> : RCT (clustered)	Soccer College level Av age 19 F 61 teams with 1435 athletes	Overall ACL injury rate: 1.7 times less than control ($P=0.198$; 41% decrease). Noncontact ACL injury rate: 3.3 times less than control ($p=0.066$; 70% decrease). No ACL injuries occurred among	Warm-up: jog, shuttle run, backward running. Stretching: Calf, Quadricep, Figure 4, hamstring, Inner thigh, Hip flexor. Strengthening: Walking lunges, Russian hamstring, Single toe-raises	PEP program. Only evidence for late season ACL injuries and

	<p><u>Methods:</u> participating teams assigned randomly to intervention or control groups. All teams reported athletes' participation in games & practices & any knee injuries. Injury rates calculated based on athlete exposures, (rate/1000 athlete exposures).</p> <p><u>Intervention:</u> teams asked to perform the PEP program 3x/week during fall 2002 season.</p> <p><u>Control group:</u> no intervention</p>	(852 control: 583 intervention)	<p>intervention athletes during practice vs 6 among control (P = .014). Game-related noncontact ACL injury rates reduced by more than half (0.233 vs 0.564; P = .218).</p> <p>Intervention athletes with history of ACL injury were significantly less likely to suffer another ACL injury compared with control athletes with similar history (P = .046 for noncontact injuries).</p>	<p>Plyometrics: Lateral hops, Forward/backward hops, Single leg hops, Vertical jumps with headers, Scissors jump</p> <p>Agility: Shuttle run with forward/backward running, Diagonal runs, Bounding</p> <p>Volume: 12 weeks total, length of season</p>	previous ACL injuries
Irmischer et al. (2004)	<p><u>Objective:</u> examine peak vertical impact forces (Fp) & rate of force development (RFD) following a 9-week, low-intensity (simple jump-landing-jump tasks) & volume (number of foot contacts per workout) plyometric-based KLIP program</p> <p><u>Study design:</u> cohort study</p> <p><u>Methods:</u> participants randomly assigned into control (n=14) & treatment (n =14) groups. GRF generated during a step-land protocol assessed at study onset & termination.</p> <p><u>Intervention group:</u> attended KLIP sessions 2x/week for 9 weeks</p> <p><u>Control group:</u> no intervention.</p>	Physically active Av. age 24 F 28 participants	<p>Significant reductions in Fp (p=0.0004) & RFD (p=0.0205) were observed in the treatment group.</p> <p>Results indicate that 9 weeks of KLIP training altered landing strategies in women to lower Fp & RFD. These changes are considered conducive to a reduced risk of knee injury while landing.</p>	<p>4 phase KLIP Jump Training Program to improve landing mechanics & reducing impact forces:</p> <p>Wall jumps, jump tucks, standing broad jump, bounding in place</p> <p>Wall jumps, jump tucks, 180's, double leg hops</p> <p>Jump tucks, single leg lateral hop</p> <p>single leg forward hop, double leg hops, 180's, single leg 45° hops.</p> <p>Wall jumps, single leg forward hops, double leg hops, 180's, standing broad jump, single leg 45° lateral hops.</p> <p>Volume: 20 minutes, 2x/week</p> <p>Duration: 9 weeks, progressively increasing number of foot contacts</p>	
Kiani et al. (2010)	<p><u>Objective:</u> investigate an intervention program specifically designed to improve awareness of injury risk, maximize adherence, and promote proper motion patterns to reduce the incidence of knee injuries among female soccer players</p> <p><u>Study design:</u> community based. Non-randomised regional approach with teams in one region assigned intervention, the other region control.</p>	Soccer Community level Age 13-19 F 1506 total participants, 777 in	<p>77% reduction in knee injuries, 90% lower incidence of non-contact injuries.</p> <p>No ACL injures in intervention group, 5 in control group.</p> <p>Reduction in number of knee injuries as well as seriousness of knee injuries.</p>	<p>Multifaceted HarmoKnee program combined with education of athletes, coaches & parents.</p> <p>Warm up: running, skipping, zig/zags</p> <p>Muscle activation: Holding + contracting to 'find' calf, quadriceps, hamstring, hip flexor, groin, hip & back muscles</p>	High compliance & continuation of the program after the study

	<p>Methods: over 9 months HarmoKnee program implemented in intervention teams. Acute knee injuries recorded in both groups</p>	intervention group		<p>Balance: Jumping focusing on proper take-off & landing Strength: Walking lunges, hamstring curls, single leg squat with toe raises Core stability: Sit-ups, plank, bridging Duration: 9 months. Full season + 12 weeks pre-season. Volume 2x/week.</p>
Krutsch et al. (2020)	<p>Objective: investigate whether specifically adapted preventive training modules reduces severe knee injuries in elite football. Study design: prospective controlled cohort study Assigned by team based on coaches' interest in participating. Methods: an IPP with 5 modules implemented in 2015–2016. 62 teams participated. Success documented by an injury report over one season. Primary outcome: reduction in severe knee injuries. Intervention: 26 teams used new trainings modules Control group: 36 continued their standard program</p>	<p>Soccer Elite players Av. age 22 M 529 players in intervention group</p>	<p>A pre-seasonal investigation identified five modules to be implemented in the training routine. The study group with the adapted training modules sustained 52 severe knee injuries (0.38/1000 h) compared to 108 severe knee injuries in the control group (0.68/1000h. ($p < 0.05$) Appropriate preventive training modules reduce severe knee injuries in elite football.</p>	<p>Exercises chosen by coaches from 5 modules: postural stability, mobilisation of lower extremity joints, leg and trunk stabilisation, jumping, and landing exercises & agility movements Pre-season & in-season, 12 minutes/training session, 2x/week. Key for sustainability of preventive training measures are programs specifically adapted to the demands of the playing level and preferences of the coaches.</p>
Letafatkar et al. (2015)	<p>Objective: determine the effects of perturbation training on knee flexion angle & NM characteristics in female athletes with QD deficit. Study design: pre-post intervention quasi experimental study Methods: EMG data of quadriceps & hamstrings (during single limb drop-landing), & knee flexion angles (during tuck-jump test) of female athletes with QD deficit completed at baseline & after 6 weeks. If performing tuck jump test there was excessive landing contact noise & peak knee flexion angle was $<30^\circ$ the women were considered as QD deficient.</p>	<p>Athletes F Av. age 24 29 total. 14 control 15 intervention</p>	<p>The VL-BF & VM-MH co-contraction in feed-forward & feedback phases significantly increased after perturbation training. Peak knee flexion angle significantly increased due to perturbation training effects on QD deficient women</p>	<p>Perturbation training. 6 weeks, 3 x 60-minute training sessions/week Exercises used rocker board, roller board, & roller board with stationary platform. Exercises progressed. The same verbal cues: “keep your knees soft,” “keep your trunk still”, & “relax between perturbations” used throughout. Balanced co-contraction ratios produced after perturbation training</p>

