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Prevention strategies and modifiable risk factors for sport-related concussions and head impacts: A systematic review and meta-analysis

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Abstract (348 words):

Objectives: This systematic review evaluated which sport-related concussion (SRC) prevention strategies are associated with reduced concussion risk and/or head impact risk. Unintended consequences and modifiable risk factors for SRC were also examined.

Design: This systematic review and meta-analyses were registered on PROSPERO (CRD42019152982) and conducted according to PRISMA guidelines.

Data sources: Eight databases [MEDLINE, CINAHL, APA PsycINFO, Cochrane (Systematic Review and Controlled Trails Registry), SPORTDiscus, EMBASE, ERIC] were searched in October 2019 and March 2022, and reference hand search from any identified systematic reviews.

Eligibility criteria for selecting studies: Study inclusion criteria were: (1) original data human research studies; (2) investigated SRC or head impacts; (3) evaluated an SRC prevention intervention or modifiable risk factor; (4) participants competing in any sport; (5) analytic study design; (6) systematic reviews and meta-analyses were included to identify original data manuscripts in reference search; and (7) peer-reviewed. Exclusion criteria were: (1) review articles, pre-experimental, ecological, case series, or case studies and (2) not written in English.

Results: In total, 220 studies were eligible for inclusion and 192 studies were included in the results based on methodological criteria as assessed through the Scottish Intercollegiate Guidelines Network (SIGN) high (“++”) or acceptable (“+”) quality. Evidence was available examining protective gear (e.g., helmets, headgear, mouthguards) (n=39), policy and rule changes (n=43), training strategies (n=34), SRC management strategies (n=12), and modifiable risk factors (n=64). Meta-analyses demonstrated a protective effect of mouthguards in collision sports (IRR=0.74;95%CI:0.64-0.89). Policy disallowing bodychecking in child and adolescent ice hockey was associated with a 58% lower concussion rate compared with bodychecking leagues (IRR=0.42;95%CI:0.33-0.53). In American football, strategies limiting contact in practices were associated with a 64% lower practice-related concussion rate (IRR=0.36;95%CI:0.16-0.80). There is some evidence to support up to 60% lower concussion rates with implementation of a neuromuscular training warm-up program in rugby. Current SRC management strategies may also reduce rates of recurrent concussion.

Conclusions: Policy and rule modifications, personal protective equipment, and neuromuscular training strategies may help to prevent SRC. Future research examining prevention strategies should incorporate prospective research designs to evaluate effectiveness, target understudied populations (e.g., women/girls, para-athletes), and integrate multifaceted methodological considerations (e.g., validated concussion surveillance, video-analysis, and instrumented mouthguards).

Systematic review registration: PROSPERO (CRD42019152982)
https://www.crd.york.ac.uk/PROSPERO/display_record.php?RecordID=152982

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What is already known?

- Primary prevention strategies in sport can reduce the high burden of concussion
- Policy eliminating body checking in ice hockey can substantially reduce concussion rates in children
- More evidence is needed to support the protective effect of mouthguards, additional padding in American football helmets, appropriate helmet fit in collision sport, policy limiting contact practice in adolescent American football, head contact rule enforcement in contact sports, and training strategies targeting modifiable intrinsic risk factors

What are the new findings?

- Mouthguards are associated with a 26% reduced rate of SRC in collision sports
- Headgear is associated with lower rates of concussion in soccer
- Policy disallowing bodychecking in child/adolescent ice hockey is associated with a 58% reduced concussion rate and there are no unintended consequences associated with reduced bodychecking experience when subsequently participating in bodychecking leagues
- Strategies limiting contact practice in American football are associated with an overall 64% lower practice-related concussion rate
- An NMT warm-up program in rugby is associated with a 32-60% lower concussion rate
- Current concussion management strategies may reduce recurrent concussion rates

Primary prevention of sport-related concussion (SRC) is a priority that can have significant public health impact in reducing SRC rates and their potential long-term consequences. The 5th International Consensus Statement on Concussion in Sport (5th Consensus) defined SRC as a traumatic brain injury induced by biomechanical forces.[1] A 2017 systematic review (SR) focused on SRC prevention informing the 5th Consensus highlighted three targets for prevention including personal protective equipment, rules/policy changes, and training strategies.[2]

Globally, there is a 1 in 5 lifetime risk of concussion.[3] An estimated 3 million people (50% children and adolescents) sustain a concussion in North America annually, 30% are recurrent and 30% remain symptomatic for more than one month.[3-5] SRC reportedly accounts for 36-60% of concussions in children and adolescents.[6,7] In Canada, 1 in 9 adolescents sustain a concussion annually.[8]

The strongest and most consistent concussion prevention evidence reported demonstrated a protective effect of policy disallowing bodychecking in youth ice hockey.[2] Meta-analyses (MA) suggested potential protective effect of mouthguard use in collision sport; however, additional research was needed. Additional promising prevention strategies identified in the previous review included thicker mandibular helmet padding and proper helmet fit in American football, rule enforcement to reduce head contact in soccer, larger international ice surface size in elite adult ice hockey, and visual training strategies in adult American football players, but required further evaluation. Future research recommendations included rigorous evaluation of SRC prevention strategies using valid injury surveillance with consideration of modifiable risk factors, potential confounders (e.g., sex, previous concussion), consistent SRC definitions, and exposure data to accurately measure SRC rates.[8] Psychological and sociocultural considerations were highlighted for implementation in the uptake and maintenance of SRC prevention strategies.[2]

The specific research questions for this SR and MA included: 1. What SRC prevention strategies reduce concussion and/or head impact risk (e.g., equipment, policy/rules, training strategies)?; 2. Are there unintended consequences of SRC prevention strategies?; and 3. What modifiable risk factors are associated with SRC risk?

Methods

Data sources and search strategy

This SR reported in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) guidelines.[9] The protocol for this SR was registered on PROSPERO: https://www.crd.york.ac.uk/PROSPERO/display_record.php?RecordID=152982[10]
Relevant studies were identified through eight databases:

1. OVID MEDLINE (R) and Epub Ahead of Print, In-Process & Other Non-Indexed Citations and Daily
2. CINAHL Plus with Full Text (Ebsco)
3. APA PsycINFO (OVID)
4. Cochrane Databases for Systematic Review (OVID)
5. Cochrane Central Register of Controlled Trials Registry (OVID)
6. SPORTDiscus with full text (Ebsco)
7. EMBASE (OVID)
8. ERIC (Ebsco)

A search focused on three identified main concepts (i.e., concussion/head impacts, sports, prevention/modifiable risk factors) was performed in October 2019 and updated in March 2022. Details of the search strategy are summarized in the methodology for the 6th International Consensus Conference on Concussion in Sport.[11] For this review, the search was pilot tested with five identified seed articles and relevant studies from the 5th Consensus,[1] then translated to all databases. Searches were limited to 2001–2022. Reference lists of selected SRs were also hand-searched to identify additional papers. Only peer-reviewed literature manuscripts were included. The search strategies for all databases are available in supplementary content and the Medline search is annotated.

