



LUND UNIVERSITY

Keeping Heads in the Game: From Head Acceleration to Exercise-Based Approaches for Sport-Related Concussion Prevention

Ivanic, Branimir

2026

Document Version:

Publisher's PDF, also known as Version of record

[Link to publication](#)

Citation for published version (APA):

Ivanic, B. (2026). *Keeping Heads in the Game: From Head Acceleration to Exercise-Based Approaches for Sport-Related Concussion Prevention*. [Doctoral Thesis (compilation), Department of Health Sciences]. Lund University, Faculty of Medicine.

Total number of authors:

1

General rights

Unless other specific re-use rights are stated the following general rights apply:

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

Read more about Creative commons licenses: <https://creativecommons.org/licenses/>

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

Keeping Heads in the Game

From Head Acceleration to Exercise-Based
Approaches for Sport-Related Concussion Prevention

BRANIMIR IVANIC

DEPARTMENT OF HEALTH SCIENCES | FACULTY OF MEDICINE | LUND UNIVERSITY



Keeping Heads in the Game

From Head Acceleration to Exercise-Based Approaches
for Sport-Related Concussion Prevention

Branimir Ivanic



LUND
UNIVERSITY

DOCTORAL DISSERTATION

Doctoral dissertation for the degree of Doctor of Philosophy (PhD) at the Faculty
of Medicine, Lund University, to be publicly defended on 6 November 2026 at
13:00 in Belfrage Hall, Klinikgatan 32, Lund.

Faculty opponent
Professor Jon Patricios

Organization: LUND UNIVERSITY

Document name: Doctoral dissertation

Date of issue 2026-11-06

Author(s): Branimir Ivanic

Sponsoring organization:

Title and subtitle: Keeping Heads in the Game: From Head Acceleration to Exercise-Based Approaches for Sport-Related Concussion Prevention

Abstract: Sport-related concussion (SRC) is an important health concern in sport, arising from biomechanical forces that produce linear head acceleration (LHA) and rotational head acceleration (RHA). Exercise-based interventions targeting modifiable factors such as cervical function may contribute to SRC prevention, but evidence remains limited. The overall aim of this thesis was to advance the evidence base concerning SRC prevention and related outcomes, with particular emphasis on exercise-based strategies and their application in female football.

Across five papers, evidence synthesis was combined with laboratory measurement, end-user-informed intervention development, and pilot evaluation. Paper I characterised head acceleration during SRC and non-concussive impacts, while Paper II evaluated the test–retest reliability of head acceleration during anticipated and unanticipated laboratory perturbations. Paper III examined the efficacy and reporting completeness of exercise interventions targeting SRC incidence, head acceleration, and neck strength. Drawing on this evidence, Paper IV used end-user workshops to refine a neck resistance training program for female football, which was subsequently evaluated in a quasi-experimental pilot in Paper V.

SRC impacts were associated with markedly greater LHA and RHA than non-concussive impacts, although variation across sports and measurement contexts highlighted the limitations of current evidence (Paper I). The laboratory protocol demonstrated moderate-to-excellent reliability without systematic between-session differences, providing a stable framework for evaluating interventions under controlled conditions (Paper II). Existing exercise research showed no clear reductions in SRC incidence or head acceleration; however, resistance training improved neck strength, indicating that cervical function was modifiable even though its influence on head kinematics and SRC risk remained uncertain (Paper III). Incomplete intervention reporting further limited interpretation and replication (Paper III). End-user input subsequently streamlined the initial neck training prototype to seven exercises requiring 3–5 minutes (Paper IV). In the pilot, the program achieved 70% adherence and was rated favourably by players and coaches (Paper V). Preliminary effects favoured the intervention across most laboratory head acceleration conditions and all assessed neck strength outcomes (Paper V).

Together, these findings establish head acceleration as a relevant but context-dependent biomechanical outcome and provide a reliable laboratory framework for evaluating exercise-based approaches to SRC prevention. The findings also provide preliminary evidence that a brief, end-user-informed neck resistance training program may reduce head acceleration and improve neck strength in female football players. Whether these laboratory effects translate into reduced head acceleration during real-world head impacts or reduced SRC incidence remains unknown.

Key words: Brain Concussion, Acceleration, Resistance Training, Neck Muscles, Sports

Classification system and/or index terms (if any)

Supplementary bibliographical information

Language: English

Number of pages: 77

ISSN and key title: 1652-8220

ISBN: 978-91-8021-942-6

I, the undersigned, being the copyright owner of the abstract of the above-mentioned dissertation, hereby grant to all reference sources permission to publish and disseminate the abstract of the above-mentioned dissertation.

Signature

Date 2026-09-01

Keeping Heads in the Game

From Head Acceleration to Exercise-Based Approaches
for Sport-Related Concussion Prevention

Branimir Ivanic



LUND
UNIVERSITY

Copyright

Pages 1-77 © 2026 Branimir Ivanic, ORCID 0009-0009-5144-6516

Paper 1 © 2026 The authors. Published by Springer Nature (licensed under CC BY 4.0).

Paper 2 © 2026 The authors. Published by Elsevier (licensed under CC BY 4.0).

Paper 3 © 2024 The authors. Published by BMJ Publishing Group (licensed under CC BY-NC 4.0)

Paper 4 © 2026 The authors. (Manuscript unpublished)

Paper 5 © 2026 The authors. (Manuscript unpublished)

Cover image by Frida Nilsson

Published by:

Department of Health Sciences

Faculty of Medicine

Lund University

Lund 2026

ISBN 978-91-8021-942-6

ISSN 1652-8220

Printed in Sweden by Media-Tryck, Lund University,
Lund, 2026



Media-Tryck is a Nordic Swan Ecolabel
certified provider of printed material.
Read more about our environmental
work at www.mediatryck.lu.se

MADE IN SWEDEN 

To my beloved

Table of contents

Abstract.....	9
List of papers.....	10
Thesis at a glance	11
Abbreviations	12
Introduction	13
Sport-related concussion (SRC).....	13
What is SRC?	13
How common is SRC?	13
Why does SRC matter?	14
Head impact biomechanics	15
Biomechanical pathway	15
Linear and rotational head acceleration	16
Measuring head acceleration.....	17
Policy and equipment in SRC prevention.....	18
Policy and rule changes.....	18
Protective equipment.....	18
Exercise-based SRC prevention.....	19
Cervical function and neck resistance training	19
Developing exercise interventions for real-world sport.....	21
Underrepresentation of female athletes in SRC research.....	22
Rationale for thesis.....	24
Overall aims of the thesis.....	25
Specific aims	25
Methods.....	26
Methodological progression & overview.....	26
Systematic reviews (Papers I & III).....	29
Design, registration, & reporting	29
Eligibility criteria & literature searches	29
Data extraction & methodological appraisal.....	31
Evidence synthesis	31

Assessment of head acceleration (Papers II & V).....	32
Application of the laboratory protocol.....	32
Participants & testing schedules.....	32
Custom-built testing apparatus.....	35
Head-perturbation protocol.....	37
Measuring & processing of LHA and RHA.....	37
Reliability evaluation (Paper II).....	38
Neck resistance training program (Papers IV & V).....	39
Development-to-evaluation process.....	39
End-user-informed program development (Paper IV)	39
Final program.....	40
Intervention delivery & implementation (Paper V)	43
Efficacy & acceptability outcomes (Paper V).....	43
Data analysis (Paper V).....	43
Ethical considerations	44
Declaration of generative AI in the writing process	44
Results	45
Head acceleration in SRC impacts (Paper I).....	45
Evidence base & methodological quality.....	45
SRC versus non-concussive impacts.....	45
Subgroup differences in SRC head acceleration	45
Reliability of the head acceleration protocol (Paper II).....	46
Test–retest reliability.....	46
Agreement & measurement variability	47
Efficacy of exercise interventions (Paper III)	48
Evidence base & risk of bias.....	48
Efficacy of exercise interventions	48
Subgroup findings for isometric neck strength	49
Reporting completeness of exercise interventions.....	49
Neck resistance training program (Paper IV)	50
Initial program prototype	50
Facilitators & barriers to SRC prevention.....	50
End-user feedback & program refinement.....	51
Evaluation & contextual adaptation.....	53
Efficacy & acceptability of the program (Paper V)	53
Participant flow & baseline characteristics.....	53
Intervention delivery, adherence, & safety	53
Efficacy outcomes.....	54
Acceptability and implementation feedback.....	55
Discussion.....	56

Head acceleration as a biomechanical target (Papers I & II)	56
Exercise interventions: evidence & gaps (Paper III)	58
Developing an end-user-informed program (Paper IV)	59
Efficacy and acceptability of the program (Paper V)	61
Methodological considerations	62
Clinical relevance and future perspectives	64
Conclusion.....	66
Acknowledgements.....	67
References	69

Abstract

Sport-related concussion (SRC) is an important health concern in sport, arising from biomechanical forces that produce linear head acceleration (LHA) and rotational head acceleration (RHA). Exercise-based interventions targeting modifiable factors such as cervical function may contribute to SRC prevention, but evidence remains limited. The overall aim of this thesis was to advance the evidence base concerning SRC prevention and related outcomes, with particular emphasis on exercise-based strategies and their application in female football.

Across five papers, evidence synthesis was combined with laboratory measurement, end-user-informed intervention development, and pilot evaluation. Paper I characterised head acceleration during SRC and non-concussive impacts, while Paper II evaluated the test–retest reliability of head acceleration during anticipated and unanticipated laboratory perturbations. Paper III examined the efficacy and reporting completeness of exercise interventions targeting SRC incidence, head acceleration, and neck strength. Drawing on this evidence, Paper IV used end-user workshops to refine a neck resistance training program for female football, which was subsequently evaluated in a quasi-experimental pilot in Paper V.