	<p><u>Intervention group:</u> 6 weeks of perturbation training over 18 sessions under physiotherapist supervision.</p> <p><u>Control group:</u> no intervention</p>			may benefit in anterior cruciate ligament injury-prevention.	
Mandelbaum et al. (2005)	<p><u>Objective:</u> determine whether a NM & proprioceptive performance program was effective in decreasing the incidence of ACL injury within a select population of competitive female youth soccer players</p> <p><u>Study design:</u> cohort study – prospective nonrandomized trial.</p> <p><u>Methods:</u> over 2 years female soccer players received training with education, stretching, strengthening, plyometrics, & sports-specific agility drills to replace the traditional warm-up.</p> <p><u>Intervention group:</u> sports-specific training intervention program</p> <p><u>Control group:</u> players from 95 teams participating in same league, age & skill matched. Regular warm up.</p>	<p>Soccer competitive</p> <p>F</p> <p>14-18y.o</p> <p>52 teams, 1041 in intervention group.</p> <p>95 teams, 1905 in control group</p>	<p>Year 1: 88% decrease in ACL injury in the enrolled subjects compared to controls.</p> <p>Year 2: 74% reduction in ACL tears in the intervention group compared to the age- and skill-matched controls.</p> <p>Using a NMT program may have a direct benefit in decreasing the number of ACL injuries in female soccer players</p>	<p>20 mins warm up program:</p> <p>3 basic warm up activities, 5 stretching techniques, 3 strengthening exercises, 5 plyometric activities, 3 soccer-specific agility drills.</p> <p>Heavy emphasis on technique with ‘soft landing,’ with hip & knee flexion.</p>	
Munro and Herrington (2014)	<p><u>Objective:</u> combine an expert & self-combination feedback protocol with the LESS to determine whether this will reduce FPPA during a DJ task.</p> <p><u>Study design:</u> Pre-post intervention study</p> <p><u>Methods:</u> measuring FPPA, dynamic knee valgus vGRF, 2D FPPA of the knee, contact time & jump height measured during a drop jump task pre- & post- an augmented feedback intervention.</p> <p><u>Intervention group:</u> received augmented video & verbal feedback</p> <p><u>Control group:</u> 8 students also studied at baseline & repeat test.</p>	<p>Recreationally active university students</p> <p>No specific sport</p> <p>Av. age 24</p> <p>20 participants total</p>	<p>Significant reduction in vGRF ($p=0.033$), FPPA ($p<0.001$) & jump height ($p<0.001$) & an increase in contact time ($p<0.001$) post feedback in the intervention group. No changes evident in the control group.</p> <p>Augmented feedback leads to significant decreases in vGRF, FPPA & contact time which may help to reduce ACL and PFJ injury risk. However, these changes may result in decreased performance</p>	<p>-Video observation of an expert performing a drop jump task</p> <p>-Completing a checklist regarding ideal landing</p> <p>-Video observation of their own landing with feedback on how to improve</p> <p>Augmented feedback reduces dynamic knee valgus, as measured via FPPA, & forces experienced during the DJ task & therefore could be used as a tool to decrease ACL & PFJ injury risk prior to, or as part of injury prevention training programs.</p>	<p>Small control group</p> <p>Feedback only provided one time.</p> <p>Decrease in jump performance following feedback.</p>

Myklebust et al. (2003)	<p><u>Objective:</u> assess the effect of a NMT program on the incidence of ACL injuries in female team handball.</p> <p><u>Study design:</u> prospective intervention study.</p> <p><u>Intervention:</u> a five-phase program (duration, 15 min) with 3 different balance exercises focusing on NM control & planting/landing skills. A physical therapist was attached to each team to follow up with the intervention program during the second intervention period. 1 control season, 2 intervention seasons.</p> <p><u>Main outcome measures:</u> number of ACL injuries during three seasons & compliance with the program.</p>	<p>Handball Division I, II & III players F No specific age 176 teams 2647 players</p>	<p>Control season: 29 ACL injuries 1st intervention season: 23 ACL injuries. 2nd intervention season: 17 ACL injuries In the elite division: Control season: 13 ACL injuries 1st intervention season: 6 ACL injuries 2nd intervention season: 5 ACL Risk of injury reduced among those who completed the program ($p < 0.01$) compared with those who did not. Entire cohort: no difference in injury rates during the second intervention season between those who complied and those who did not comply ($p = 0.31$).</p>	<p>Good compliance essential Exercises based on those developed by Caraffa et al. (1996) with a wobble board progression plus balance and floor exercises specific to handball. Duration: 5 weeks, 3 x weekly. No length of time per session specified. Focus on knee position over toe, two footed landing with emphasis on hip and knee flexion.</p>	<p>Statistically significant improvement only for elite players</p>
Naclerio et al. (2013)	<p><u>Objective:</u> determine the effects of a 4-week, lower body IPP, involving two unstable closed kinetic chain and one stable open kinetic chain exercises, on the force and optimal length of the knee flexors.</p> <p><u>Study design:</u> RCT</p> <p><u>Methods:</u> 20 participants randomly assigned to a training (n=10) or control group (n=10). Before & after a 4-week training period all participants performed a MVC hamstring test. Hamstring isometric knee angle–torque relationship assessed at 3 different angles.</p> <p><u>Intervention:</u> body weight training, 1 stable open chain exercise, & 2 unstable multi-joint, closed chain exercises.</p>	<p>Soccer College level M Av. age 23</p>	<p>Largest torque increases in training group at 35° & 80° knee flexion (11% & 15%) Pre- & post-test comparisons indicate a significant increase in torque at 80° knee flexion ($p = .001$). The 11% difference at 35° was associated with a moderate effect but did not reach statistical significance ($p = .081$) An IPP combining unstable closed kinetic chain exercises with stable open kinetic chain eccentric exercise increases force at a more closed position & possibly at more open angles on the knee angle–torque relationship.</p>	<p>Recommendations: Use of both stable-open and unstable-closed kinetic chain exercises emphasizing eccentric hamstring and knee stabilization. 3 sets of 8 reps of one open-chain exercise (Nordic curl) & two closed-chain exercises—forward lunges on a Bosu® & eccentric single leg dead lifts Exercises should emphasize specific joint and muscle functions including eccentric hamstring and knee stabilization exercises. Quadriceps & unstable exercise should be included Duration: 4-weeks, 3 sessions/week.</p>	