Selection of studies

The full text of all potentially relevant studies was independently reviewed by one of two lead authors (CE or PE) and one other author to determine final study selection. Study inclusion criteria were: (1) contained original human research data full-text studies only; (2) investigated an outcome of SRC or head impacts; (3) evaluated an SRC prevention intervention (e.g., protective equipment, rules/policy, training) to reduce SRC and/or recurrent SRC and/or head impacts or modifiable risk factor; (4) participants competing in any sport (excluding recreational activities) including all nationalities, genders, age groups, and performance level; (5) analytic study design including a comparison group [e.g., randomised controlled trial (RCT), quasi-experimental, cohort, case-control, cross-sectional]; (6) SRs were included to identify original data manuscripts in reference search; (7) peer-reviewed. Exclusion criteria were: (1) review articles, pre-experimental, ecological, case-series, or case-studies and (2) not written in English.

Data extraction and risk of bias assessment

Data extracted included study design, duration, year, country, participants (e.g., sport, level, sex, age), concussion definition, intervention/control or level of modifiable risk factor, concussion incidence rate (IR) or prevalence by study group, and effect estimate [e.g., incidence rate ratio (IRR), risk ratio (RR), hazard ratio (HR), odds ratio (OR)] (supplemental content). Effect estimates are reported based on describing a protective effect (prevention intervention) or increased risk (modifiable risk factor). Where not reported and data were available, an effect estimate was calculated. Data were extracted by two authors for each paper (CE or PE) and one additional co-author. Either consensus was achieved, or a third author (CE or PE) discussed discrepancies. Two authors (CE or PE and other co-author) independently assessed risk of bias (ROB) as per data extraction based on the Downs and Black (DB) checklist for methodological quality[12] and the study design-appropriate Scottish Intercollegiate Guidelines Network (SIGN) critical appraisal checklists[13]. Only studies deemed to be high quality ("++") or acceptable ("+") based on SIGN criteria were included in results and MAs. Analyses included consideration of child (5-12 years) vs adolescent (13-18 years) vs adult (>18 years) where applicable. Sex and/or gender and parasport vs able-bodied considerations were included where possible. Quality of evidence and grading strength for key recommendations for each research question was assigned (PE and CE) using the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) system (supplemental).[14]

Meta-analyses

Data for MAs were synthesized with summary estimates. Risk ratios (RR), incidence rate ratios (IRR), and hazard ratios (HR) were considered comparable and kept for analysis.[15] The consolidation of effect estimates was made by recalculating them when they were reported as odds ratios to reflect IRRs or RRs. When effect estimates were not available, they were calculated based on information provided. RRs were derived using concussion frequency and population from each study group (e.g., policy allowing bodychecking vs. no bodychecking). When person-time data were reported (e.g., player match-hours, athlete-exposures), IRRs were computed. Articles were excluded from MAs if they did not include number of concussions (or head impacts) over either person-time or total number in cohort. A random effects model using the DerSimonian–Laird method computed measures of heterogeneity and adjusted summary effect estimates. All analyses were completed using Stata 17.[16] Standard errors were computed using previously described methods.[17,18] Forest plots were examined by sport and age.

Results

The search yielded 16,121 studies (Figure 1). In total, 220 studies [6/220 (3%) female-focused; 115/220 (52%) child and/or adolescent-focused] were included for data extraction and ROB assessment and categorized by sport and prevention or modifiable risk factor. Modifiable risk factors are included in supplemental content.

[insert Figure 1]

Risk of Bias Assessment

A total of 28 studies (13%) had low methodical quality ("-") based on SIGN criteria. Of the remaining 192 studies, most (169/192;88%) were sufficient quality ("+") with the remaining (23/196;12%) excellent quality ("++"). The median DB ROB assessment for included studies was 13/33 (range:6-24). Several common limitations were inadequate reporting on adverse events, description of population representativeness, loss to follow-up, validity/reliability of outcome measures, a-priori sample size, and insufficient adjustment for potential confounders.

Prevention Strategy Evaluation Studies

Personal Protective Equipment

Helmets

Comstock et al[19] demonstrated a significantly lower SRC rate from stick/ball contact in male adolescent lacrosse players with mandated hard shell helmets with full facial protection compared with girls allowed (but not mandated) to wear flexible headgear (RR=0.38;95%CI:0.31-0.49).[19] Emerging evidence suggests proper helmet fit in adolescent American football[20] may reduce concussion symptom severity ($p<0.01$) and duration of symptoms ($p=0.04$), as well as reduce SRC odds (OR=0.37;95%CI:0.15-0.96) in children and adolescent ice hockey.[21] Five studies examined different helmet types in American football.[22-26] Collins et al[22] reported a 31% lower SRC rate (RR=0.69;95%CI:0.5-0.96) in high-school football when comparing a helmet with thicker padding over the zygoma/mandible area to traditionally designed helmets. Rowson et al[23] also reported a 46% lower rate of SRC with greater padding (RR=0.54;95%CI:0.24-0.72) in college football players. Two studies did not find a difference in the SRC rate, head impact characteristics, or time loss following SRC by helmet type in adolescent football,[24,25] however, a 19% lower SRC risk (OR=0.81;95%CI:0.68-0.96) was reported in professional football players wearing National Football League approved helmets compared with players wearing unapproved helmets.[26] Greenhill et al[20] compared different helmet liner types (air bladder versus foam or gel) and found differences in individual concussion symptoms, but not in the total number of concussion symptoms reported. One study examined helmet age in high-school American football and found no association with SRC rates.[24]

Headgear

Fifteen studies examined headgear use in rugby, soccer, lacrosse, Australian football, and boxing (supplemental).[27-41] Based on combining data from team-based collision sports, a MA suggests a potential protective effect between headgear use and SRC rates (IRR=0.84;95%CI:0.67-1.04) (Figure 2) but this was not statistically significant. When stratified by sport, headgear was protective against SRC in soccer (IRR=0.64;95%CI:0.44-0.92) but not lacrosse or rugby.