SRC impacts were associated with markedly greater LHA and RHA than non-concussive impacts, although variation across sports and measurement contexts highlighted the limitations of current evidence (Paper I). The laboratory protocol demonstrated moderate-to-excellent reliability without systematic between-session differences, providing a stable framework for evaluating interventions under controlled conditions (Paper II). Existing exercise research showed no clear reductions in SRC incidence or head acceleration; however, resistance training improved neck strength, indicating that cervical function was modifiable even though its influence on head kinematics and SRC risk remained uncertain (Paper III). Incomplete intervention reporting further limited interpretation and replication (Paper III). End-user input subsequently streamlined the initial neck training prototype to seven exercises requiring 3–5 minutes (Paper IV). In the pilot, the program achieved 70% adherence and was rated favourably by players and coaches (Paper V). Preliminary effects favoured the intervention across most laboratory head acceleration conditions and all assessed neck strength outcomes (Paper V).

Together, these findings establish head acceleration as a relevant but context-dependent biomechanical outcome and provide a reliable laboratory framework for evaluating exercise-based approaches to SRC prevention. The findings also provide preliminary evidence that a brief, end-user-informed neck resistance training program may reduce head acceleration and improve neck strength in female football players. Whether these laboratory effects translate into reduced head acceleration during real-world head impacts or reduced SRC incidence remains unknown.

List of papers

1. Ivanic B, Cronström A, Rasi M, Ageberg E. Head acceleration magnitude in sport-related concussive impacts: A systematic review and meta-analysis. *Sports Med.* 2026 May 26. doi: 10.1007/s40279-026-02448-x.
2. Ivanic B, Cronström A, Ryan N, Eckner JT, Ageberg E. Test–retest reliability of a laboratory-based head acceleration testing protocol. *J Sci Med Sport.* 2026 Jun;29(6):578-586. doi: 10.1016/j.jsams.2026.01.005.
3. Ivanic B, Cronström A, Johansson K, Ageberg E. Efficacy of exercise interventions on prevention of sport-related concussion and related outcomes: A systematic review and meta-analysis. *Br J Sports Med.* 2024 Dec 2;58(23):1441-1451. doi: 10.1136/bjsports-2024-108260.
4. Ivanic B, Reuter A, Cronström A, Ageberg E. End-user-informed development of a neck resistance training program for sport-related concussion prevention: Bridging evidence and practice. Submitted 2026.
5. Ivanic B, Cronström A, Ryan N, Ageberg E. Efficacy and acceptability of an end-user-informed neck resistance training program on outcomes related to sport-related concussion prevention in female football. Submitted 2026.

Thesis at a glance

Paper I	
Aim	To systematically review the magnitudes of LHA and RHA associated with SRC impacts in team-sport athletes of all ages and both sexes.
Main results	SRC impacts were associated with markedly greater LHA and RHA than non-concussive impacts. However, LHA and RHA magnitudes during SRC impacts varied substantially across the examined subgroups.
Conclusions	LHA and RHA are relevant biomechanical outcomes associated with SRC. However, substantial variability limits their use as stand-alone indicators of injury risk.
Paper II	
Aim	To evaluate the test–retest reliability of a novel laboratory-based protocol for inducing and measuring head acceleration in multiple directions under anticipated and unanticipated conditions.
Main results	The protocol demonstrated moderate-to-excellent test–retest reliability across directions and anticipatory conditions, with no systematic bias. Variability was generally greater for RHA and under unanticipated conditions.
Conclusions	The protocol provides a reliable, controlled framework for evaluating head acceleration and potential intervention effects.
Paper III	
Aim	To systematically review the efficacy of exercise interventions on SRC incidence, LHA, RHA, and neck muscle strength, and to assess the completeness of intervention reporting.
Main results	Neuromuscular warm-up programs did not significantly reduce SRC incidence, although more frequent implementation showed potential benefits. Resistance training did not significantly affect LHA or RHA but produced a large improvement in neck strength. Intervention reporting was frequently incomplete.
Conclusions	Evidence remains insufficient to determine whether exercise interventions prevent SRC or reduce head acceleration. Resistance training can improve neck strength, but its relevance to SRC prevention remains uncertain, and more complete intervention reporting is required.
Paper IV	
Aim	To describe the development of a novel, evidence-informed neck resistance training program for SRC prevention in female football, incorporating knowledge, experience, and feedback from end-users.
Main results	End-user workshops informed the final intervention. The resulting program consisted of seven exercises, required 3–5 minutes to complete, and included an educational component.
Conclusions	End-user involvement enabled the development of a brief, context-specific program that balanced available evidence with the practical requirements of female football.
Paper V	
Aim	To evaluate the efficacy and acceptability of an end-user-informed neck resistance training program targeting outcomes related to SRC prevention, including LHA, RHA, and neck muscle strength, in female football.
Main results	The six-week program produced greater reductions in LHA and RHA across most directions under both anticipatory conditions, alongside greater improvements in neck strength. Players and coaches reported favourable acceptability.
Conclusions	Building on identified evidence gaps, the program demonstrated preliminary efficacy in reducing head acceleration and increasing neck strength in female football players, although its effects on real-world head impacts and SRC incidence remain unknown.

LHA, linear head acceleration; RHA, rotational head acceleration; SRC, sport-related concussion.

Abbreviations

AEs	Athlete exposures
CERT	Consensus on Exercise Reporting Template
CHAMP	Consensus Head Acceleration Measurement Practices
CI	Confidence interval
CTE-NC	Chronic traumatic encephalopathy neuropathologic change
g	Gravitational acceleration
GRADE	Grading of Recommendations Assessment, Development, and Evaluation
ICC	Intraclass correlation coefficient
I^2	Heterogeneity statistic
MD	Mean difference
MVIC	Maximal voluntary isometric contraction
NCAA	National Collegiate Athletic Association
Rad/s ²	Radians per second squared
RCT	Randomised controlled trial
RR	Risk ratio
RoB 2	Cochrane Risk of Bias 2 tool for randomised trials
SD	Standard deviation
SEM	Standards error of measurement
sEMG	Surface electromyography
SMD	Standardised mean difference
SRC	Sport-related concussion
η^2	Eta squared

Introduction

Sport-related concussion (SRC)

What is SRC?

Sport-related concussion (SRC) has been defined as “a traumatic brain injury caused by a direct blow to the head, neck or body resulting in an impulsive force being transmitted to the brain that occurs in sports and exercise-related activities” (1). The rapid acceleration generated by such an impact causes differential motion between skull and brain, exposing brain tissue to pressure gradients and strain (2).

These mechanical effects can disrupt neuronal function and initiate a neurometabolic cascade involving increased energy demands, reduced energy availability, and alterations in cerebral blood flow and neuronal communication, all of which may contribute to SRC symptoms and signs (3). SRC is therefore primarily considered a functional and physiological brain injury. Loss of consciousness is not required, symptoms and signs may appear immediately or develop over time, and standard structural neuroimaging is usually normal (1). Together, these characteristics can make SRC difficult to recognize at the time of injury, which has historically complicated estimates of how commonly it occurs.

How common is SRC?

Historically, estimates of SRC have been limited by incomplete recognition and reporting (4, 5). In a survey of 1,532 high-school American football players, only 47.3% of those who recalled sustaining an SRC during the season reported it, commonly because they did not recognise the injury, underestimated its severity, or wanted to remain in competition (4). As awareness and guidance increased, the reported SRC rate across 12 high-school sports rose 4.2-fold between 1997–1998 and 2007–2008, an increase that may have been partially attributable to improved recognition and injury coding (6). Despite these improvements, non-disclosure continues to be documented among youth athletes, suggesting that reported SRC rates may still underestimate its occurrence (7).

Even with improved surveillance, no single estimate adequately represents SRC incidence because rates vary by sport, competitive level, population, case definition

and identification, and availability of medical personnel (8, 9). Surveillance across 23 National Collegiate Athletic Association (NCAA) sports recorded an overall incidence of 4.13 SRCs per 10,000 athlete-exposures (AEs), with the highest rates observed in male ice hockey and female football at 7.35 and 7.15 per 10,000 AEs, respectively (10). Across these collegiate sports, the competition-related rate was approximately four times the practice-related rate (10). Among children and adolescents, a recent meta-analysis reported a pooled incidence of 1.41 SRCs per 1,000 AEs across 21 sports (8). SRC incidence was highest in collision sports and competition settings, whereas age did not significantly moderate incidence (8).

Sex-related differences are similarly sport dependent (11). A meta-analysis of 38 studies found significantly higher rates among female athletes in football and basketball, with female-to-male rate ratios of 1.76 and 1.99, respectively, although this pattern was not consistent across other sex-comparable sports (11). Taken together, SRC occurs across a wide range of sports but is more frequently reported in collision and contact sports, during competition, and among female athletes in certain comparable sports (8, 10, 11). However, the importance of SRC cannot be understood from its frequency alone and must also be considered in relation to its consequences for affected athletes.

Why does SRC matter?

SRC can produce physical symptoms (e.g., headache, dizziness), cognitive symptoms (e.g., difficulty concentrating or remembering), emotional symptoms (e.g., irritability, anxiety), and sleep-related symptoms (12). The number and severity of these vary considerably between athletes and may change throughout recovery (1). Nevertheless, most athletes recover relatively quickly (13). A systematic review and meta-analysis of 278 studies found that 93% of athletes had fully returned to learning without additional academic support by 10 days (13). In the same review, the pooled mean times to symptom resolution and unrestricted return to sport were approximately 14 and 20 days, respectively (13).