Olsen et al. (2005)	<p><u>Objective:</u> to investigate the effect of a structured warm-up programme designed to reduce the incidence of knee and ankle injuries in young people participating in sports.</p> <p><u>Study design:</u> cluster randomized controlled trial with clubs as the method of randomization.</p> <p><u>Intervention:</u> a structured warm-up programme to improve running, cutting, & landing technique as well as NM control, balance, & strength.</p> <p><u>Outcome measure:</u> rate of acute knee/ankle injuries over one season</p>	<p>Handball Aged 15-17 1837 participants in intervention group 879 in control group 90% F</p>	<p>129 acute knee or ankle injuries occurred. 81 injuries in the control group (0.9 injuries/1000 player hours) & 48 injuries in the intervention group (0.5 injuries/1000 player hours)</p> <p>Fewer injured players were in the intervention group than in the control group 4.8% v 8.6%</p> <p>A structured warm up program can prevent knee & ankle injuries in young people playing sports.</p>	<p>Recommendations: Structured warm up program as part of regular training. Focus on quality movement & progressing in difficulty Multi-directional warm-up. Sport-specific jumping and landing movements Sport-specific single leg exercises Nordic Hamstring exercises</p>	<p>Knee & ankle injuries</p>
Omi et al. (2018)	<p><u>Objective:</u> determine the effectiveness of a hip-focused ACL IPP in female basketball players</p> <p><u>Study design:</u> cohort study. 12-year Prospective Intervention Study. 4-year observation period, 8-year intervention period.</p> <p><u>Methods:</u> incidence rates of ACL injuries collected in observation period. Afterwards a hip-focused ACL IPP was implemented for 8 years. 309 players tracked in observation period & compared with 448 players in the intervention period. <u>Outcome measures:</u> AEs, ACL numbers, MOIs, RR, ARR, NNT, & compliance.</p>	<p>Basketball College level players F Av. age 19 775 participants</p>	<p>Observation period: 16 ACL injuries (13 noncontact MOIs), 0.25/1000 AEs</p> <p>Intervention period: 9 ACL injuries (8 noncontact MOIs), 0.10/1000 AEs</p> <p>Significant RR reduction was observed ($P=0.017$) with ARR and NNT of 0.032 & 31.6 respectively.</p> <p>The noncontact ACL injury incidence also showed significant RR reduction ($P=0.026$), with ARR and NNT of 0.024 & 41.3 respectively.</p>	<p>Multiple types of exercises that progressed in difficulty Sport-specific movements Focus on hip joint (strengthening of hip abductors and external rotators with open then closed kinetic chain) especially with jumping. High levels of compliance 20 minutes, 3x/week preseason and in season</p>	<p>Mean compliance rate during the intervention periods (8 years) was 89%.</p>
Pánics et al. (2008)	<p><u>Objective:</u> determine the contributing effects of proprioception on knee joint position sense among team handball players.</p> <p><u>Study design:</u> prospective cohort study Knee position sense measurements before and after the program.</p> <p><u>Methods:</u> 2 teams followed prospectively for one season. 20 players in the intervention team followed a prescribed proprioceptive training programme while 19 players in the control team did not have a specific training program. JPS</p>	<p>Handball Professional players F Mean age 23</p>	<p>The proprioception sensory function of players in the intervention team significantly improved ($p<0.05$). No improvement in the sensory function in the control team ($p<0.05$).</p> <p>Proprioception training improves the JPS in elite female handball players. This may explain the effect</p>	<p>Joint position sense increased after proprioception-focused training program based on Myklebust et al.'s program: Running in multiple directions Squats, DL & SL Wobble Board exercises & dynamic balance Sport-specific drills Stretches</p>	<p>Knee position sense improvements not reduced injuries.</p>

	measured. Assessments performed before & after the season.		of neuromuscular training in reducing the injury rate.		
Shimokochi et al. (2009)	<p><u>Objective:</u> examine the relationships of knee-extensor moment with ankle plantar-flexor & hip-extensor moments. To examine the relationship between knee moment & COP as a measure of NM response to COM position.</p> <p><u>Study design:</u> cross-sectional Study</p> <p><u>Intervention:</u> 18 participants performed a SL landing from a 45-cm box onto a force plate. Kinetic & kinematic data collected.</p> <p><u>Outcome measures:</u> Pearson product moment correlation coefficients calculated among KEMpk, sagittal-plane ankle & hip net internal moments, & anterior-posterior COP relative to foot COM at KEMpk.</p>	<p>Not sport-specific</p> <p>Recreationally active</p> <p>F</p> <p>Av. age 22.3</p>	<p>Lower KEMpk related to both greater ankle and hip moments.</p> <p>More anterior displacement of COP was related to greater Ankle moment & lower KEMpk</p> <p>Results suggest that participants who lean the whole body forward during landing may produce more plantar-flexor moment & less knee-extensor moment, possibly increasing hip-extensor moment and decreasing knee extensor moment production.</p>	<p>Recommendations:</p> <p>Encouraging a 'leaning forward' position during landing may be a technique to help stabilize the knee by decreasing quadriceps contraction demand while increasing hamstring contraction.</p>	
Stearns and Powers (2014)	<p><u>Objective:</u> determine the influence of a hip-focused training program on LE biomechanics during a DJ task.</p> <p><u>Study design:</u> Descriptive Laboratory Study</p> <p>Lower limb biomechanics assessed before and after training program</p> <p><u>Methods:</u> 21 women participated in a 4-week training program consisting of hip-focused plyometric & balance perturbation exercises (3 times/wk, 30 min/session).</p> <p><u>Outcome measures:</u> max isometric strength of hip extensors, hip abductors, & knee extensors assessed, along with LE biomechanics during a DJ task.</p>	<p>21</p> <p>recreationally active women</p> <p>Age 18-25</p>	<p>After training subjects demonstrated: Significantly greater max isometric strength of hip extensors ($P<.01$) & hip abductors ($P=0.004$). No significant difference in knee extensor strength.</p> <p>Significantly greater peak knee flexion ($P<0.001$) & hip flexion ($P=0.008$) & a lower knee/hip extensor moment ratio ($P =0.001$) with landing. Significantly lower peak knee abduction angles ($P=0.04$) & average knee adductor moments ($P<0.001$).</p>	<p>Focus: Hip Muscle performance with plyometrics & balance perturbation</p> <p>Duration: 4 weeks</p> <p>Frequency: 3 x 20-30 min sessions/week</p> <p>Progressions: 3 levels of difficulty, mostly increased time performing an exercise. Participants progressed to the next level only when able to perform current level exercises with correct form.</p> <p>Feedback: verbal & visual feedback at each session</p>	
Swart et al. (2014)	<p><u>Objective:</u> evaluate the cost effectiveness of training methods & screening strategies for preventing ACL injuries</p> <p><u>Study design:</u> cohort study - Economic evaluation</p>	<p>'Cutting sports'</p> <p>M & F</p> <p>14-22 y.o</p>	<p>Universal NMT of all athletes was the dominant strategy, with better outcomes & lower costs compared with screening. On average, the implementation of a universal NMT</p>	<p>Universal NMT of all athletes has better outcomes and costs compared to screening programs.</p>	<p>Mostly focused on cost</p>

Methods: a decision-analysis model created to evaluate 3 strategies for young athletes participating in organized sports: (1) no training or screening, (2) universal NMT, & (3) universal screening, with NMT identified high-risk athletes only.