[insert Figure 2]

Face-shields/Faceguards

Five studies in ice hockey examined the impact of full, half, or no face-shields (supplemental).[42-46] Three studies demonstrated that full-face shields were not associated with lower SRC rates compared with half-visors.[42-44] Benson et al[42] reported that players who sustained an SRC while wearing a half-visor had more time-loss than players wearing full-face shields. No association was found between SRC odds with half-visor use compared with no visor in professional ice hockey players (OR=1.34;95%CI:0.72-2.48).[45]

Eyewear

Protective eyewear was examined in three studies across lacrosse and field hockey.[47-49] Lincoln et al[47] compared IRs before and after policy mandating protective eyewear in female high school lacrosse players. Despite lower eye and overall head/face IRs after policy change, the SRC rate increased (IRR=1.6;95%CI:1.1-2.3). Two studies examined protective eyewear and eye injuries among high school field hockey players and reported a reduction to head/face injuries, but no reduction in SRC rates (IRR=0.96;95%CI:0.57-1.59;IRR=0.77;95%CI:0.58-1.02).[48,49]

Mouthguards

The protective effect of mouthguards was evaluated in eight studies across several sports with conflicting results.[27,28,31,34,50-53] Five studies included in a MA demonstrate that mouthguard use was associated with a 26% lower SRC rate (IRR=0.74;95%CI:0.64-0.85) (Figure 3). This protection was significant in ice hockey (IRR=0.72;95%CI:0.60-0.87) but not in rugby (IRR=0.80;95%CI:0.51-1.27) (Figure 3). Protection was significant across mixed age groups (children, adolescents, and adults). Dentist fit mouthguards were not associated with additional SRC protection compared with off-the-shelf types,[24,50,54] nor were other specialized mouthguards.[55]

[insert Figure 3]

Jugular Vein Compression Collars

Two studies examined the use of a jugular vein compression collar and head impacts in adolescent ice hockey and American football players demonstrating that head impact frequency and severity were not reduced by wearing a collar.[56,57]

Policy, Rule, or Law Changes

Eight studies examined the effectiveness of policies disallowing bodychecking in child and adolescent ice hockey and subsequent SRC rates.[58-65] Combining studies with individual level injury and exposure data and a study using hospital-based surveillance demonstrated a 58% lower SRC rate where policy disallowed bodychecking (IRR=0.42;95%CI:0.33-0.53) (Figure 4). Further, prior bodychecking experience in games was not associated with lower SRC rates in leagues permitting bodychecking, suggesting no unintended consequences.[66,67]

[insert Figure 4]

Fair play rules (additional points for not exceeding a predetermined number of penalty minutes) in 11-14 year old ice hockey led to a reduction in head impacts (RR=0.24;95%CI:0.07-0.78) but not SRC rates.[68] No association was found between team penalty minutes per game and their opponents' game-related SRC rate.[69] However, implementation of game suspension for exceeding a threshold for penalty minutes was associated with lower odds of SRC (OR=0.44;95%CI:0.23-0.85).[70]

The application of a rule that made targeting an opponent's head illegal (Rule 48; National Hockey League) was not associated with a reduced SRC incidence in professional ice hockey.[71] In ages 11-14, a zero tolerance for head contact rule did not reduce SRC rates [IRR(range)=1.85-7.91)] as rates were higher following this change.[72] Despite this rule change, there was no difference in primary (direct player-to-player) (IRR=1.05;95%CI:0.86-1.28) and secondary head contact rates (head contacts to the boards, glass, net or ice surface) (IRR=0.74;95%CI:0.5-1.11), or the proportion of primary head contact penalties (<14%).[73] SRC rates decreased (rate difference=-1.82 concussions/1000 plays;95%CI:-2.49--1.14) in the seasons after policies removed the two-line pass rule (a rule that disallowed direct passing across the defending teams blueline and redline) and inclusion of stricter rule enforcement to prevent obstruction in professional play.[74]

Policy enforcing red cards for high elbows or intentional elbow to head contact in professional soccer was associated with a non-significant reduction in SRC (IRR=0.71;95%CI:0.46-1.09) and significant reduction in overall head injury (RR=0.81;95%CI:0.67-0.99).[75,76] After heading the ball was banned in 2015 by the U.S. Soccer Federation in players under 10 and in games for players aged 10-13, an increase in SRC relative to other injuries (OR=1.29;95%CI:1.09-1.52) was seen in emergency departments in players aged 10-13.[77] The heading ban also included an initiative to improve concussion education and implementation of more uniform concussion management.[77] Rules minimizing intentional contact to the head or neck and the use of bodychecking in adolescent male lacrosse led to lower bodychecking-related concussion rates during practices (IRR=0.29;95%CI:0.12-0.70) and matches (IRR=0.51;95%CI:0.29-0.91).[78] In professional baseball, a rule limiting collisions between the base runner and the catcher at home plate was associated with a significant reduction in catcher concussion rates (RR=0.31;95%CI:0.11-0.85).[79,80] A rule change in rugby limiting the frequency of interchange replacements did not reduce SRC rates (IRR=0.59;95%CI:0.04-9.48).[81] Policy reducing the maximum height of the legal tackle in rugby from the line of the shoulders on the ball carrier to the line of the armpits did not reduce SRC rates (IRR=1.31;95%CI:0.85-2.01) (supplemental).[82]

Studies comparing head impacts between youth tackle football and flag football where tackling was not permitted are summarized in supplemental content.[83-87] Several policy/rule change initiatives have been examined to reduce head impacts and SRC rates in American football. Kerr et al[88] demonstrated that SRC rates did not differ when child and adolescent level players were grouped based on age and weight rather than just age only (RR=0.6;95%CI:0.3-1.4). Restricting the frequency and/or duration of collision practices in adolescents reduced head contact and practice-related concussion rates.[89-92] Similar policy changes have not been successful at the collegiate level (supplemental).[93-95] A MA combining studies indicated a 64% reduction in practice-related concussion rates when policy and non-policy approaches to limiting contact in practices were implemented across adolescent and adult leagues (IRR=0.36;95%CI:0.16-0.80) (Figure 5). The MA examining all strategies to reduce practice-related head impacts in adolescents indicated a 53% reduction, but this was not significant (supplemental). After the kickoff line was moved up and touchback line moved back (aimed to increase kickoffs landing in the end zone and the likelihood of more touchbacks), a significant reduction in SRC rate was seen at the collegiate level (rate difference per 1000 plays during kickoff=-8.88;95%CI:-13.68--4.09).[96]

[insert Figure 5]