An important minority, however, experience persisting symptoms, defined as symptoms lasting more than four weeks (1). Because symptoms such as headache, fatigue, sleep disturbance, anxiety, and concentration difficulties are not specific to SRC, persisting symptoms may be caused by the SRC, reflect pre-existing or co-occurring conditions, or result from a combination of factors (1). Up to 30% of children and adolescents experience symptoms lasting four weeks or longer (14). Alongside the duration and trajectory of recovery, symptom burden may also differ between athletes. In a sex-based comparison of NCAA athletes participating in comparable sports, female athletes reported greater symptom burden than male athletes, although overall recovery trajectories were similar between sexes (15). SRC history is also associated with greater recurrence risk. A meta-analysis of

23,411 children found that those with a previous SRC had more than three times the risk of sustaining subsequent SRC (16).

Repeated SRCs and long-term exposure to repetitive head impacts have raised concerns about cumulative effects on brain health (17). Across the evidence reviewed, former amateur athletes were not shown to have an elevated risk of later-life mental health problems or neurological disorders (17). Some studies of former professional athletes reported associations with dementia or amyotrophic lateral sclerosis (ALS), but confounding and high risk of bias prevent causal conclusions (17). Chronic traumatic encephalopathy neuropathological change (CTE-NC) has been identified after death in some former athletes with extensive exposure to repetitive head impacts (1). However, CTE-NC is a postmortem neuropathological finding rather than a clinical diagnosis, and its prevalence among former athletes and the general population remains unknown (1). CTE-NC should therefore be acknowledged as an important area of concern and continuing research without implying that one or more SRCs necessarily lead to later neurodegenerative disease (1, 17).

Together, the immediate symptom burden, disruption of sport and daily life, possibility of persisting symptoms, risk of recurrence, and concern regarding cumulative consequences make SRC an important target for prevention. Because SRC begins with the transmission of mechanical forces to the brain, understanding the biomechanics of head impacts is central to explaining how these injuries occur and how their risk might be reduced (2).

Head impact biomechanics

Biomechanical pathway

From a biomechanical perspective, SRC can be represented as a sequence in which external loading to the head, neck, or body produces head motion, which may generate mechanical responses within the brain and ultimately contribute to physiological disturbance and clinical injury (18). Head acceleration characterises how rapidly the head's linear or rotational velocity changes and therefore lies between the external load and the internal brain response (2). The resulting acceleration is shaped by loading characteristics and interactions among the head, neck, and body, so apparently similar impacts can produce different patterns of head motion (2, 18).

As the head accelerates, the inertia of the brain generates internal loading that can produce pressure gradients and deform neural tissue, commonly characterised by strain and strain rate (18). Because tissue-level responses cannot be measured

directly during sporting impacts in living athletes, head acceleration is commonly used as a practical biomechanical surrogate through which the loading experienced by the brain can be investigated (19, 20). Head acceleration is therefore an upstream biomechanical indicator rather than a direct measure of tissue damage or neurological dysfunction.

At the group level, some evidence suggests that greater head acceleration magnitudes are associated with a higher probability of SRC, and this proposed relationship has been used to develop biomechanical injury-risk functions (21). However, reported head acceleration magnitudes during SRC impacts vary substantially across studies and contexts (2, 22). The extent of this variability across relevant subgroups remains unclear. Nevertheless, the position of head acceleration within the biomechanical pathway makes it valuable for characterising head impacts and evaluating interventions intended to reduce mechanical loading of the brain. Understanding this role requires separate consideration of the linear and rotational components of head acceleration.

Linear and rotational head acceleration

Linear head acceleration (LHA) represents the rate of change in the linear velocity of the head's centre of gravity and is commonly reported as peak resultant acceleration in gravitational units (g), whereas rotational head acceleration (RHA) represents the rate of change in angular velocity and is expressed in radians per second squared (rad/s^2) (20, 23). Together, they describe complementary components of the head's six-degree-of-freedom motion (23).

LHA and RHA are associated with different predominant mechanical responses within the brain (24, 25). LHA primarily generates intracranial pressure gradients, the magnitude and distribution of which are influenced by acceleration characteristics and by brain size and shape (25). RHA produces relative motion between the skull and brain and is particularly associated with shear deformation and brain-tissue strain (24). These mechanisms are not mutually exclusive, as pressure and strain can develop during the same impact and the resulting tissue response reflects the combined characteristics of the head motion (24, 25).

Sporting impacts rarely produce purely linear or purely rotational motion (2). A force directed through the head's centre of gravity produces translation, whereas a force applied away from it creates a moment that rotates the head (20). Therefore, most impacts generate both components simultaneously (2). LHA and RHA are mechanically related but represent different aspects of head motion, meaning that neither completely characterises the loading experienced by the brain when considered alone (21). For that reason, both measures are commonly examined together as complementary indicators of biomechanical exposure relevant to SRC. Their usefulness, however, depends on how accurately and reliably head motion can

be captured, making the approach used to measure head acceleration an important consideration (20, 26).

Measuring head acceleration

During sport participation, wearable head-impact measurement devices use accelerometers and angular-rate sensors incorporated into helmets, headgear, headbands, skin patches, or mouthguards to record head motion (27, 28). These devices capture head-acceleration events during training and competition, providing ecologically relevant information about the frequency and magnitude of real-world exposure and, when combined with video, the context in which events occurred (27, 28). This ecological value comes with limited experimental control because real-world impacts occur under highly variable conditions (27, 28). Whether an athlete anticipated the event is also not captured directly by wearable sensors (29). Field studies are therefore well suited to characterising exposure but less able to isolate why a particular head response occurred.

In addition, the accuracy of wearable measurements depends substantially on how securely the sensor is coupled to the skull. Helmet-, headgear-, and skin-mounted sensors can move relative to the skull and distort recorded kinematics, whereas custom-fitted mouthguards generally provide closer coupling through the upper dentition, particularly when the jaw is clenched (30, 31). Nevertheless, performance varies with the device, fit, sampling rate, filtering and impact conditions, requiring validation for the intended application (30). Accurately measuring kinematics and correctly detecting an event are also separate requirements. Movement or equipment contact can create false-positive recordings, while recording thresholds and classification algorithms can miss genuine events (27). Time-synchronised video is therefore recommended to verify recorded events and provide context, although it cannot remove all uncertainty (27).

Laboratory testing complements field measurement by using inertial sensors or motion-capture systems to quantify responses to controlled, non-injurious perturbations of the head-neck system (29). Standardised loading and participant instructions permit repeated comparisons and help isolate the effects of factors such as neck strength or muscle activation (29, 32). Instructions to relax or brace before loading can also create conditions representing anticipated and unanticipated impacts under otherwise consistent testing (29, 32). However, non-injurious loading, constrained movement, and artificial apparatus cannot reproduce the full complexity of sporting impacts (29). Interpretation therefore depends on protocol validity and test–retest reliability, requiring study methodology to be standardised and reported transparently (29, 33). Field and laboratory methods are therefore complementary, with field methods characterising real-world exposure and laboratory methods isolating mechanisms under controlled conditions.

Policy and equipment in SRC prevention

Policy and rule changes

Policy and rule changes seek to prevent SRC by reducing exposure to potentially injurious contact across entire sporting populations. These approaches may eliminate particular forms of contact, reduce the frequency or duration of contact exposure, alter how contact situations are performed or increase the penalties applied to dangerous play (34, 35). Approaches that remove or substantially reduce a recognised exposure have shown the clearest benefits (34). Disallowing body checking in child and adolescent ice hockey was associated with a 58% lower SRC rate, while limiting contact in American football practice was associated with a 64% lower practice-related SRC rate, although the certainty of evidence was lower for the latter (34).

Evidence is less consistent for rules intended to deter dangerous behaviour while retaining the contact event itself. In youth ice hockey, a zero-tolerance head-contact policy did not reduce direct or indirect head-contact rates, and fewer than 14% of direct player-to-player head contacts were penalised after implementation (36). In professional male football, introducing a red-card sanction for intentional elbow-to-head contact was associated with reductions in elbow-to-head contacts and overall head injuries, but the accompanying reduction in SRC did not reach statistical significance (37). Together, these findings indicate that sanction-based rules are most likely to produce preventive effects when they are consistently enforced and result in changes in player behaviour (36, 37).

Policy evaluation remains difficult because league-wide changes rarely permit randomisation and may coincide with changes in SRC recognition and reporting. Studies should therefore confirm that the targeted exposure or behaviour changed and monitor any unintended shifts in risk (34, 35). Female athletes remain particularly underrepresented, with female-specific estimates reported in only four of 21 policy or rule-change studies in a recent systematic review (38). Findings from male-dominated settings should therefore not be assumed to transfer directly to female athletes. This sex-based evidence gap remains equally important when considering protective equipment.

Protective equipment

Helmets and padded headgear absorb and distribute impact energy, whereas mouthguards and facial protection are primarily designed to prevent dental, facial, and ocular injuries (39). Although helmets reduce the risk of serious structural head injuries in relevant sports, these benefits should not be assumed to provide equivalent protection against SRC (39). Some helmet designs and padding

configurations may reduce SRC risk in American football, but current evidence is insufficient to conclude helmets consistently prevent SRC across sports (34).

Evidence across specific equipment types illustrates this variability. In collegiate American football, one helmet model was associated with a 53.9% lower SRC risk than an older comparator, indicating that protection can differ between helmet models (40). Mouthguards have established benefits against orofacial injuries (41). Their use was also associated with a 26% lower SRC rate across collision sports, although the effect was significant in ice hockey but not in rugby and was driven largely by one ice hockey study (34). By contrast, a meta-analysis of three randomised trials involving 6,311 football and rugby players found no reduction in SRC with soft padded headgear (42). More recent female-specific evidence introduces further uncertainty. A 2025 meta-analysis combining one randomised trial and two cohort studies found that headgear was associated with a 30% lower SRC rate among adolescent female football and lacrosse players, but the certainty of the evidence was very low (38).