Outcome measures: risk of injury, risk reduction from training, sensitivity & specificity of screening based on published data from clinical trials. Costs of training & screening programs estimated based on literature. Sensitivity analyses performed on key model parameters to evaluate their effect on base case conclusions.

program would save \$100/player/season & would reduce the incidence of ACL injury from 3% to 1.1%/season.

Screening not cost effective within the range of reported sensitivity and specificity values.

<p>Zebis et al. (2013)</p>	<p><u>Objective:</u> investigate the medial & lateral hamstring muscle activation balance during 14 selected therapeutic exercises. <u>Study design:</u> quasi-experimental design. <u>Methods:</u> EMG activity during 14 exercises compared for ST and BF activation. A two-way analysis of variance performed to determine differences.</p>	<p>Handball & soccer players Elite F Av. age 23</p>	<p>Kettlebell swing & Romanian deadlift targeted specifically ST over BF ($p < 0.05$) at very high levels of normalized EMG (73–115% of MVC). In contrast, the supine leg curl and hip extension specifically targeted the BF over the ST ($p < 0.05$) at very high levels of normalized EMG (75–87% of MVC)</p>	<p>Kettle Bell Swings & Romanian Dead Lifts specifically targeted ST over BF. These exercises are recommended as part of an IPP.</p>
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Focus on other aspects of program/how exercises are performed

<p>Cederström et al. (2021)</p>	<p><u>Objective:</u> evaluate enjoyment of MOTIFS training as compared to CaU knee injury training. <u>Study design:</u> block-randomized 2 × 2 cross-over trial Intervention group: MOTIFS training integrates sport-specific experiences and equipment into physical exercises to increase individualized realism and meaning. <u>Control group:</u> CaU - solely physical exercise.</p>	<p>Team ball sports Currently or previously active Age 18-31 50%M, 50%F</p>	<p>PACES scores were better following MOTIFS training than CaU. Between-groups differences in SAM Valence Arousal & Dominance, RPE, training duration, & pulse were higher following MOTIFS training than CaU training. * MOTOr Imagery to Facilitate Sensorimotor Re-Learning (MOTIFS)training</p>	<p>To increase enjoyment of a knee IPP: MOTIFS training is recommended. Integration of sport-specific experiences and equipment into physical exercises to increase individualized realism and meaning E.g. If ball sport, incorporate the ball. If skiing, incorporate skiing-like exercises or equipment. Mental imagery incorporated into every exercise. The mental image of the movement scenario was a main focus, e.g., dribbling past an opponent.</p>
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	Outcome measures: PACES, SAM; subscales (Valence, Arousal, Dominance), Perceived exertion, pulse, duration, & movement quality.				
Dawson and Herrington (2015)	<p><u>Objective:</u> compare hip-strengthening & skill-acquisition training to examine if they can improve LE biomechanics, potentially preventing injury, & to examine whether changes can be maintained after 6 weeks without practise.</p> <p><u>Study design:</u> controlled laboratory study (non-blinded)</p> <p><u>Methods:</u> 17 volunteers (9F, 8M) completed a 6-week study. 9 participants allocated to a hip-strengthening program; 8, to a skill-acquisition program</p> <p><u>Outcome measures:</u> Measurements of clam-exercise strength, hip-abduction strength, frontal-plane projection angle, hip-adduction angle, & a qualitative score taken at baseline, 6 weeks, & 12 weeks.</p>	<p>Recreationally active individuals</p> <p>F & M</p> <p>Av. age 27.8</p>	<p>Improvements in: frontal-plane projection angle ($P<0.001$), hip-adduction angle ($P<0.007$), & qualitative score ($P=0.005$) skill postintervention, which were retained at the 12-week retest in both groups.</p> <p>A 6-week intervention of either hip-strengthening or skill-acquisition training improved lower limb biomechanics. The changes in biomechanics after skill training were retained at 12 weeks, suggesting a change in motor patterning that could be favourable to longer-term injury prevention.</p>	<p>A 6-week intervention of strength-based or skill-based training induces meaningful changes in lower limb alignment during a single-legged squat.</p> <p>Skill & strength training induced the same improvements, but skill training had the additional benefit of reduced time to complete the intervention</p> <p>Frequency: 3x/week</p>	<p>Very small study group.</p>
Dix et al. (2021)	<p><u>Objective:</u> identify barriers to implementation of IPPs among collegiate women's soccer coaches.</p> <p><u>Study design:</u> cross-sectional survey</p> <p><u>Methods:</u> a custom survey based on the RE-AIM (reach, effectiveness, adoption, implementation, maintenance) framework & existing literature sent to coaches.</p>	<p>Soccer</p> <p>College level</p> <p>F</p>	<p>29 responses. 19 users of IPP's, 10 non-users of IPP's.</p> <p>Cost most highly ranked barrier to implementing an IPP among Non-users. "Who should be responsible for completing an IPP," Users said "Coaches" (47%) & "Other" (21%). Non-users said "Strength & conditioning" (50%) & "Athletic trainers" (30%). Respondents who marked "Other", elaborated that it was the responsibility of coaches, athletes, and additional staff members.</p>	<p>Barriers to implementing an IPP: Cost, adherence</p> <p>Recommendations: Team-based approach with coach and rehabilitation professional, assigning responsibilities to athletes</p>	
Finch et al. (2014)	<p><u>Objective:</u> to describe the structure implemented programs & compares players' end-of-season views about program variants.</p>	<p>Australian</p> <p>Rules Football</p>	<p>Participants in the NMC program found it less physically challenging but more enjoyable & potentially of</p>	<p>Most frequently made suggestions by participants:</p> <ul style="list-style-type: none"> - Shorter duration <15 minutes - More variety of exercises/drills 	

	<p><u>Study design:</u> study was nested within a larger group clustered RCT of the effectiveness of two exercise-training programs (control & NMC) for preventing knee injuries.</p> <p><u>Methods:</u> a post-season self-report survey, derived from Health Belief Model constructs, included questions to obtain players' views about the benefits & physical challenges of the program in which they participated.</p>	<p>Community level M >18 years old 442 players completed survey</p>	<p>more benefit. Suggestions from players about improvements & future implementation included: reducing duration, increasing range of drills/exercises & promoting its injury prevention & other benefits to players. Players provide valuable feedback about the content and focus of implemented exercise-training programs, that will directly inform similar, or more successful future programs.</p>	<p>Any program must include all components of balance, plyometrics & technique & ensure cues for correct side-stepping & landing movements. Promotion of injury prevention & other benefits to players. NMC exercises are more enjoyable.</p>	
<p>Welling et al. (2017)</p>	<p><u>Objective:</u> determine the effects of verbal external focus (EF), verbal internal focus (IF) & video instructions (VI) on landing technique (i.e., kinematics and kinetics) during training & retention.</p> <p><u>Study design:</u> RCT</p> <p><u>Methods:</u> 40 athletes assigned to the IF (n=10), EF (n=10), VI (n=10) or CTRL group (n=10). A jump-landing task was performed as a baseline, followed by two training blocks & a post test. One week later, a retention test was conducted without specific instructions or feedback. Kinematics and kinetics were captured using a motion analysis system</p>	<p>Healthy ball sports athletes M & F Av. age 22</p>	<p>Males and females in the EF & VI instruction group showed beneficial results during & after the training session, in terms of improved landing technique. Retention was achieved after only a short training session.</p>	<p>Retention of movement technique depending on instruction type. ACL IPPs should include EF and/or VI instructions to improve kinematics and kinetics and achieve retention. External focus and video instruction on landing technique resulted in correct movement retention for landing technique one week later. A verbal internal focus did not.</p>	<p>No long-term retention testing</p>