Five studies examined various targeting rules that have been implemented at all levels of American football play.[97-101] Aukerman et al[97] reported a higher SRC rate during plays in which a targeting penalty was called versus a non-targeting play at the collegiate level (IRR=36.9;95%CI:22.4-60.7). Hanson et al[98] reported a 32% reduction in weekly concussion reports among professional defensive players after implementing the crown of the helmet rule (penalizing players intentionally initiating contact using the top of their helmet). Baker et al[99] demonstrated a 40% lower SRC rate (RR=0.60;95%CI:0.50-0.73) after the targeting rule was broadened.[99] After implementing targeting rules, a reduction was found in adolescent SRC rates (p=0.04) and concussions caused by helmet to helmet contact (p=0.03) presenting to emergency departments.[100] Westermann et al[101] reported a higher SRC rate in seasons after implementing targeting rules (IRR=1.34;95%CI:1.08-1.66).[101] When considering potential unintended consequences, Hanson et al[98] and Westermann et al[101] reported increased lower extremity IRs in professional and collegiate football after targeting rules were implemented. This was contrary to Baker et al[99] who did not report any increased lower extremity IR at the professional level, but did note an increase in games missed from lower extremity injury. A MA including three of these studies suggests that targeting rules were not associated with reduced SRC rates (IRR=0.77;95%CI:0.38-1.56) (Figure 6).

[insert Figure 6]

Training Strategies:

Examining off-field training strategies, Clark et al[102] demonstrated an 85% reduction in SRC risk (RR=0.15, p<0.001) in American football players following vision training. Training strategies targeting head impact outcomes are summarized in the supplemental material.[103-105] A 10-week training program including exercises focused on increasing core strength was associated with lower SRC rates in adolescent American football, soccer, and volleyball players.[106]

Cluster-RCT evaluation of on-field training strategies demonstrated efficacy of a neuromuscular training (NMT) warm-up strategy (e.g., balance, whole body resistance, static neck contractions, plyometric training, landing/cutting manoeuvres).[107] NMT was associated with 59% lower SRC rates in school-boy (ages 14-18) rugby players (RR=0.41;90%CI:0.17-0.99) when completed ≥3 times/week, compared to standard practice warm-up.[107] Attwood et al[108] evaluated a NMT program compared with a standard practice warm-up in adult men's community players demonstrating a 60% lower SRC rate (RR=0.4;90%CI:0.2-0.7).[108] An NMT evaluation in players aged 12-19 showed significant reductions in training and match-injury IR in those completing the NMT three or more times per week, but did not show any reduction in SRC rates specifically.[109] Community players who trained <3 hours/week were more likely to sustain a SRC sooner than those who practiced ≥3 hours/week (HR=0.68;95%CI:0.48-0.94).[110] Adult players with poorer dynamic balance performance had higher SRC odds than players with optimal balance performance (OR=3.63;95%CI:1.20-10.97).[111]

Kerr et al[112] (aged 8-15 years) and Shanley et al[113] (adolescent) demonstrated that child and adolescent American football players exposed to a comprehensive coach education program (i.e., proper equipment fitting, tackling technique, strategies for reducing player contact, concussion awareness) had significantly lower practice-related head impacts and game and practice-related concussion rates (RR=0.67;95%CI:0.19-0.91), relative to players in leagues that did not participate.[112,113] When the education program was coupled with instituted guidelines restricting contact in practices, there was an 82% lower practice-related concussion rate in players aged 11-15 (IRR=0.18;95%CI:0.04-0.85) but not players aged 5-10 (IRR=0.82;95%CI:0.15-4.48) compared with those who did not have any education or contact restriction.[114] The addition of a player safety coach whose responsibility was to ensure other coaches adhered to proper safety protocols was associated with a reduction in practice-related concussions (IRR=0.12;95%CI:0.01-0.94) but not game-related concussions (IRR=0.14;95%CI:0.02-1.11).[115]

American football training strategies to reduce head impacts are summarized in supplemental.[116-133]

Concussion Management Strategies

After concussion laws were enacted (e.g., mandatory removal from play, requirements to receive clearance to return to play from a licensed health professional, and education of coaches, parents, and athletes), an initial increase in recurrent SRC rate trends was seen across adolescent sports, but then a decrease was seen 2.6 years after the laws went into effect.[134,135] Arakkal et al[135] found that in US States where the category of healthcare provider was specified for return to play clearance, recurrent SRC rates were lower than in States where the healthcare provider was not specified (1.59%/standardized month;95%CI:-0.22- 3.42); however, this was not significant. When examining multiple design elements of the concussion laws (i.e., strength of law, number of law revisions, speed of law adoption), Yang et al[136] demonstrated lower recurrent SRC rates when States had more law revisions (≥2 versus <2) and adopted laws later. Increasing strength of law (based on 13 discrete evidence-based concussion law provisions) did not reduce recurrent SRC rates.

Across adolescent and adult sports, a symptom-free waiting period after sustaining a SRC did not reduce clinical recovery time or reduce risk of recurrent SRC.[137] However, over the past 15 years, improved concussion protocols in collegiate American football players (e.g., pre-season concussion education, pre-participation assessments, structured plan for concussion diagnosis, post-injury management, and return to play) have shown significantly longer symptom durations, symptom-free waiting periods, and return to play, with a significantly lower risk of recurrent SRC.[138] Charek et al[139] suggested that players who reported continuing to play for more than 15 minutes after a SRC took longer to recover than those that continued to play for fewer than 15 minutes or were removed immediately. This was contrary to the findings by Zynda et al[140] where adolescent players presenting to a pediatric sport medicine clinic experienced similar recovery times when they reported continuing to play following a SRC compared with those that did not. Zynda et al[140] also demonstrated a longer time before presentation at the clinic was associated with a prolonged recovery time. This finding was consistent with a study in youth and adolescent ice hockey (ages 11-17 years), where those that delayed seeing a physician (>7 days) also had a longer clinical recovery time.[141] SRC recovery was not significantly different between adolescent ice hockey players that played in a bodychecking league and those who did not.[141] When examining SRC rates at the professional level in American football following initiatives to reduce concussions (e.g., targeting rule changes, eliminating specific practice drills and in-game blind-side blocks) as well as improve concussion detection and diagnosis (e.g., introduction of a centralized clinical electronic health record, Athletic Trainer spotter program, unaffiliated neurotrauma consultants), a 23% decrease in game-related concussions was observed (IRR=0.76;95%CI:0.65-0.88).[142] Teramoto et al[143] did not find an association between SRC rates in professional American football players and the number of days of rest, game location, or timing of the bye week. Number of days of rest was also not related to risk of repeat SRC.[143] Similarly, Gardner et al[144] did not find any association between the rate of SRC in professional rugby players and the number of days rest between matches or the match location.