These conflicting findings show that protective effects cannot be generalised across equipment types, sports, or populations. No protective device should therefore be considered a complete solution, and equipment is best viewed as one component of a multifaceted prevention strategy. Whereas policy and equipment primarily modify impact exposure or the loading transmitted to the head, exercise-based prevention shifts attention to the athlete's physical and neuromuscular capacity to respond to that loading (32, 43).

Exercise-based SRC prevention

Cervical function and neck resistance training

Preventive attention has also focused on exercise-based strategies that may modify how athletes physically respond when an impact occurs (44). One proposed strategy is neck resistance training, based on the premise that greater cervical strength and improved neuromuscular function may enhance control of the head when external forces are applied (44, 45). By generating forces and moments that oppose externally induced motion, the cervical muscles may increase head-neck stiffness and couple the head more firmly to the torso, thereby limiting head motion (44, 45). Through this proposed pathway, greater cervical strength and appropriately timed activation could attenuate the head's kinematic response and potentially reduce SRC risk, providing a theoretical basis for targeting cervical function within exercise-based prevention (32, 45).

Cervical strength is commonly quantified as the peak force or moment generated during a maximal voluntary isometric contraction, typically measured using handheld or fixed dynamometry in various cervical directions (44, 45). This provides a practical measure of direction-specific force-generating capacity. Greater maximal strength creates the potential to generate larger opposing forces and moments when external loading attempts to move the head (45). However, strength measured under static conditions does not establish how rapidly, for how long, or how appropriately this capacity can be expressed during a brief and multidirectional sporting impact (44). Maximal isometric strength is therefore an important but incomplete representation of cervical function.

The timing of cervical muscle activation is another important component of this biomechanical pathway. During sport participation, anticipated contact may allow an athlete to pre-activate and co-contract the cervical musculature before loading begins. Unanticipated contact provides less opportunity to prepare and leaves the early response more dependent on existing muscle activity and reactive activation (32, 46). In a laboratory study of 46 male and female contact-sport athletes, greater isometric strength and anticipatory activation were independently associated with smaller changes in linear and angular velocity during controlled impulsive loading across multiple directions (32). Evidence from sporting impacts is less consistent, with anticipation associated with lower RHA during moderate-intensity impacts in youth ice hockey, but not during more severe hockey impacts or among high-school American football players, while effects on LHA were generally absent (46). Alongside maximal strength and anticipatory activation, rate of force development, muscle endurance, and strength balance may also influence head acceleration and potentially SRC risk (44).

Observational evidence relating cervical strength to head acceleration has produced promising but mixed findings. A systematic review of five cross-sectional football heading studies found that greater neck strength was associated with lower head acceleration during purposeful heading, although the strength and direction of these relationships differed between muscle groups, heading tasks, and kinematic outcomes (47). Conversely, among 49 high-school and collegiate American football players, the odds of sustaining higher-magnitude impacts during play were unrelated to maximal strength but were lower in those with greater cervical stiffness and smaller angular displacement following laboratory perturbation (48). These findings suggest that cervical strength may contribute to head control, but its relationship with head acceleration may depend on how strength is expressed and interacts with anticipation, technique, and impact characteristics.

Prospective evidence linking cervical strength with diagnosed SRC is similarly promising but inconsistent. In a study of 6,704 male and female high-school athletes, weaker preseason neck strength was associated with subsequent SRC, with each additional pound of overall neck strength corresponding to 5% lower adjusted odds of SRC (49). Among 225 male professional rugby players, a 10% increase in

neck-extension strength was associated with a 13% lower SRC rate, whereas no significant associations were observed for the other strength directions (50). A more recent prospective study of 43 adolescent male rugby players also found that lower neck-extension strength was associated with greater odds of subsequently sustaining SRC, although only 11 players sustained the injury within this small, single-school cohort (51). In contrast, a prospective study of 136 male professional rugby players found that preseason measures of neck strength and endurance had little clinical value for predicting subsequent SRC (52). Moreover, studies have used different testing positions, devices, and protocols, limiting direct comparisons between their findings (44).

Overall, cervical function provides a plausible modifiable target because it may influence the dynamic response of the head when impacts cannot be avoided. However, evidence linking cervical function to head acceleration and diagnosed SRC remains mixed, and neck resistance training should currently be regarded as a promising strategy rather than an established method of SRC prevention. Establishing whether this rationale translates into preventive benefit requires well-designed intervention studies that target the relevant components of cervical function, evaluate head-acceleration responses under anticipated and unanticipated loading conditions, and determine whether such interventions can be implemented consistently within real-world sporting environments.

Developing exercise interventions for real-world sport

Developing an intervention with a plausible mechanism and demonstrating that it can produce its intended outcomes under controlled conditions are necessary first steps in injury prevention (53, 54). Efficacy describes whether an intervention can work under ideal, closely controlled conditions, whereas effectiveness concerns whether it produces meaningful outcomes when delivered by its intended users under routine real-world conditions (54). Efficacy studies can tightly control delivery and provide substantial research involvement, but these conditions are difficult to reproduce in community sport (54, 55). Preventive impact therefore also depends on whether teams have sufficient time, resources, personnel, and organisational support to integrate an intervention and maintain its use (56). This helps explain why interventions that succeed in controlled studies may not become established in practice. In a recent mixed-methods study, only around one-third of programmes represented in the survey had been scaled beyond their original trials, with limited resources and inadequate organisational support among the reported barriers to wider scale-up (55).

Effectiveness and sustained implementation are shaped by contextual factors operating across athletes, coaches, teams, and sporting organisations (56, 57). Athletes must perceive a programme as relevant and manageable, coaches determine whether time is allocated to it during training and how its delivery is

supervised, and organisations influence the facilities and support available (56). In Swedish female football, programme fit, player engagement, training resources, and organisational support interacted to influence the adoption and use of an injury-prevention programme (58). Contextual fit is therefore more likely when intended end-users are involved during development and planning rather than only after an intervention has been finalised (53, 57). End-users can identify practical barriers that may not be apparent to researchers, allowing the intervention to be adapted to its intended setting (53, 57). This process should remain iterative while preserving the underlying scientific rationale and core components expected to produce planned effects (53, 54).

The aim of such involvement is to develop an intervention that is both contextually relevant and straightforward to deliver (53, 56). Exercise-based programmes are more likely to be implemented when they are brief, provide clear instructions, and can be adapted and integrated into existing activities (56, 58). In university female rugby, participants engaged well with neck resistance training once they understood its potential benefits, but requested greater exercise variety and adaptability, and preferred group delivery at the start of team training (59). Any simplification must nevertheless preserve the training dose needed to retain the intended mechanism of action (44, 53). Evaluation should therefore examine intervention effects alongside implementation outcomes such as acceptability, feasibility, adoption, fidelity, and sustainability, helping to distinguish an ineffective intervention from one that was not delivered or used as intended (54, 60). Context-specific development is particularly important for female athletes, who have historically been underrepresented in injury-prevention research (61, 62).

Underrepresentation of female athletes in SRC research

Female athletes have historically been underrepresented in SRC research, which has frequently focused on predominantly male samples and male-dominated sports (63). An evaluation of 171 studies informing three influential SRC consensus and position statements found that 80.1% of participants were male, more than 40% of studies included no female participants, and only two used exclusively female samples (63). More recent evidence indicates some progress. Research informing the Amsterdam 2022 consensus included more studies with female participants than research informing the Berlin 2016 consensus, although female athletes remained underrepresented overall (64).

Numerical inclusion alone does not ensure that evidence meaningfully informs practice for female athletes, as studies may include both female and male participants but pool their data without reporting sex-specific estimates or examining whether associations or intervention effects differ between groups (65).

In the systematic review informing the 2025 International Olympic Committee Female, Woman and/or Girl Athlete Injury Prevention consensus, only 40 of 108 SRC studies reported female-specific estimates, including only 19 of 67 studies evaluating preventive strategies (38). Findings derived predominantly from male athletes may be relevant to female athletes, but their applicability should be examined rather than assumed (61). At group level, evidence suggests that female and male athletes may differ in reported SRC occurrence and injury mechanism (66). Differences have also been reported in head-impact exposure and cervical characteristics (67, 68). Addressing underrepresentation therefore requires adequately powered samples of female athletes, transparent reporting, sex-specific analyses, and direct evaluation within the populations for whom interventions are intended (61, 65). Such research is necessary to ensure that future SRC-prevention recommendations are informed by evidence that adequately represents the athletes expected to use and benefit from them.

Rationale for thesis

Effective SRC prevention requires a clearer understanding of the biomechanical factors associated with injury. LHA and RHA are commonly used as biomechanical indicators of the forces acting on the head, yet uncertainty remains regarding how well they distinguish SRC from non-concussive impacts. It is also necessary to establish whether the magnitude of LHA and RHA during SRC impacts differ across sports and athlete populations. Clarifying these relationships is important for interpreting head acceleration as a surrogate outcome and identifying meaningful targets for preventive interventions.

The use of head acceleration as an outcome also depends on the availability of reliable testing methods. Although field-based measurements capture impacts in real-world sporting environments, the influence of factors such as impact direction and anticipation can be difficult to isolate. A reliable laboratory-protocol is therefore needed to measure LHA and RHA under controlled conditions and examine variables that may influence the attenuation of head acceleration. Alongside this methodological work, existing exercise-based interventions must be synthesised to identify which strategies may prevent SRC or reduce head acceleration, as well as which intervention characteristics are sufficiently described and feasible to replicate.

Female athletes have historically been underrepresented in SRC prevention research, despite high reported SRC rates in sports such as football. This limits the extent to which existing evidence can be applied confidently to female football players and highlights the need for interventions developed specifically within this context. Developing an exercise-based program together with football end-users may help ensure that it is informed by both available evidence and the practical requirements of team-based football.