Abbreviations: ARR - Absolute Risk Reduction, AE - Athlete-Exposures, AV. – Average, BF – Biceps Femoris, CaU – Care as Usual, COP – Centre of Pressure, COM – Centre of Mass, DJ – Drop Jump, EMG – Electromyographic, EM - Extensor Moment, F – Female, FPPA - Frontal Plane Projection Angle, GRF - Ground Reaction Force, INT – Integrative Neuromuscular Training, IPP – Injury prevention program, JPS - Joint Position Sense, KEMpk - Net Peak Knee-, KLIP – Knee Ligament Injury Prevention, LE – Lower Extremity, LESS – Landing Error Scoring System, M – Male, MH – Medial Hamstring, MVC – Maximum, Voluntary Contraction, MOI - Mechanisms Of Injury, NNT - Numbers Needed to Treat, , NMC – Neuromuscular Control, NMT – Neuromuscular Training, NM – Neuromuscular, PACES – Physical Activity Enjoyment Scale, PEP Program – Prevent Injury and Enhance Performance, QD – Quadriceps dominance, Q:H – Quadricep: hamstring, RCT – Randomized, control trial, RR - Relative Risk, SAM - Self-Assessment Manikin, SL – Single leg, ST – semitendinosus, vGRF – Vertical Ground Reaction Force, VL – Vastus Lateralis, VM - Vastus Medialis

3.2.4.2 Summary of review articles

Thirty-three review articles were identified and recommended the following rehabilitation components: strength training (15), plyometrics (13), multiple components/variety (12), balance (10), core strengthening (8), pre-season training (8), neuromuscular training (8), agility training (6), be completed as a warm up (6), sport specific exercises (6), hamstring strengthening (5), stretching (5), balance not effective on its own (5), at least 20 minutes/session (5), visual and verbal feedback (4), landing technique (4), proprioceptive exercises (4), high compliance (4), programs to include measurable performance gains (3), hip exercises (3), high levels of feedback (3), running (2), coach-led (2), single leg exercises (2), exercises addressing knee valgus (2), external focus, education around injury mechanisms (2), at least 3x/week (2), at least 6 weeks (1), longer duration (1), with a healthcare professional present (1), speed training (1), implicit learning (1), progress neurocognitive challenges (1), be longer than 3 months (1), be completed at every training session (1), eccentric training (1), mobility (1).

4. DISCUSSION

The aim of this scoping review was to map existing research in the field of skiing and knee injury prevention to determine what an exercise-based program to reduce the risk of knee injuries in ski instructors should include, and how it could best be implemented. There is a paucity of research in this area, however by searching existing research in the areas of skiing injury risk reduction, mechanisms of knee injury while skiing, and exercise-based programs in other sports, evidence-informed recommendations for a potential program design and for future research can be made.

4.1 Existing research for reducing skiing knee injuries

4.1.1 Existing non-exercise-based prevention strategies

For decades ski equipment has been studied, and modified to reduce the risk of knee injuries in both recreational and elite skiers (Spörri et al., 2017). Research in this area continues to the present, for example, Ruedl et al. (2022) have recently been investigating ski shapes and dimensions and their relation to ACL injuries. They aimed to evaluate the impact of ski geometry on ACL injury and found that an increase in ski length, tip width of the ski, standing height at the rear ski binding were independent equipment-related risk factors for an ACL injury. They suggest shorter skis, narrower ski tips, and lower rear binding heights to reduce ACL injury risk, due to the reduced external rotation and shorter lever arms these ski shapes result in.

Other injury prevention strategies suggested in the literature include; ensuring bindings are correctly adjusted, ensuring runs are not overcrowded, skiing at a slower speed (Koehle et al., 2002), addressing low visibility issues, optimizing trail design and signage (Bianchi & Brügger, 2015; Hume et al., 2015), to ski within one's ability level, and to not ski while fatigued (Swedberg et al., 2016). None of the above studies focused on ski instructors specifically but the recommendations to ski within one's ability level, and not while fatigued are relevant to ski instructors as they ski very frequently and for long durations every day (Viola et al., 1999).

4.1.2 Existing education-based prevention strategies

There were three programs that looked at the impacts of an education program (Ettlinger et al., 1995; Jørgensen et al., 1998; Roberts, 2013). Ettlinger et al. (1995) utilized a training program which had ski instructors watch a video to learn about common mechanisms of injury.

Jørgensen et al. (1998) had recreational skiers watch a video while on a bus whilst travelling to the ski hills. The video contained general information on a number of topics including proper equipment selection and warming up.

Roberts (2013) had mountain employees (which included instructors) attend a 30-minute proprioception awareness workshop, which involved learning about spine and pelvis stabilization, and simple proprioception drills to increase stability at the spine, hip, knee, and shoulder. Stability was stressed from the perspective of enhanced performance as well as to decrease the risk of injury. Other studies have shown that if a program enhances performance it will get more compliance (Hewett et al., 2006). All three of these studies resulted in a reduction in injuries, indicating that an educational component to an exercise program could be beneficial. This is potentially because if a ski instructor is aware of common causes of knee injury, they will try to avoid those putting themselves in those situations. Mehl et al. (2018) have also recommended an educational component about typical mechanisms of injury and potential modifications to endangering movements.

Ettlinger et al. (1995) is cited frequently, possibly because it is one of the only studies in the area of knee injury prevention in skiing, and possibly because it had remarkably high injury prevention results. They provided ski instructors and patrollers with educational training, showing videos about common injury mechanisms. Staff from 20 ski resorts, who participated in the training, reduced their risk of a serious knee injury by 62% over three years when compared to a control group of staff from 22 different ski resorts which received no training. This study, however, has been criticized for its methodological quality with poor data reporting, scoring 20/100 possible points in an evaluation by Thacker et al. (2003). The study also took place during a time when skis and binding shapes and technology were changing rapidly, therefore making their results less applicable to the current period.