Discussion

This comprehensive SR and MA includes original data studies evaluating primary and secondary SRC prevention strategies to reduce concussion, recurrent concussion, and/or head impact rates in various sports. Further, studies evaluating unintended consequences of SRC prevention strategies and studies examining potential modifiable risk factors for SRC were included. Concussion prevention strategies include personal protective equipment, policy/rule changes, training strategies, environmental targets, and management strategies targeting recurrent concussion. Potential modifiable risk factors have also been identified for future prevention strategies development, implementation, and evaluation (supplemental).

Protective equipment

Studies evaluating helmet design and/or materials including flexible panels and helmet fit remain an opportunity for SRC prevention. Cohort studies have indicated that thicker padding over the zygoma/mandible area may reduce SRC rate in American football.[22,23] Two studies have identified that secure helmet fit may reduce SRC rates and severity.[20,21] Biomechanical studies with appropriate controls remain an opportunity to support more rigorous helmet standards for manufacturing and establishing sport-specific helmet fit criteria.

Studies evaluating headgear report mixed findings with regards to SRC protection. When data were combined across studies in lacrosse, rugby, and soccer in a MA, headgear did not reduce SRC rates although the point estimate did suggest an 18% reduction overall (IRR=0.82;95%CI:0.65-1.03). By sport, headgear use was associated with lower SRC rates in soccer but not rugby or lacrosse. Further evaluation of different headgear design and materials is warranted. Headguards were not protective against stoppages due to head contact in one study evaluating their use in boxing. Policy mandating headguards in male boxing was removed prior to the 2016 Rio Olympics (supplemental).[41]

Ice hockey studies evaluating face shielding suggest that full face shielding does not offer significant protection against SRC over half visors.[42-44] Limited evidence suggests that full face shielding may offer protection against SRC severity based on time loss.[42] Full facial protection does provide superior protection against orofacial injuries compared with half visors.[145] Eyewear use has been recommended in lacrosse and field hockey to reduce head and face injury but does not appear to reduce SRC rates.[47-49]

Mouthguards are well established in protecting against orofacial injury across sports,[146] but their use as a SRC prevention measure has been controversial. A MA combining ice hockey and rugby studies demonstrated mouthguard use was associated with an overall 26% reduction in SRC rates. While this reduction was found when combining studies, a large majority (83%) of the weight came from one study in ice hockey due to the precision of the estimates. A previous MA examining mouthguard use suggested a similar point estimate that was not statistically significant (IRR=0.81;95%CI:0.6-1.1).[2] When stratified by sport, the effect of mouthguards was significant for adolescent ice hockey but not for adult rugby, potentially suggesting mouthguard use is a marker of safety behaviour or previous concussion in elite rugby but not adolescent ice hockey. Results from this MA suggest mouthguards should be worn in ice hockey and its use is recommended in other collision sports given the potential concussion protection in addition to orofacial protection. Future studies with rigorous injury surveillance methodologies and consideration of potentially confounding covariables are still recommended to further the understanding of mouthguard and concussion across sport, particularly in children and adolescents. RCTs are likely unethical in some collision sports where their use is already mandated but case-control approaches may be considered.[2]

Currently, there is not sufficient evidence to recommend the use of compression collars to reduce SRC risk or head impact frequency or severity despite the hypothesis that these devices may reduce microstructural changes based on advanced imaging.[56,57]

Policy and Rules

The MA assessing the effectiveness of rule changes disallowing bodychecking in children and adolescent ice hockey shows an overall 58% reduction in SRC rates. Surveillance following policy restricting bodychecking demonstrated no unintended injury consequences with fewer years of body checking experience.[66,67,147] A recent video-analysis study has also suggested no player performance deficits associated with disallowing bodychecking.[148] Head contact rule changes in ages 11-14 and adult professional level have not shown reduced SRC risk.[71,72] Referral patterns, referee behaviours, surveillance methods, and increased media attention and concussion awareness may all contribute to reducing the effectiveness of head contact policies.[2] Given the evidence suggesting continued high rates of head contacts occurring at the adolescent level even after the introduction of head contact policy,[73] greater referee training in sports that disallow head contact may be an avenue for future research examination. Limiting head contacts in soccer, lacrosse, and baseball have led to lower concussion or head impact rates.[75,76,78-80]

Policy limiting the number and duration of contact practices in American football has led to reduced SRC and head impact rates in adolescents.[89-92] Limiting the number of contact practices did not have as much success in terms of reducing SRC risk or head impacts at the collegiate level as teams were noted to run longer duration practices and with more intense contact (supplemental).[93-95] Further restrictions on limiting practice duration may help in decreasing head impacts and SRC risk at the collegiate level. Based on the results of the MA examining targeting rules in American football (e.g., prohibiting initiating contact to an opponent above the shoulders, lowering the head or initiating contact with the crown of the helmet, targeting of defenseless players in the head/neck area), these policy changes did not significantly reduce SRC rates (IRR=0.77;95%CI:0.38-1.56). It is unclear whether the implementation of targeting rules led to increased lower extremity IRs.[98,99,101] Moving the kickoff line up significantly reduced SRC rates at the collegiate level in American football.[96] Similarly, Ruestow et al[149] examined the effect of the free kick rule in professional football and found a non-significant reduction in head injuries (IRR=0.33;95%CI:0.09-1.21). Other concussion initiatives (e.g., targeting rule changes, eliminating specific practice drills, and in-game blind-side blocks) at the professional level are associated with decreased game-related concussions.[142]

Training Strategies:

Studies across sports examining vision/cognitive training programs have reported mixed findings with regards to lowering SRC and head impact risk (supplemental).[102-104,150,151] Potential differences between studies may include training program components and differences between sports such as rules (e.g., tackling vs. bodychecking) and positions of play. Exercise warm-up programs that include several components (e.g., balance, resistance, landing and cutting) have been shown to reduce SRC rates in rugby.[107,108] Comprehensive coach education that included several other components such as strategies to reduce player contact has been shown to reduce SRC and head impacts in child and adolescent American football.[112-115] Many studies support limiting contact and equipment during practice drills and improving tackling and blocking techniques to reduce SRC and head impact kinematics.[116-129,131-133] Across sports, concussion education programs without additional strategies have been shown to improve concussion knowledge and promote potential behavioural changes, yet there is a paucity of research evaluating whether these programs reduce SRC rates.[152,153] Future studies in other sports evaluating similar exercise programs with additions of sport-specific components are warranted.