Finally, developing an intervention does not establish whether it works or can be implemented successfully. An evidence-based and end-user-informed program must therefore be evaluated for both its efficacy in improving outcomes relevant to SRC prevention and its acceptability among those expected to use and deliver it. Collectively, these needs provide the rationale for the five papers in this thesis, progressing from evidence synthesis and methodological development to intervention design and applied evaluation in female football.

Overall aims of the thesis

The overall aim of this thesis was to advance the evidence base concerning SRC prevention and related outcomes, with particular emphasis on exercise-based strategies and their application in female football.

Specific aims

1. To systematically review the magnitudes of LHA and RHA associated with SRC impacts in team-sport athletes of all ages and both sexes (Paper I).
2. To evaluate the test–retest reliability of a novel laboratory-based protocol for inducing and measuring head acceleration in multiple directions under anticipated and unanticipated conditions (Paper II).
3. To systematically review the efficacy of exercise interventions on SRC incidence, LHA, RHA, and neck muscle strength, and to assess the completeness of intervention reporting (Paper III).
4. To describe the development of a novel, evidence-informed neck resistance training program for SRC prevention in female football, incorporating the knowledge, experience, and feedback from end-users (Paper IV).
5. To evaluate the efficacy and acceptability of an end-user-informed neck resistance training program targeting outcomes related to SRC prevention, including LHA, RHA, and neck muscle strength, in female football (Paper V).

Methods

Methodological progression & overview

This thesis comprised five connected papers that used different but complementary methods to examine SRC prevention. The papers progressed through two main research strands, which came together in the final paper (Figure 1).

The first strand focused on the biomechanical assessment of head acceleration. Paper I synthesised evidence concerning the magnitudes of LHA and RHA associated with SRC impacts, establishing the biomechanical context and rationale for the controlled laboratory assessment evaluated in Paper II. The second strand focused on exercise-based SRC prevention. Paper III synthesised evidence concerning efficacy and reporting completeness of exercise interventions, providing an evidence base for Paper IV, in which a neck resistance training program was developed by incorporating knowledge, experience, and feedback from end-users in female football.

These two strands converged in Paper V. The paper drew on the biomechanical evidence established in Paper I, the laboratory assessment protocol evaluated in Paper II, the exercise-intervention evidence synthesised in Paper III, and the end-user-informed program developed in Paper IV. Paper V subsequently evaluated the efficacy and acceptability of the program in an applied female football setting. This progression involved systematic review, laboratory reliability, mixed-methods development, and quasi-experimental evaluation methods. An overview of the designs, populations, and methods of the five papers is provided in Table 1.

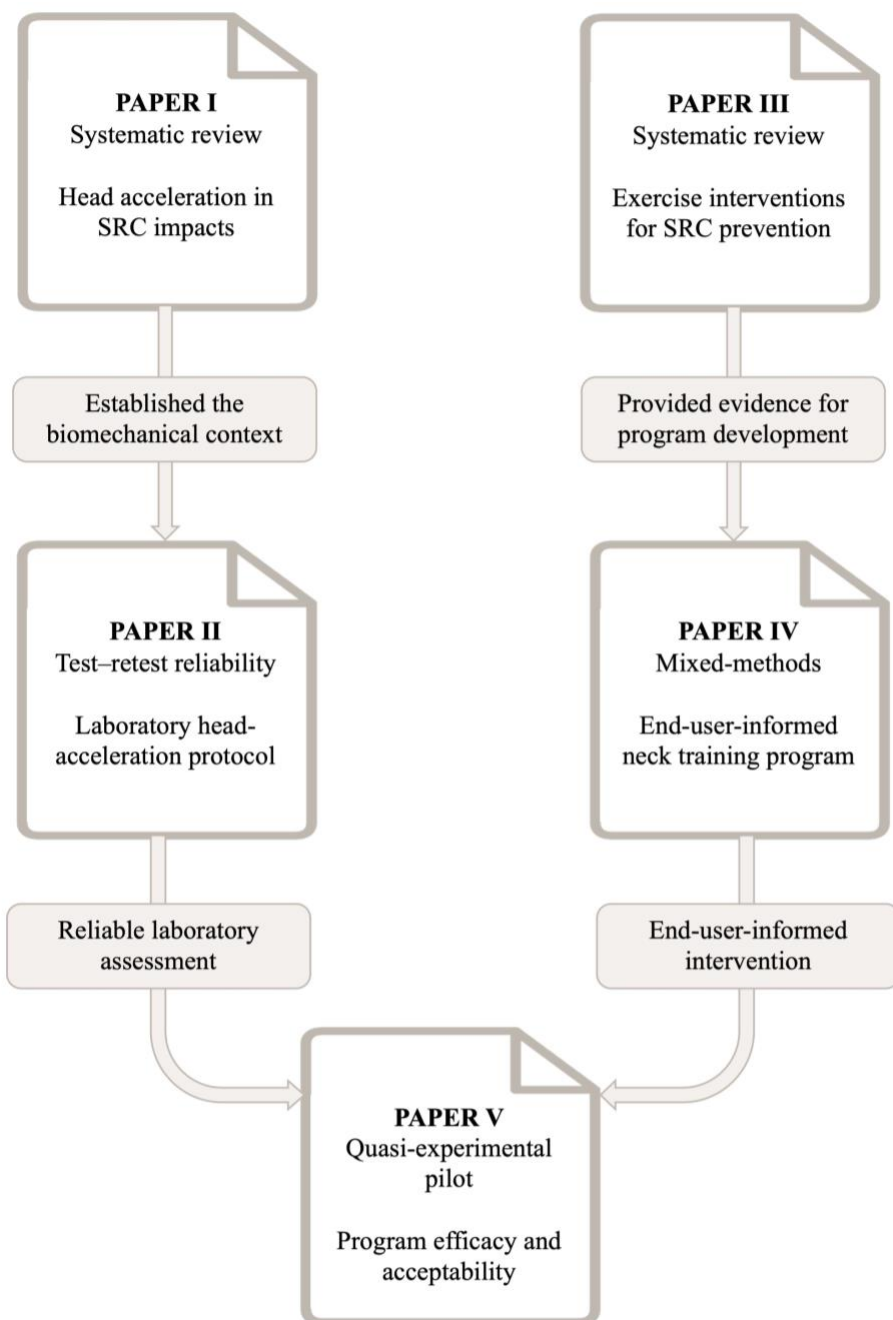


Figure 1. Methodological progression of the five papers included in the thesis.

Table 1. Overview of the included papers.

Paper I	
Study design	Systematic review and meta-analysis.
Materials	30 articles; 3,262 team-sport athletes; 12% female.
Methods	Systematic search of three databases. Extraction of LHA and RHA associated with SRC and non-concussive impacts. Risk of bias assessed using the NIH Quality Assessment Tool and certainty of evidence using GRADE.
Data analysis	Random-effects meta-analyses comparing SRC and non-concussive impacts; subgroup, heterogeneity, sensitivity, and publication-bias analyses.
Paper II	
Study design	Laboratory-based test–retest reliability study.
Participants	30 physically active adults; 50% female.
Methods	Standardised perturbations in four directions under anticipated and unanticipated conditions during two sessions within one week. LHA and RHA measured using motion capture.
Data analysis	ICC _(3,1) , SEM%, and Bland-Altman analyses.
Paper III	
Study design	Systematic review and meta-analysis.
Materials	26 articles; 5,249 participants; 4% female.
Methods	Systematic search of six databases. Exercise interventions evaluated for SRC incidence, LHA, RHA, and neck strength. Risk of bias, certainty of evidence, and CERT reporting completeness assessed.
Data analysis	Meta-analyses using risk ratios and standardised mean differences; subgroup, meta-regression, heterogeneity, and sensitivity analyses.
Paper IV	
Study design	Mixed-methods development study.
Participants	Nine football end-users (six coaches/medical staff, three players); 67% female.
Methods	Two sequential end-user workshops used to develop and refine a neck resistance training program for female football.
Data analysis	Workshop discussions analysed qualitatively using thematic analysis and integrated to inform program development. Quantitative responses summarised descriptively.
Paper V	
Study design	Quasi-experimental pilot study.
Participants	27 female football players completed follow-up: intervention, n=14; control, n=13.
Methods	Six-week neck resistance training program. Pre-post assessment of LHA, RHA, and neck strength, alongside adherence, safety, and acceptability.
Data analysis	Group $\times$ time mixed ANOVA with partial η^2 ; descriptive analysis of adherence, safety, acceptability, and open-ended feedback.

ANOVA, Analysis of variance; CERT, Consensus of Exercise Reporting Template; GRADE, Grading of Recommendations Assessment, Development, and Evaluation; ICC, intraclass correlation coefficient; LHA, linear head acceleration; NIH, National Institutes of Health; RHA, rotational head acceleration; SEM, standard error of measurement; SRC, sport-related concussion.

Systematic reviews (Papers I & III)

Design, registration, & reporting

Papers I and III used systematic review and meta-analysis designs. The protocols for both reviews were preregistered in the International Prospective Register of Systematic Reviews (PROSPERO): Paper I under CRD42024584070 and Paper II under CRD42023435033. Paper I was reported in accordance with Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidance (69). Paper III followed the PERSiST guidance for implementing PRISMA 2020 in exercise, rehabilitation, sport medicine and sport science (70).

Eligibility criteria & literature searches

Search strategies for Papers I and III were developed with support from experienced librarians and tailored to the aim of each review. For Paper I, MEDLINE, Scopus, and SPORTDiscus were searched on 4 September 2024, and the search was updated on 10 November 2025. For Paper III, MEDLINE, Embase, CINAHL, Scopus, Web of Science Core Collection, and SPORTDiscus were searched between 24 and 26 June 2023. The searches combined database-specific subject headings and free-text terms. Paper I focused on SRC and head acceleration, whereas Paper III focused on exercise interventions and outcomes related to SRC prevention (i.e., SRC incidence, head acceleration, and neck muscle strength). No restrictions on publication year or language were applied. Reference lists of included articles and relevant reviews were also searched.