4.1.3 Existing exercise-based prevention strategies

There is a clear lack of research in the area of exercise-based knee injury prevention strategies for ski instructors. The initial search for existing programs returned 12 results with relevant information on injury prevention for skiing, two of which had ski instructors as part of their study population. There were no studies found that directly looked at an exercise-based IPP for ski-instructors. There were three previously mentioned programs that looked at the impacts of an education program (Ettlenger et al., 1995; Jørgensen et al., 1998; Roberts, 2013). Three looked at the effect of exercise on knee injury prevention (Roberts, 2013; Vitale et al., 2018; Westin et al., 2020). Ettlenger et al. (1995) utilized a training program which had ski instructors watch a video to learn about common mechanisms of injury.

Roberts (2013) investigated injury prevention for ski instructors, lift operators, and ski patrollers. Prior to the season, participant's knee stability was evaluated using a validated assessment tool (Developed by Performance Stability (Ludlow, UK)) with two independent assessors. Only 7% of participants were determined to have 'good stability'. As the season commenced staff were offered printed materials and workshops in nutrition and proprioception. The 30-minute proprioception workshop focused on body positioning, including drills to help increase spine, hip, knee, and shoulder stability. The result was an 65% overall reduction in employee injuries at participating resorts, compared to resorts which did not use the program ($P < 0.0001$) and a reduction in injuries requiring time off work ($P < 0.06$). The location of injuries was not recorded however, just the total number of injuries. Roberts (2013) also looked at improving eating habits of employees to improve blood glucose stability. It is unclear whether the nutritional, or proprioceptive component of the study contributed to the results. No post-intervention stability testing was completed due to the difficulties of conducting research in a workplace setting; therefore, it is unknown whether the proprioception workshop helped to increase knee stability.

Westin et al. (2020) implemented an exercise-based program for students at a Swedish ski high school which successfully reduced ACL injuries by 45%. The program, like previous mentioned studies, consisted of watching a video about ACL injuries and their prevention every three weeks. It then had indoor and outdoor (on skis) neuromuscular focused exercises, concentrating on single leg exercises being performed to the same level on both sides, as well as core strengthening. The definition of performing to the same level was not clarified nor measured; no techniques were given for how this was achieved.

This program by Westin et al. (2020) involved exercises/drills while skiing. To increase enjoyment, and therefore compliance, Cederström et al. (2021) recommend incorporating sport specific experiences and equipment. Programs that both improve performance and prevent injury are shown to have higher compliance (Hewett et al., 2006). An exercise program for ski instructors could also contain exercises performed on skis. Exercises on skis that could both improve performance and reduce injury risk could include single leg exercises, jumping exercises, and exercises using audio and visual cues to change directions.

This high school cohort (Westin et al., 2020) is a similar population in some respects to ski instructors, as the participants skied every day. The age group for this study was 16–19-year-olds, which is younger than the average age of most ski instructors and therefore not as comparable. Likewise Vitale et al. (2018) looked at an exercise program for junior ski racers (average age 18) who skied 6 days per week. They used an 8-week body weight training program, as part of a warmup, which included plyometrics and core exercises. This resulted in an improvement in Y-balance test scores, a relevant test for the ski instructor population, which correlates to lower extremity injury risk (Plisky et al., 2009).

Other researchers have conducted literature searches for exercise-based IPPs for skiing. Their results have been comparable to those of this study. Hébert-Losier and Holmberg (2013) conducted a

systematic review to determine what exercise-based injury prevention recommendations there were for recreational skiing and snowboarding. Out of 30 studies identified, none contained exercise recommendations. The majority of studies recommended either making equipment changes, or third party involvement (such as ski resorts improving signage) as a primary method of reducing injuries. Koehle et al. (2002), Swedberg et al. (2016), and Davey et al. (2019) all found no existing exercise-based IPPs but recommended one be developed. Overall, in our search of the existing literature, there were eight studies found that recommend exercise as a method of injury prevention for skiers. Three of these eight studies investigated the effectiveness of exercise as a method of injury prevention for skiers. The remaining five studies made generic recommendations for exercise for injury prevention for skiing, commenting on the likely benefits of pre-season conditioning and ski-specific exercise programs and the need for research in this area.

4.2 Common mechanisms of knee injury while skiing and options to mitigate

Many mechanisms were identified as causing knee injuries, with the result often being a valgus moment of the knee, with an external rotation of the tibia; a rapid forwards movement of the tibia, with a backwards movement of the skier's centre of mass (COM); or knee hyperextension. A 'backwards fall' was the most common mechanism of injury identified. This is frequently the result of the skier landing with their COM towards the back of their skis, resulting in their skis moving rapidly forwards, often resulting in a valgus movement of the knee, coupled with an anterior pull of the ski boot on the shin.

4.2.1 Implications for exercise-based prevention

Bahr and Krosshaug (2005), in their recommendations for injury prevention research, state that among the key program components to include, a comprehensive understanding of the mechanism of injury is required. Given the common mechanisms of knee injury while skiing it could be recommended

that programs contain exercises to address landing techniques, knee valgus movements, hamstring strength and overall balance, trunk, and knee stability.

Aune et al. (1995) specifically looked at the contraction of knee flexors and extensors relating to a backwards fall in skiing. They determined that knee flexor (hamstring and gastrocnemius) activity upon landing while skiing may protect the knee, but probably not enough to prevent an ACL tear. Bere et al. (2013) suggested that exercises should be dynamic and try to minimize tibial internal rotation and valgus movements. Fu et al. (2019) suggested training 'a neutral landing' and quadricep strengthening so that a skier can recover from a backwards fall. Similarly, Hame et al. (2002) recommend being able to recover from a hyperflexion position and Heinrich et al. (2021) recommended landing position training to improve hamstring muscle activation patterns and reduce peak ACL force when landing. Overall, these studies suggest a need for physical conditioning that increases a skier's physical robustness and resilience. Because training to specifically avoid certain kinematics is difficult, in this context, the use of videos demonstrating the common mechanisms of knee injury would also be helpful.

Based on the studies reviewed, and their research into mechanisms of knee injury while skiing, an exercise program to prevent these injuries would include jumping and landing training, exercises which can improve resilience to knee valgus movements, exercises to help recovery from a knee hyperflexion position, and strengthening of knee and trunk musculature, particularly hamstring muscles. These exercises could be combined with the use of videos to educate ski instructors on the common injury mechanism.

Many of these injury mechanism studies related to injury of competitive skiers, either racers or freestyle specialists. Rossi et al. (2003) suggested that ski instructors spend a considerable amount of time skiing at low speeds and below their skill level, in which case the backwards fall mechanism may not be as common. The mechanism of injury of a ski instructor is likely to be more similar to that of a

recreational skier, than a competitive skier. Ruedl et al. (2011) found a forward twisting fall to be the most common mechanism of ACL injury in recreational skiers. An IPP program for ski instructors should include exercises to address this mechanism of injury

4.3 Exercise program components

4.3.1 Structure and seasonal timing of a program

The length of reviewed programs ranged between 4 and 16 weeks, with about 12 weeks most common. Several successful studies (6) recommended the programs take place both pre-season and in season. These studies were mostly based on a long soccer season with for example 12 weeks of pre-season training followed by 6 months of in-season (Kiani et al., 2010). With a typical ski season only being 4-5 months, an ideal program would likely be 6 months in duration, with potentially less progression of exercises than there might be over a soccer season. Reviews have suggested that the longer the program, the greater the neuromuscular training (NMT) prophylactic effects are. (Mehl et al., 2018; Sugimoto et al., 2014).