Other Strategies to Reduce Concussion Risk, Head Impacts, or Severity

Child and adolescent ice hockey leagues that have fair play programs help reduce the number and severity of penalties,[154-158] but it is unclear whether these programs also help reduce SRC risk.[68,70] Initial evidence suggests players are at lower risk of overall injury when venues utilize a flexible board/glass system rather than a traditional system, which may extend to a lower SRC risk as well.[159] See supplemental for further discussion on secondary prevention.[139-141,160]

Strengths and Limitations

This comprehensive SR and MA evaluated prevention strategies and modifiable risk factors for SRC, head impacts, and SRC severity. Some papers that were included in the previous SR that informed evidence based prevention strategies for the 5th Consensus were not included in this review.[1,2] This is due to stricter inclusion criteria such as limiting publication years, a focus on sport (not recreational activities), and only studies of stronger methodological quality.[12,13] Studies must have been published in English, introducing potential language bias. Measurement bias (including self-report) was prevalent in the many studies. Any measurement bias with regards to concussion definition was likely non-differential and equal across study groups between the probability of a concussed player being classified as non-injured and a non-injured as concussed. Small samples have limited the ability to examine age, sex/gender effects and para-sports. Not all studies controlled for potentially confounding variables or clustering effects in team sports. Our results are limited in that studies assessing head injury broadly or TBI were excluded if they did not specify concussion. Studies that primarily considered all injury as the outcome of interest may have been missed based on our search strategy. Several included papers commented on how increased media attention, awareness of concussion, and concurrent concussion education programs may have influenced concussion reporting rates which may have affected individual study results.

See supplemental for further discussion regarding head impacts.[161-167]

Conclusions

Some of the strongest evidence for SRC prevention is through policy and strategies restricting body checking or contact across several child, adolescent, and adult sports. Continued research examining prospective rule changes and associated biomechanical investigation is recommended as is research examining helmet fit and types. Mouthguards are associated with a lower overall risk of SRC and should be worn in ice hockey. Neuromuscular warm-up programs have a protective effect in reducing SRC in rugby, with future research required to consider other sport contexts and greater attention to concussion-targeted training components. Certain modifiable risk factors such as neck strength require further evaluation to elucidate their role in SRC prevention. The continued evaluation of SRC and head impact prevention strategies targeting sport-specific extrinsic (e.g., rules) and intrinsic (e.g., previous concussion history) risk factors are required. Appropriate evaluation designs (e.g., RCTs, cohort, case-control) using validated injury surveillance methodologies, consideration of potential confounding variables (e.g., concussion history), and with common concussion definitions consistent with consensus definitions are needed. Video-analysis and instrumenting players (e.g., mouthguards) support concussion surveillance evaluation approaches. Consideration of individual player exposure data (i.e., player participation) to measure IRs and clustering effects for team-based sports is also important. Psychological and sociocultural factors continue to be important considerations in the uptake and maintenance of SRC prevention strategies.

Key Recommendations

1. What SRC prevention strategies reduce concussion and/or head impact risk (e.g., equipment, policy/rules, training strategies)?

- Mouthguard recommendation and/or policy in ice hockey (GRADE quality rating: Low)
- Policy disallowing bodychecking in child/adolescent ice hockey should be supported for all children and most levels of adolescent ice hockey (GRADE quality rating: High)
- Strategies limiting contact practice in American football should inform related policy and recommendations for all levels (GRADE quality rating: Low)
- NMT warm-up program recommended in rugby and more research needed for females and other team sports - focus on exercise components targeting concussion prevention (GRADE quality rating: Moderate)
- Policy mandating optimal concussion management strategies to reduce recurrent concussion rates is recommended (GRADE quality rating: Very low)

2. Are there unintended consequences of SRC prevention strategies?

- Prior bodychecking experience in ice hockey games was not associated with lower concussion rates when adolescent players played in leagues permitting bodychecking, suggesting no unintended consequences of policy disallowing bodychecking to refuse policy recommendation above (GRADE quality rating: Moderate)
- Future research should consider evaluation of unintended consequences of concussion prevention strategies across all contexts

3. What modifiable risk factors are associated with SRC risk?

- Lower concussion rates have been demonstrated in certain sports when matches are played on an artificial turf field compared with a natural grass field. Further research should target detailed understandings of playing surface and associated mechanisms of injury prior to concussion prevention strategy recommendations (GRADE quality rating: Low)
- Further prospective analytic research designs examining neck strength as a potential modifiable risk factor for concussion are needed to inform future development of related concussion prevention strategies (GRADE quality rating: Very low)
- Future sport-specific research evaluating optimal tackle technique to reduce concussion risk in rugby is necessary before informing related prevention strategy targets (GRADE quality rating: Low)

Supplemental Content

Prevention Strategy Evaluation Studies (Head Impacts)

Headgear

Loosemore et al[41] examined headguard use in boxing and found a higher match stoppage rate (RR=1.75;95%CI:1.02-3.00) due to head blows when headguards were worn.

Face-shields/Faceguards

In American football, no difference in head impact severities (e.g., linear and rotational accelerations) was reported between collegiate players wearing heavier or lighter faceguards.[46]

Policy, Rule, or Law Changes

While the policy reducing the maximum height of the legal tackle in rugby from the line of the shoulders on the ball carrier to the line of the armpits did not reduce SRC rates (IRR=1.31;95%CI:0.85-2.01), a 30% reduction in contact to the ball carriers' head and neck area was observed.[82]

Of the studies comparing head impacts between youth tackle football and flag football, higher frequency and severity of head impacts were observed in children and adolescents in tackling leagues in four studies,[83-86] but were similar in another.[87]

In American football, a collegiate policy that eliminated two-a-day preseason practices led to an increase in the number of preseason contact days, average hourly impact exposure, and a 20% higher head impact rate in the preseason.[94] Later policy reducing the number of pre-season on-field practices also had little impact on overall head impact burden.[95]

[insert Figure 7]

Training Strategies (Head Impacts):

A pilot study by Antonoff et al[103] examined a vision training program in collegiate male and female ice hockey players that largely suggested no differences in several head impact measures between study groups. Adolescent ice hockey players completing a computerized cognitive training program had lower head impact frequencies and cumulative linear accelerations than control players.[104] Pre-season functional movement ability was not related to head impact characteristics in adult American football players.[105]

On days of diagnosed concussion, American football players sustained more head impacts and head impacts of greater severity compared with days without diagnosed concussion.[116] A helmetless tackling and blocking intervention in American football was examined in two RCTs where the intervention group practiced for a period without helmets and shoulder pads while the control group trained with full equipment.[117,118] In collegiate players, the intervention group had 30% fewer head impacts per exposure by the end of the season,[117] and in adolescent players, a lower game-related head impact rate at weeks 4 and 7 of the playing season was seen but was not different by the end of the season.[118] Many studies have supported the use of equipment-limited practices and limiting contact drills in practices to reduce concussion and head contact risk in child, adolescent, and adult players.[119-130] A significantly lower risk of SRC was observed when collegiate players practiced in shells (helmets and pads only) or when helmets only were worn compared with full equipment practices.[120,128] Players on teams where coaches were given weekly reports on their players' head impact frequency and severity had lower impact rates than players on teams where coaches did not receive head impact reports.[131] Poor tackling form was associated with higher magnitude impacts in children and adolescent football players.[132] After incorporating a targeted data-informed tackle and blocking drill behavioural intervention aimed to improve tackling and blocking technique, Champagne et al[133] showed significant reductions in the frequency of practice-related head impacts ($p<0.01$).