All identified records were imported into Covidence (Veritas Health Innovation, Melbourne, Australia) (71), where duplicates were removed and the selection process was managed. Two review authors independently screened titles and abstracts before assessing potentially eligible full-text articles against predefined eligibility criteria. Disagreements were resolved through discussion between the two review authors, with the remaining authors consulted when agreement could not be reached. An overview of the main differences in the eligibility criteria and methods of Papers I and III is provided in Table 2.

Table 2. Comparison of eligibility criteria and methods in Papers I and III.

Component	Paper I	Paper III
Review focus	Magnitudes of LHA and RHA associated with diagnosed SRC impacts.	Efficacy and reporting completeness of exercise interventions targeting outcomes related to SRC prevention.
Population	Male and female athletes of any age and competitive level participating in team sports.	Male and female athletes of any age and competitive level, and healthy individuals from the general population.
Exposure/intervention	On-field match or training impacts associated with an SRC diagnosed by a qualified professional.	Exercise interventions of any modality or delivery method. Cognitive training, protective equipment, and policy or rule changes were excluded.
Comparator	Non-concussive on-field impacts, when reported; a comparator was not required for inclusion.	Control intervention without cervical exercises and/or no intervention.
Outcomes	Peak LHA and/or RHA.	SRC incidence, LHA, RHA, and/or isometric neck strength.
Eligible study designs	Observational and experimental studies.	RCTs, cluster RCTs, crossover RCTs, and quasi-experimental studies.
Search dates and databases	MEDLINE, Scopus, and SPORTDiscus searched on 4 September 2024; search updated on 10 November 2025.	MEDLINE, Embase, CINAHL, Scopus, Web of Science Core Collection, and SPORTDiscus searched between 24 and 26 June 2023.
Critical-appraisal tool	NIH Quality Assessment Tool for Observational Cohort, Cross-Sectional, and Case-Series Studies; articles classified as good, fair, or poor quality.	Cochrane Risk-of-Bias Tool for Randomised Trials (RoB 2); outcomes classified as low risk, some concerns, or high risk of bias.
Intervention reporting	Not assessed.	Reporting completeness assessed using CERT.
Certainty of evidence	GRADE; certainty initially rated as low because the included evidence was predominantly observational.	GRADE; certainty initially rated as high because the eligible designs were intervention trials.
Methods of synthesis	Random-effects restricted maximum-likelihood meta-analyses reporting SMDs and MDs. Subgroup analyses by sport, age, sex, session type, and instrumentation type.	Random-effects meta-analyses reporting RRs for SRC incidence and SMDs for continuous outcomes. Subgroup analyses by exercise modality, age, and sex, with post hoc meta-regression where heterogeneity was detected.

CERT, Consensus on Exercise Reporting Template; GRADE, Grading of Recommendations Assessment, Development and Evaluation; LHA, linear head acceleration; MD, mean difference; NIH, National Institutes of Health; RCT, randomised controlled trial; RHA, rotational head acceleration; RoB 2, Risk-of-Bias Tool for Randomised Trials; RR, risk ratio; SMD, standardised mean difference; SRC, sport-related concussion.

Data extraction & methodological appraisal

Data extraction and methodological appraisal were conducted independently by the same reviewer pairs who completed the study-selection process. When relevant information was missing or unclear, the authors of the included articles were contacted by email.

General study information and participant characteristics were extracted in both reviews. The remaining data were specific to the aims of each review. In Paper I, the authors extracted information on head-acceleration instrumentation and the frequency, characteristics, and magnitudes of SRC and non-concussive impacts. Sport, sex, competitive or educational level, session type, and instrumentation type were also recorded for subgroup analyses. In Paper III, the authors extracted descriptions of the intervention and control conditions and changes from baseline in SRC incidence, LHA, RHA, and isometric neck muscle strength.

Different appraisal tools were used because the reviews included different study designs. In Paper I, the authors assessed methodological quality using the 14-item National Institutes of Health (NIH) Study Quality Assessment Tool for observational cohort, cross-sectional, and case-series studies and classified each study as good, fair, or poor quality (72). In Paper III, the authors assessed risk of bias separately for each outcome using the revised Cochrane Risk of Bias tool for randomised trials (RoB 2) and classified the overall judgement for each outcome as low risk of bias, some concerns, or high risk of bias (73).

Evidence synthesis

In both reviews, the authors performed quantitative synthesis when articles reported sufficiently comparable outcomes; otherwise, findings were presented narratively. Random-effects models were used because variation in participant characteristics and study methods was expected. Pooled estimates were reported with 95% confidence intervals (CI). Standardised mean differences (SMDs) were interpreted as small (0.2), medium (0.5), or large (0.8) (74). Statistical heterogeneity was assessed using the I^2 statistic and interpreted according to established guidance (75).

In Paper I, analyses were performed in Stata (v. 18) using random-effects restricted maximum likelihood models. The authors synthesised peak LHA and RHA and compared SRC with non-concussive impacts using SMDs and mean differences (MDs). Prespecified subgroup analyses examined differences by sport, age group, sex, session type, and instrumentation type. Differences between subgroups were examined using the Qb statistics. Sensitivity analyses excluded articles with poor methodological quality, impacts without video verification, recording thresholds below 10 g, or only one reported SRC impact.

In Paper III, analyses were conducted in Review Manager Web (RevMan Web; v. 4.26.0). The authors performed a meta-analysis when at least two articles reported the same outcome. SRC incidence was analysed as a dichotomous outcome using a random-effect Mantel–Haenszel model and expressed as a risk ratio (RR) with a 95% CI. LHA, RHA, and neck muscle strength were analysed as continuous outcomes using random-effects inverse-variance models and expressed as SMDs with 95% CIs. Subgroup analyses were conducted by intervention modality, age group, and sex. Post hoc meta-regression was performed in Stata (v. 18) to explore study-level variables that could contribute to heterogeneity. Sensitivity analyses excluded articles involving the healthy general population, cluster-randomised or quasi-experimental designs, and articles judged to have a high risk of bias.

Potential reporting bias was examined using funnel plots and Egger’s test. The certainty of evidence was evaluated using GRADEpro in accordance with the GRADE handbook (76). The certainty of evidence was initially rated as low in Paper I because it was derived from observational studies and as high in Paper III due to the inclusion of randomised trials. In Paper III, the authors also assessed the reporting completeness of each exercise intervention using the Consensus on Exercise Reporting Template (CERT) (77). The CERT contains 16 items that were rated as adequately or inadequately reported, producing a total score from 0 to 19, with higher scores indicating more complete reporting.

Assessment of head acceleration (Papers II & V)

Application of the laboratory protocol

A laboratory-based protocol for inducing and measuring LHA and RHA in multiple cervical directions under anticipated and unanticipated conditions was used in Papers II and V. In Paper II, the authors administered the protocol across two sessions to evaluate its test–retest reliability. In Paper V, the authors subsequently used the protocol to assess the intervention and control groups at baseline and after the six-week study period. The shared procedures and study-specific differences are described below.

Participants & testing schedules

In Paper II, the authors recruited healthy, physically active individuals through advertisements posted at Lund University and snowball sampling. Individuals were eligible if they were 16–40 years old and regularly participated in physical activity, either independently or through organised sport. They were excluded if they had a current upper- or lower-body injury, had experienced a neck or head injury or related

pain during the preceding three months, or were unable to voluntarily activate the cervical muscles to brace for the anticipated trials. Each participant attended two laboratory sessions within one week.

In Paper V, the research team approached coaches and club representatives from senior female football teams competing in Swedish Divisions 1–4 in Scania. Recruitment was therefore conducted at team level. Players were eligible if they were at least 15 years old, regularly participated in team training or matches, and were expected to remain available throughout the six-week study period. Players were excluded if they had a current injury involving the upper or lower limbs, torso, neck or head, or had sustained a neck or head injury during the preceding three months. Players in both the intervention and control groups completed laboratory assessments at baseline and after the six-week study period.

Within each paper, the authors conducted the repeated assessments in the same motion-analysis room at the Movement and Reality Lab (MoRe-Lab, Faculty of Medicine, Lund University), using the same equipment and laboratory setup, with the testing procedures and environmental conditions kept as consistent as possible. In Paper II, the same two researchers administered all test and retest sessions. In Paper V, the first author conducted testing together with one of three trained research assistants. The principal differences in participant eligibility and testing schedules are summarised in Table 3.

Table 3. Comparison of participant recruitment, eligibility, and testing schedules in Papers II and V.

Characteristic	Paper II	Paper V
Recruitment	Individual-level recruitment of healthy, physically active individuals through flyers posted at Lund University and snowball sampling.	Team-level recruitment through coaches and club representatives of senior female football teams competing in Swedish Divisions 1–4 in Scania.
Allocation	Not applicable; all participants formed a single test–retest sample.	One team was allocated to the intervention group and one to the control group without randomisation. The intervention team was selected purposively based on its capacity to deliver the program.
Inclusion criteria	Aged 16–40 years and regularly participated in physical activity, either independently or through organised sport.	Aged ≥ 15 years, regularly participated in team training or matches, and expected to remain available for team activities throughout the six-week study period.
Exclusion criteria	Current upper- or lower-body injury; neck or head injury or related pain during the preceding three months; or inability to voluntarily activate the cervical muscles to brace during anticipated trials.	Current injury involving the upper limbs, lower limbs, torso, neck, or head; or neck or head injury during the preceding three months.
Testing occasions	Two laboratory sessions: test and retest.	Two laboratory assessments: baseline and follow-up in both the intervention and control groups.
Interval of assessments	Sessions conducted within one week.	Follow-up conducted after the six-week intervention period.
Purpose of repeated testing	To evaluate the test–retest reliability of the laboratory protocol for measuring LHA and RHA.	To evaluate changes in LHA, RHA, and neck muscle strength following the intervention compared with the control condition.
Laboratory standardisation	Test and retest sessions conducted in the same motion-analysis room using identical equipment and setup. Lighting, temperature, and room layout were kept consistent.	Baseline and follow-up assessments conducted in the same motion-analysis room using the same equipment and setup for both groups. A standardised protocol was followed, and lighting, room temperature, and room layout were kept consistent.
Testing personnel	The same two researchers conducted all test and retest sessions.	The first author conducted each session together with one of three trained project assistants, who rotated between sessions.