A pre-season training component is also recommended by Mehl et al. (2018) in their guidelines for knee and ACL injury prevention, with pre-season training programs showing significantly greater effects than in-season alone. Alentorn-Geli et al. (2009) hypothesised that due to the length of time required for motor learning to occur, an exercise program will be more effective to begin pre-season, and in addition, that fatigue later in the season makes learning new motor patterns difficult. Compliance with an exercise program is critical to its' success however (Sugimoto et al., 2012) and it's likely an in-season program would have greater compliance, as instructors could complete it directly before going to work. It would also be more cost-effective (Alentorn-Geli et al., 2009). Because of this, a program that started with a pre-season block of higher frequency and continued with less frequency through to the

midway point of the ski season would be most ideal. With the seasonal nature of their work, ski instructors may not be physically present pre-season to participate in an exercise program. Engagement with stakeholders would be key here to determine how a preseason component could be implemented, potentially online.

Training programs of 15-30 minutes were most common, with exercises performed a minimum of once per week, but most commonly three times per week, and usually as part of a warmup. Some programs recommended higher frequency during pre-season than in-season, with others recommending the opposite, largely based on the length of the season. Sugimoto et al. (2014) found that programs 20 minutes or longer in duration had greater reductions in ACL injuries. When surveying community Australian Football players on their preferences for an IPP, a shorter duration (<15 minutes) was a frequent suggestion. To both maximize efficacy and compliance a 20-minute training session would be recommended.

Strength and conditioning literature suggests lower extremity strength training 2-3 times per week, with no proven benefit to higher frequency (Ralston et al., 2018). If following a higher frequency preseason and a lower frequency in season, a program for ski instructors could be conducted three times/week preseason and 2 times/week in season, with 20-minute sessions for a total duration of 6 months.

4.3.2 Components of a program

Of the reviewed studies, 15 incorporated NMT. NMT consists of exercises aimed at improving sensorimotor control and attaining functional joint stabilization by addressing the quality of movement in all three movement planes (Ageberg & Roos, 2015). NMT for the lower extremities typically involves multiple joints and muscle groups performed in functional weight-bearing positions (Ageberg & Roos, 2015). Emphasis is on the quality and efficiency of movement, as well as alignment of the trunk and

lower limb (LL) joints (Ageberg & Roos, 2015). NMT has been shown to be effective in reducing knee injuries, particularly ACL injuries in young females (Yoo et al., 2010). Given the higher age of ski instructors, there needs to be more research to confirm the effectiveness of NMT in an older population.

Plyometric exercises are an effective method to train landing mechanics and dissipate landing forces, as well as the fast recruitment of LL musculature (Doeringer et al., 2018). Landing techniques and plyometrics exercises were frequently cited as components of a successful knee IPP with some studies saying they are essential components (Finch et al., 2014). In contrast, Sugimoto et al. (2015) found greater ACL injury reduction between programs that included plyometrics and those that did not, but this was not statistically significant. Given many knee injuries happen in skiing from jumping landings and backwards falls, plyometrics could be beneficial, and should be included in a program for ski instructors.

Strength training components recommended by reviewed studies included hamstring strengthening, (Zebis et al., 2013), eccentric training (Koller et al., 2015), and hip strengthening exercises to address knee valgus (Omi et al., 2018) and a focus on the non-dominant leg (Koller et al., 2015; Westin et al., 2020). Hamstring muscles are important because they resist anterior translation of the tibia relative to the femur, and work with the quadriceps for general knee stabilization and protection, which is relevant for ACL injury prevention in alpine skiing (Koller et al., 2015). Koller et al. (2015) showed that recreational skiing was associated with prolonged eccentric quadriceps and hamstrings fatigue and therefore suggested eccentric exercises as part of a training program. Their assumption is that concentric types of endurance training (eg, biking, walking) do not prevent fatigue during eccentric (ie, skiing) types of endurance exercise. Further research is warranted here (Koller et al., 2015). Hamstring exercises recommended included Nordic hamstring curls, kettlebell swings, Romanian deadlifts (RDLs), and single leg RDLs. Decreased hamstring strength relative to quadriceps is implicated

as a potential contributor to increased LL injuries and potentially ACL injury risk, particularly in female athletes with Q.D deficit. Q.D refers to the tendency to stabilize the knee primarily using the quadriceps muscles, this deficit can alter co-contraction of hamstrings and quadriceps (Letafatkar et al., 2015). Begalle et al. (2012) showed that a single leg RDL exercise showed the most balanced quadriceps: hamstring ratio. Single leg RDL's would therefore be good exercises to include in the suggested program.

Core stability is defined as the ability to maintain proper alignment of the lumbopelvic-hip complex in various postures and loading conditions (Willson et al., 2005). There is a clear relationship between trunk muscle activity and lower extremity movement (Willson et al., 2005), therefore Fischer (2006) recommends core strengthening as part of a comprehensive NMT program as it is possible that core muscle weakness, may contribute to increased valgus movement at the knee and therefore increased risk of ACL injury. Clinical guidelines (Arundale et al., 2018) state there is level I evidence (from high quality systematic reviews or Randomised Controlled Trials) for the inclusion of core and proximal stability exercises in a knee IPP. Programs that did not include core/proximal control exercises did not reduce injury rates (Arundale et al., 2018). Sample core exercises from the reviewed studies include: plank, side-plank, bridges and crunches.

In line with the common mechanisms of knee injury while skiing, controlling knee valgus movements is important. Plyometrics, single leg, and multiple direction exercises have been suggested to improve knee kinematics and more importantly to increase resilience to knee valgus (Barendrecht et al., 2011; Fischer, 2006). Munro and Herrington (2014) specifically looked at the impact of video feedback on improving drop landing strategies. They found that augmented feedback led to significant decreases of dynamic knee valgus and forces experienced during a drop jump task and should be implemented as part of an IPP. This study was completed in a closed, laboratory setting however, and it is not known how these improvements might transfer to more functional tasks in open environments.