Discussion

Other Strategies to Reduce Concussion Risk, Head Impacts, or Severity

While it remains unclear whether players who continue to play after a suspected concussion have longer recovery times than those who were removed immediately,[139,140] all players should be removed immediately and assessed whenever a player shows any symptoms or signs of sport-related concussion (secondary prevention).[1] Studies suggest that a longer delay in seeing a sports medicine physician following concussion is associated with a longer recovery time.[140,141,160] This suggests that earlier clinical management and initiation of the return to play protocol may lead to earlier resolution of symptoms and return to play. Alternatively, this may be due to players that have more persistent and higher intensity of symptoms seeking care.[141] However, Kontos et al[160] reported no differences on symptom severity between those that were evaluated before and after 7 days.

Strengths and Limitations

We note that studies examining head impacts and severity do not necessarily translate to SRC risk. A wide variety of head impact sensors were used across the included studies that examined head impact kinematics. The validity and reliability of some sensors is either not known or was not mentioned in some studies. There may also be imprecision of these sensors when video confirmation was not included.[161] As part of our inclusion criteria, only studies that contained original data human research studies were included but we acknowledge that *in vivo* biomechanical studies can further inform and support injury prevention strategies.[162-167]

Modifiable Risk Factors for Concussion

Environment

The effect of altitude on SRC risk was examined in seven studies and suggested conflicting results.[168-174] Four studies suggested that higher altitude was associated with a reduced SRC risk,[168-171] two that reported higher altitude increased risk,[172,173] and one that suggested no association.[174] In addition to examining American football separately, Smith et al[170] combined data from various adolescent sports which further suggested higher altitude was protective against game and practice concussion risk across sports. Conversely, Lynall et al[173] and Li et al[172] both suggest higher altitude increased SRC risk but had conflicting results when examining recovery times. Lynall et al[173] reported no difference in the symptom resolution time but a greater percentage of collegiate athletes retuned to activity in 1 to 6 days when the SRC was sustained at a lower altitude. Li et al[172] suggested higher altitude was associated with prolonged recovery, despite less severe symptoms at initial injury.

Lawrence et al[174] found a significantly greater risk of SRC in professional American football when games were played at mean-day temperature of ≤9.7°C (≤49.5°F) compared with a mean game-day temperature of ≥21.0°C (≥69.8°F). However, Mihalik et al examined several environmental conditions including ambient temperature as well as physiologic conditions (e.g., body temperature, hydration status) which were not associated with head impact biomechanics in collegiate players.[175] Risk of game-related concussion at the professional level was not associated with a change in time zone.[174]

Playing surface type, size, or characteristics

Ten studies examined SRC risk and playing surface type (i.e., natural grass versus artificial turf fields) or provided data so risk could be calculated across American football, rugby, and soccer.[174,176-184] Compared with natural grass fields, four studies supported a lower risk when matches were played on an artificial turf field.[176-179] The point estimates from five studies also supported these findings but were not statistically significant,[174,180-183] while data from the remaining study did not suggest any association.[184] A meta-analysis combining estimates from nine of the studies demonstrated 40% lower SRC rates (IRR=0.60;95%CI:0.47-0.76) when matches were played on an artificial turf field compared with a natural grass field (Figure 8). In exploratory sport and age-specific analysis, this protective effect seems similar across sports and ages. Similar overall rates of SRC in youth American football players were demonstrated when examining different infill weights of artificial turf systems,[185] but lower rates of SRC occurred when turf systems included a pad underlay versus no pad underlay.[186]

[insert Figure 8]

There is evidence at the elite level in adolescent and adult ice hockey to support games being played on international sized ice surfaces (204 feet long by 100 feet wide) compared with the smaller North American size (200 feet long by 85 feet wide) or the intermediate size (94 feet wide) to reduce head impacts.[187,188] Ice hockey venues that utilize flexible board/glass systems compared with traditional systems had a non-significant 57% reduction in SRC risk (IRR=0.43;95%CI:0.18-1.01) in elite level play.[159]

Neck strength

There were conflicting results from the four studies that examined neck strength, endurance, or circumference as a modifiable risk factor for SRC risk.[189-192] Collins et al[189] reported a 5% reduction in the odds of SRC for every one pound increase in overall neck strength across adolescent sport participants (OR=0.95;95%CI:0.92-0.98). Farley et al[190] reported a 13% lower rate of SRC for every 10% increase in neck extension strength in professional rugby players (IRR=0.87;95%CI:0.78-0.98); however, other individual neck strength measures, a composite strength measure, and the ratio of flexion:extension were not significantly associated with SRC. These findings are not supported by Baker et al[191] or Esopenko et al[192] who did not find any association with collegiate athletes SRC risk and pre-season deep neck flexor endurance or neck circumference measures, respectively.

Eleven studies evaluated neck strength measures and head impact characteristics.[193-203] Five studies suggested that stronger cervical measures were associated with lower magnitude head impacts across several sports.[193-197] Fitzpatrick et al[198] found a significant relationship with linear acceleration but not rotational velocity when impacts from individual directions were compared to the strength of their opposing cervical action in blind soccer players. Using a cluster RCT design, Peek et al[199] reported the addition of neck strengthening exercises to a boys and girls (aged 12-17 years) soccer warm-up programme led to reductions in linear and angular velocity during purposeful ball heading. This was contrary to Mansell et al[200] and Eckner et al[201] where an 8-week neck strengthening program did not influence head acceleration measures. Mihalik et al[202] and Kelshaw et al[203] did not find any relationship between neck strength measures and head impact kinematics in adolescent ice hockey players and lacrosse players, respectively.