LHA, linear head acceleration; RHA, rotational head acceleration; SD, standard deviation.

Custom-built testing apparatus

In Papers II and V, the authors assessed head acceleration using the same custom-built apparatus designed to deliver brief, controlled mechanical perturbations to the head and neck. Participants sat upright on an adjustable seat against a rigid backrest. Straps positioned across the chest and lower back restricted movement of the upper torso, thereby limiting its contribution to the measured head and neck response. A closely fitted head harness was secured around the chin and occipital region and connected to the apparatus by a taut steel wire.

The steel wire passed through a pulley system and was connected to a mechanical cable clamp. External perturbations were generated by releasing a 1-kg cylindrical weight from a predefined height selected according to the participant's body mass. The falling weight engaged the cable clamp, producing a brief tensile force that was transmitted through the wire and head harness. The pulley arrangement allowed the force to be directed along the intended plane of head motion.

Several procedures were incorporated to promote consistent loading and participant safety. The authors verified the force generated across the available drop heights using a digital load cell, while a padded stopper limited the maximum displacement of the cable. The harness fit, torso restraints, and cable tension were checked before testing. The authors applied the same standardised apparatus and safety procedures at each assessment occasion in both papers. The apparatus is illustrated in Figure 2.

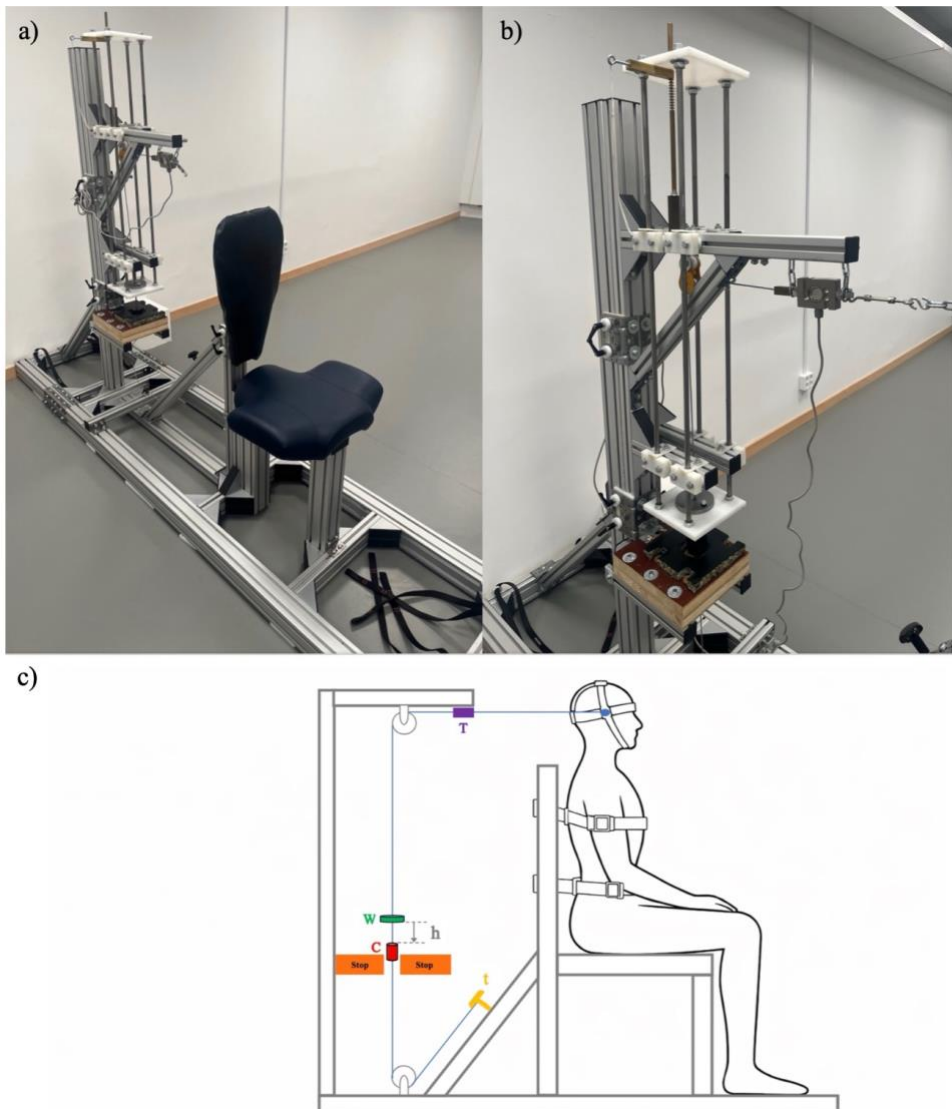


Figure 2. Custom-built laboratory apparatus and experimental setup for controlled head acceleration testing in Papers II and V. **(a)** Complete apparatus; **(b)** close-up view of the dropping mechanism; and **(c)** schematic of the experimental setup during forced cervical extension. The tension adjustment knob (**t**) removed cable slack, while the in-line force transducer (**T**) measured cable tension. The 1-kg weight (**W**) was released from a predefined drop height (**h**) onto the mechanical cable clamp (**C**), generating a rapid tensile force that was transmitted through the cable and head harness. The padded stopper (**Stop**) limited the maximum cable displacement. *Reproduced from Ivanic, et al. (78), © 2026 the authors, under CC BY 4.0.*

Head-perturbation protocol

At each assessment occasion in Papers II and V, the authors administered head perturbations in four directions: flexion, extension, right lateral flexion, and left rotation. The order of the directions was randomised across participants. Each direction was assessed under anticipated and unanticipated conditions.

During anticipated trials, participants were instructed to maximally activate the cervical muscles and brace before the external load was released. During unanticipated trials, participants wore an eye mask and were instructed to keep the cervical muscles relaxed. The authors used standardised verbal instructions throughout testing and monitored surface electromyography (sEMG) signals in real time to confirm that participants followed the intended activation condition.

For each direction and condition, participants completed one familiarisation trial followed by three recorded trials. A 30-second rest period was provided between trials. The authors applied the same testing sequence, participant instructions, and number of trials at each assessment occasion in both papers.

Measuring & processing of LHA and RHA

In Papers II and V, the authors recorded head motion using a three-dimensional motion-capture system (Qualisys AB, Gothenburg, Sweden) sampling at 100 Hertz (Hz). Four reflective markers attached to the head harness formed a tracking cluster. Before testing, additional markers were placed over the left and right tragi, and infraorbital notches. These markers and the measured head mass were used to define a participant-specific reference frame centred on the estimated head centre of mass. A static calibration linked the anatomical markers to the tracking cluster, after which the anatomical markers were removed. An additional marker attached to the falling weight identified the onset of the external perturbation. The positioning of the reflective markers and sEMG sensors is shown in Figure 3.

Raw kinematics data were processed in MATLAB (MathWorks, Natick, USA). Head motion was calculated relative to the position and orientation of the head at the onset of the perturbation, assuming that the restrained torso remained fixed. LHA and RHA were calculated in three axes and combined to obtain resultant LHA and RHA. The peak resultant value was extracted from each recorded trial. LHA was expressed in units of gravitational acceleration (g), while RHA was expressed in radians per second squared (rad/s^2).



Figure 3. Placement of surface electromyography (sEMG) sensors and reflective markers used during head-acceleration testing: (a) anterior, (b) lateral, and (c) posterior views. *Reproduced from Ivanic et al. (78), © 2026 the authors, under CC BY 4.0.*

In Paper II, the authors examined LHA and RHA separately for each perturbation direction and anticipatory condition. In Paper V, the authors retained these direction-specific outcomes and additionally calculated composite LHA and RHA values. Composite outcomes were calculated separately for anticipated and unanticipated conditions. Before analyses, the authors visually inspected the motion-capture data for movement artefacts and excluded affected trials. Wireless sEMG sensors (Ultium EMG, Noraxon, USA) were positioned bilaterally over the sternocleidomastoid muscles and cervical extensors immediately below the occipital hairline. The researchers monitored the signals visually in real time to verify cervical muscle activation during anticipated trials and a relaxed state during unanticipated trials.

Reliability evaluation (Paper II)

In Paper II, all analyses were performed in Stata (v. 18). Data from the two testing sessions were summarised using means and standard deviations. Test-retest reliability was quantified using intraclass correlation coefficients ($ICC_{3,1}$) based on a two-way mixed-effects model for absolute agreement and single measurements

(79). ICC estimates were reported with 95% CI and interpreted as poor (<0.50), moderate ($0.50\text{--}0.75$), good ($0.75\text{--}0.90$), or excellent (>0.90) (79).

Absolute measurement precision was evaluated using the standard error of measurement (SEM) and the SEM expressed as a percentage of the pooled mean (SEM%) (80, 81). Agreement between sessions was further examined using Bland–Altman plots displaying the mean between-session difference and 95% limits of agreement. Paired-samples t-tests were used to assess whether systematic differences were present between the two testing sessions.