A multifaceted program is more effective than a single component exercise program for reducing ACL injuries (Arundale et al., 2018). Dargo et al. (2017) found that no single component of strength, balance, plyometrics, running or stretching were more successful than others. When community football members were surveyed about their preferences for an exercise training program one of the most frequent items of feedback was for more variety (Finch et al., 2014). Therefore, a potential IPP for ski instructors should have variety of exercises and types of exercises

4.3.3 How a program is implemented

Many of the studies involved an exercise program incorporated into a warmup. It appears the main benefit to this structure is it saves time. It can be more practically implemented and adhered to. (Voskanian, 2013). For example, Gilchrist et al. (2008) had soccer teams replace their regular 20-minute warmup with a 20-minute neuromuscular focused warmup, resulting in no extra time or sessions per week required for its implementation. This is true if, especially in the case of team sports, a warmup and practice session are already occurring. However, transferring this to a ski instructor's daily routine is likely to result in extra time required. If a ski school is running training for instructors, a warmup could be incorporated into this training. Another benefit of a warmup program is that there is no extra equipment required, and it can take place in any location (Herman et al., 2008), which could include on snow, with exercises such as those use by Westin et al. (2020) which included ski shuffles and turns with the inside ski lifted.

Other aspects of an IPP that appeared in the search results related to how exercises were implemented. Some studies focused on motor learning concepts with two studies describing how implicit learning improves motor skill acquisition and improves the effectiveness of IPPs (Benjaminse & Otten, 2011; Gokeler et al., 2018) and two studies emphasizing the importance of an external focus (Gokeler et al., 2018; Welling et al., 2017). The aim of implicit learning methods is to minimise the

amount of explicit knowledge about the performance of a skill, for example by using analogy instructions (Gokeler et al., 2018). An external focus is induced when a participant's attention is directed towards the outcome of a movement, for example instructions to 'jump and land on the marker' (Gokeler et al., 2018). These motor learning could easily be implemented to an IPP for ski instructors.

With regards to implicit learning, Benjaminse and Otten (2011) suggested that participants must be able to see themselves performing a task (such as a jump landing) and problem-solve independently to improve technique. Having an external focus when performing an exercise promoted an automatic process and better transfer to sport-specific skills (Benjaminse et al., 2015). Instructions for a task can easily be modified to promote an external focus for example with a single leg RDL instructions could be 'stand on one leg and tip forwards to make a T-shape'. These strategies to optimize motor learning in the context of a knee IPP are also supported by Gokeler et al. (2018), who emphasise the need for ACL IPP's to be more tailored to the sport and individual and involve more complex, open environments.

Cederström et al. (2021) looked at the use of motor imagery in knee injury prevention training. They found that when sport-specific experiences, equipment or imagery was incorporated, participants enjoyed the program more. For example, in a program for ski instructors there could be video or mental imagery of tasks such as skiing moguls. The use of ski poles could be a way of incorporating ski equipment into an indoor training session.

Other studies focused on the implementation of an exercise program. Pfile and Curioz (2017), in their review of ACL injury prevention programs for female athletes, recommend programs to be coach-led as these programs were found to be equally effective for injury prevention as those led by healthcare professionals but at a lower cost. Similarly, Hewett et al. (2006) in a meta-analysis found that coach-led programs were more likely to have good compliance, potentially because the coaches also

don't want their players to be injured, and are personally more invested than an external professional. Dix et al. (2021) looked at barriers coaches faced when implementing an IPP. They recommend a team-based approach where coaches, rehabilitation professionals and athletes all contribute. In addition, there is evidence to suggest that group/supervised programs are easier to implement and adhere to (Burke et al., 2005). In a ski school context, the cost-savings and trainer buy-in would also be relevant when considering who to lead a program. Ideally an instructor trainer would lead the training, with guidance from a physiotherapist, following Padua et al. (2014)'s successful "train the trainer" approach, where trainers are provided with ample time and resources to gain competence with exercises, self-efficacy, and leadership, and program design and implementation barriers are considered along with solutions before going live with the program.

4.4 Limitations

There were very few studies that were focused on exercise-based knee injury prevention for skiing and none specifically on a ski instructor population. Most exercise programs found were based on soccer or other team sports. It is unclear how much correlation there is between team and individual sports or between sports and professions in terms of program efficacy. Potential programs could have been looked into in more depth from an occupational health perspective.

Of ski instructors who are members of the PSIA, the average age is 50, and 70% of members are male (PSIA, 2012). Many of the existing programs have focused on young female athletes. It is not known how applicable these programs are for an older population. Research based on an exercise program with a wider age range and mixed gender participants would be valuable to the ski instructor population. This could also have been investigated more thoroughly, potentially with an additional search strategy. Components of IPPs for masters athletes may be applicable to include such as

cardiovascular endurance training (Catapano et al., 2022) especially given ski instructors ski all day (PSIA, 2021).

4.5 Applications

Prior to the implementation of this suggested program (see below), further research into real world contexts, and implementation facilitators and barriers is warranted. Frameworks such as Translating Injury Prevention into Practice (TRIPP) (Finch, 2006) and Padua et al. (2014)'s seven step process help translate research findings into practical, effective interventions that can be applied in the real world. A recent review by Ross et al. (2021) found that most IPPs were lacking data about key implementation factors and few were informed by the context in which the strategy was implemented (TRIPP stage 5). They suggested that prior to implementation, key stakeholders and end users are engaged. In this case that would mean qualitative research with ski areas, ski instructor associations, and ski instructors. Padua et al. (2014) recommended investigating the following barriers prior to implementing a program: time (time of day, frequency, duration), personnel (who would be leading the training), environment (location, equipment availability), organization (organization/s goals and support). This would be especially relevant in determining how a pre-season training component could work. For example, would an online option be well-received?

As discussed earlier, watching videos of common knee injury mechanisms while skiing has been shown to effectively reduce injuries. An exercise program, as outlined below, combined with the use of educational videos could make an ideal program for reducing knee injuries in ski instructors.

Based on the evidence surrounding this topic, components of an exercise-based IPP for ski instructors have been summarised and are presented in table 6.

Table 6.

Summary of components for an exercise-based injury prevention program for ski instructors

Component	Details
Duration and frequency	Pre + in-season 20-minute sessions 2-3 times/week Ideally as a warm up
Exercises	Exercises to improve knee joint control and to limit valgus, hyperextension and hyperflexion movements Plyometrics – including landing drills A variety of lower limb exercises with a neuromuscular focus Single leg, hamstring and core exercises Include ski-specific exercises and imagery
Other factors for successful implementation	Led by a ski instructor trainer Use an external focus and video feedback to enhance motor learning Implemented at the resorts, potentially remotely in the lead up to the ski season and then incorporated into training as a warmup during the winter season Formatted to work with the timing and everyday work demands of ski instructors

CONCLUSION

The mapping of evidence by this scoping review is significant and sets the stage for the development of an exercise-based knee injury prevention program for ski instructors. There is a lack of research on exercise-based IPP's for ski instructors, and little in the wider field of skiing in general. Based on the literature reviewed, the types of exercises, time elements, learning strategies and other components have been suggested and could form an appropriate program. This program could be accompanied by educational videos regarding common mechanisms of injury. There are numerous examples of successful programs from other sports but their applicability to the older age of ski instructors, and the seasonal nature of their work isn't known. More research is needed in this area. Future research, such as an RCT investigating the effectiveness of such a program would be essential, as would qualitative input into its' content from identified stake holders.

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