Tackle or heading technique

Several video analysis studies examined rugby tackle characteristics and risk of SRC or head injury assessment (HIA; a protocol that a player enters when they display on-field signs or symptoms of concussion and is subsequently removed from play and is assessed). Tierney et al[204] identified several tackle characteristics such as the tackler having a "head up and forward/face up" and "head placement on correct side of ball carrier" which had a lower propensity to result in an head injury assessment. Tucker et al[205] identified head contact between a tackler's head and the ball carrier's head or shoulder was significantly more likely to cause an HIA than contact below the level of the shoulder in Rugby Union. An upright tackler was also more likely to experience an HIA than when bent at the waist.[205] These findings were supported in Rugby League by Gardner et al[206] who also suggested the greatest risk of a tackler HIA occurred when head contact was very low (e.g., knee, boot) or high (e.g., head and elbow), and that HIAs were most common following head to head impacts. When the tackler accelerated into the tackle, when the tackler was moving at high speed, or a tackle with head to head contact have also been identified as significantly increasing SRC risk.[207] Tierney and Simms[208] examined the tackle height when an HIA for the tackler occurred and when the intended primary contact was to the upper trunk of the ball carrier, a greater HIA propensity was found for a front on upper body shoulder tackles and side on smother tackles. When the intended primary contact was to the lower leg of the ball carrier, a greater tackler HIA propensity occurred when a front on or side on shoulder tackles.[208] Suzuki et al[209] showed a lower risk of SRC for the tackler when the ball carrier took a side step prior to contact, and a higher risk when the tackler's head or neck did not remain bound to the ball carrier after contacting the ball carrier. Work by Davidow et al[210] demonstrated technical deficiencies for both the tackler and ball carrier when head impacts in matches occur suggesting both players are responsible for each other's safety during the tackle.

In female soccer, higher head kinematics have been demonstrated in adults in different game scenarios (e.g., from goal kicks and punts) and in children and adolescents when improper technique is used (i.e., contacting the ball with the top of the head rather than the front).[211,212] However, one study in males and females examining a variety of technique measures in a controlled environment in adolescents and adults was not related to head impact severities.[197]

Other modifiable risk factors

The initial work by Harpham et al[150] suggested collegiate American football players with lower visual and sensory performance sustained more severe head impacts than higher performers; however, an examination at the adolescent level by Schmidt et al[151] did not support these findings.

Collegiate athletes reporting poor quality or inadequate sleep such as clinically moderate to severe insomnia or excessive daytime sleepiness were at higher risk of sustaining a SRC.[213] Across youth sports, Collins et al[214] showed a significantly greater proportion of concussions during illegal play compared with the proportion of concussions not related to illegal activity (25.4% vs 10.9%; injury prevalence ratio=2.35;95%CI:1.71-3.22). This was supported by Mihalik et al[215] in adolescent ice hockey where collisions that involved an infraction had significantly higher head impact severity than collisions not involving an infraction.

At the high school level, most concussions resulting from player contact occurred from the front or side of the head.[216] Further, Kerr et al[216] also identified that players had their head down at the moment of contact in a higher proportion of concussions caused by top of the head impacts than concussions from contact to other head areas (injury proportion ratio=3.6;95%CI:3.2-4.0). Martini et al[217] demonstrated fewer head impacts during practices when adolescent teams utilized the pass first system compared with the run first system, but the pass first system had higher severity impacts during practices and games. This was supported by the findings by Lee et al[218] where the number of head impacts over 20 g was nearly double for run plays than pass plays in professional players. At the professional level, however, passing plays are associated with a higher odds of SRC than running plays (OR=1.7;95%CI:1.2-1.4),[219] and the risk of SRC has also been related to the primary offensive system used by teams.[220] In either running or passing plays, professional players on the offensive line starting in a down stance (i.e., 3- or 4-point stance) have a higher likelihood of sustaining a head impact than players in an upright (i.e., 2-point) stance.[218] Contrary findings at the adolescent level have been suggested though where higher magnitude head impacts were seen in players using a 2- or 3-point stance relative to the 4-point stance.[221] Significantly higher odds of SRC have also been demonstrated when a punt is returned versus when it is not returned.[222]

Two studies examining Olympic karate did not find a difference in SRC risk when athletes competed in a team competition with no weight limits compared with an individual competition where the athletes were grouped based on strict weight limits.[223,224] Taekwondo competitors that utilized blocking skills were less likely to receive a head blow or suffer a SRC (OR=0.57;95%CI:0.37-0.88) than those that did not.[225] In mixed martial arts, there was no difference in the risk of SRC based on referee experience, whether the fight was arranged by a matchmaker or not (matchmakers are individuals within a promotional organization who determine which athletes will compete against each other), or bout length.[226]

Male adolescent ice hockey players that did not meet physical activity volume recommendations (one hour daily) had more than twice the SRC rate of players who met the recommendation.[227] Adolescents with more safe play knowledge did not have a lower risk of head impact frequency or severity compared to those with less knowledge.[228]

A lower ball pressure and mass have been related with less severe head impact kinematics in adolescent players when heading.[229] Despite the recommendation that limiting headers in adolescents still learning proper heading technique may help reduce head impact frequency and severity,[211] Comstock et al[230] suggests that most concussions from heading occur due to contact with another player rather than the ball itself.

Discussion

Additional modifiable risk factors

Conflicting results have been presented by studies examining the association between altitude and SRC risk. The purported reason that higher altitude may lower SRC risk is from fluid accumulation in the brain when exposed to higher altitudes which decreases intracranial brain movement during potentially concussive blows,[168,170] although Connolly et al[169] suggests this reason isn't fully adequate. Smoliga and Zavorsky[171] discuss that while they also found an overall protective effect against SRC with higher altitude, they caution that the effect was primarily driven by one season of data. Further, their analysis is a reminder that every true and well measured causal factor is a predictor but not every predictor is a causal factor.[231-233]

Results of our meta-analysis suggest a 40% lower SRC rate when playing on a turf field system compared with natural grass. When stratified by sport in an exploratory manor, the effects were statistically significant for rugby but not in American football or soccer despite the point estimates for these sports also suggesting a lower SRC risk on artificial turf. The overall estimate from our study was similar to a previous meta-analysis.[234] Mechanism of injury is likely an important consideration for these type of analyses, but was not considered in our analysis.

While there is some evidence to suggest that stronger neck strength may lower SRC risk,[189,190] this association is not clear based on the studies to date.[191,192] Several different neck strength measures have been examined across studies, and of the studies to suggest an association exists, only select measures were statically significant. Future well designed prospective studies are recommended to better understand the relationship between the components of neck strength and SRC risk. The incorporation of head on neck strength components into a whole-body warm-up programme in reducing SRC risk may also be an avenue for future studies to examine. Generally, most studies examining neck strength and head impact kinematics have suggested that stronger neck strength reduces head impact severity, although not all results from studies identified in this review agreed.

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