Neck resistance training program (Papers IV & V)

Development-to-evaluation process

The neck resistance training program progressed through connected development and evaluation stages. In Paper IV, the authors developed an evidence-informed prototype based on the findings of Paper III and established resistance training principles (82). The prototype was examined during an initial workshop with end-users working in Swedish female football, whose knowledge, experience, and feedback informed its refinement. The revised program was subsequently tested during a second on-site workshop with players and coaches, allowing further adaptation to the team-training context.

In Paper V, the final end-user-informed program was implemented three times per week over six weeks and evaluated using a quasi-experimental pilot design. The intervention group completed the program alongside regular football activities, while the control group continued its usual training. The evaluation included changes in LHA, RHA, and neck muscle strength, together with players' and coaches' perceptions of program acceptability.

End-user-informed program development (Paper IV)

In Paper IV, the authors used a mixed-methods design combining qualitative workshop methodology with quantitative questionnaire data. Participants for the first workshop were recruited purposively through local football-club communication channels and direct email contact. Four end-users participated, comprising two females and two males working within Divisions 1 and 2 female football. Their roles and experiences included athletic training, physiotherapy, coaching, and previous football participation. The workshop was conducted at Lund University in October 2024, lasted approximately two hours, and was designed to support discussion and participant-to-participant interaction.

Participants first received a presentation of the prototype, watched a video demonstration of the exercises, and were given access to the equipment so that they could examine and try the program. They then completed a traffic-light activity using colour-coded sticky notes to assess exercise selection, equipment requirements, program frequency and duration, and adaptation and progression. Concerns and suggested changes were subsequently discussed as a group. Participants also completed a priority-mapping activity using two-dimensional grids to consider the importance and feasibility of implementation, the perceived efficacy of the program and its similarity to existing practice, and the anticipated adoption and adherence in relation to available support and resources. Individual ratings were followed by moderated group discussions in which participants explained their decisions and considered alternative perspectives.

The group discussions were audio-recorded and transcribed using speech-recognition software on an offline computer, after which the first author checked and corrected the transcripts. The transcripts and written contributions from the workshops activities were imported into NVivo (v. 14) and analysed together using reflexive thematic analysis following Braun and Clarke's six-phase process (83). Initial coding and theme development were primarily inductive, while program-specific feedback was subsequently mapped deductively onto the broader analytic structure. The first author led the analysis, with interpretations and theme development discussed iteratively within the research team. The qualitative findings guided decisions concerning exercise selection, equipment, program duration, progression, and adaptation to regular football activities. They also informed the development of a study-specific questionnaire for the second workshop.

The second workshop involved five end-users from a Division 3 female football team: three female players and two assistant coaches, one female and one male. The workshop was held at the team's regular premises in February 2026 and lasted approximately one hour, providing an opportunity to examine the revised program within its intended training environment. Following a practical demonstration, the players and coaches completed the entire program and discussed its compatibility with existing team routines. Players and coaches subsequently completed separate questionnaires containing adapted items from the Acceptability of Intervention Measure (AIM), Intervention Appropriateness Measure (IAM), and Feasibility of Intervention Measure (FIM), together with additional study-specific items (84). All items were rated on five-point Likert-type scales, and responses were summarised descriptively at the individual level and separately for players and coaches.

Final program

The final program comprised seven exercises distributed across three sequential blocks. Each block combined one rolling static neck activation exercise with one or two dynamic resistance exercises, collectively targeting cervical flexion, extension,

and rotation in both directions (Table 4, Figure 4). Each session required approximately 3–5 minutes and was intended to be delivered by coaches at the group level as part of the team’s regular football warm-up. Three sessions per week were prescribed.

The rolling static exercises were performed for 30–60 seconds, with progression achieved by gradually increasing the duration at the team level. The dynamic exercises were performed for 8–12 repetitions using a head harness with adjustable resistance tubing. Resistance was individualised and increased when a player could complete the prescribed repetitions with correct technique and without discomfort. Before the beginning of the program, players and coaches received an educational presentation covering SRC, the biomechanical rationale for neck resistance training, correct exercise technique, and relevant safety considerations. Coaches also received practical instructions on program delivery, progression, and safety.

Table 4. Structure, prescription, and progression of the final neck resistance training program.

Block	Exercise type	Cervical moment	Prescription	Progression
1	Rolling static activation	Flexion	30–60 seconds	Increase duration weekly at the team level.
	Dynamic activation	Flexion	8–12 repetitions	Increase resistance at the individual level when 12 repetitions can be completed with correct technique.
	Dynamic activation	Extension	8–12 repetitions	Increase resistance at the individual level when 12 repetitions can be completed with correct technique.
2	Rolling static activation	Left rotation	30–60 seconds	Increase duration weekly at the team level.
	Dynamic activation	Right rotation	8–12 repetitions	Increase resistance at the individual level when 12 repetitions can be completed with correct technique.
3	Rolling static activation	Right rotation	30–60 seconds	Increase duration weekly at the team level.
	Dynamic activation	Left rotation	8–12 repetitions	Increase resistance at the individual level when 12 repetitions can be completed with correct technique.

Note. Exercises were performed sequentially within each block. Sessions lasted approximately 3–5 minutes and were prescribed three times per week as part of the regular football warm-up.



Figure 4. Examples of neck exercises included in the program: (A, B) rolling static neck flexion; (C, D) dynamic neck flexion. *The individual shown in the image provided consent for publication.*

Intervention delivery & implementation (Paper V)

The intervention was delivered over six weeks, with three sessions planned per week. The team's assistant coaches delivered the program, while the first author provided on-site support once per week and maintained regular contact between visits. The assistant coaches recorded player attendance and program completion; and documented progression in exercise duration and resistance. Players were instructed to report any intervention-related adverse events to the responsible coaches. During the same period, the control group continued its usual pre-season football training. The first author remained in weekly contact with the control team's head coach to confirm that regular training continued throughout the study period.

Efficacy & acceptability outcomes (Paper V)

Peak LHA and RHA were the primary outcomes and were assessed at baseline and follow-up using the laboratory-based head acceleration protocol described in Paper II. Direction-specific and composite outcomes were calculated under anticipated and unanticipated conditions.

Isometric neck muscle strength was assessed using a protocol informed by guidance for neck-strength measurement in athletic populations (85). Following a one-minute cervical warm-up, participants were seated with the torso stabilised and a head harness connected to a handheld dynamometer fixed to wall-mounted bars. Maximal voluntary isometric contraction (MVIC) was assessed in flexion, extension, left lateral flexion, and right rotation. Participants completed one familiarisation and two recorded trials per direction. The highest force was converted to a neck muscle moment, and a composite outcome was calculated across directions.

Acceptability was assessed in the intervention group at the end of the six-week period using questionnaires based on the Theoretical Framework of Acceptability (TFA) (86). The questionnaires included seven role-adapted statements rated on a five-point scale and two open-ended questions addressing barriers and suggestions for continued use. MVIC force values were recorded in Newtons (N), which were then converted to moments (N·m) by multiplying each force value by the estimated neck moment arm.

Data analysis (Paper V)

All analyses were performed in Stata (v. 19.5). Baseline, follow-up, and change values were summarised using means and standard deviations. Baseline differences between groups were explored using Welch's independent-samples t-tests. Intervention effects were examined using mixed-design analyses of variance (ANOVA), with group as the between-subject factor and time as the within-subject factor. The group-by-time interaction represented the difference in change between

the intervention and control groups. LHA and RHA were analysed separately for each direction, composite score, and anticipatory condition, while neck strength was analysed by direction and as a composite score.

Between-group differences in change were reported with 95% CI and p-values. Partial eta squared (η^2), with 95% CI was used as the standardised effect-size measure for the group-by-time-interaction. Values of 0.01–0.05, 0.06–0.13, and ≥ 0.14 were interpreted as small, medium, and large effects, respectively (74). Statistical significance was set at $p < 0.05$.

Acceptability responses were analysed descriptively after negatively worded items had been reverse-scored. Player responses were presented as medians and interquartile ranges, while coach responses were presented as medians and ranges. Open-ended responses were summarised narratively to describe perceived barriers and suggestions for continued program use.

Ethical considerations

Papers I and III synthesised previously published research and did not involve the direct recruitment of human participants. Papers II, IV, and V, which involved human participants were conducted in accordance with the ethical principles of Declaration of Helsinki (87). Ethical approval for these studies was granted by the Swedish Ethical Review Authority (approval number 2024-04579-01). Participant safety and well-being were prioritised throughout the research process. Before participation, all participants received information about the relevant study and provided informed consent.

Declaration of generative AI in the writing process

During the preparation of this thesis, the author used OpenAI's ChatGPT to support language editing, including reducing word count and improving readability. The author critically reviewed, verified, and edited all AI-assisted content and takes full responsibility for the final content of the thesis.

Results

Head acceleration in SRC impacts (Paper I)

Evidence base & methodological quality

Paper I included 30 articles comprising 3,262 athletes, of whom only 12% were female. Across the included articles, 2,363,613 head impacts and 465 SRCs were reported, with 344 SRCs explicitly associated with a single identifiable impact event. The evidence base was dominated by American football and measurements obtained using helmet-mounted sensors. LHA during SRC impacts was reported in 29 articles and RHA in 19, while 16 articles also reported non-concussive impacts, including LHA data in 15 and RHA data in nine. No articles were rated as having good methodological quality, with 23 (77%) rated as fair and seven (23%) as poor.

SRC versus non-concussive impacts

The pooled mean peak LHA was 69.6 g for SRC impacts and 25.3 g for non-concussive impacts, corresponding to a large difference (SMD 2.42, 95% CI 1.73–3.12). Similarly, the pooled mean peak RHA was 4,931 rad/s² for SRC impacts and 1,966 rad/s² for non-concussive impacts, also representing a large difference (SMD 1.99, 95% CI 1.17–2.81). Heterogeneity was substantial for both LHA ($I^2 = 87\%$) and RHA ($I^2 = 89\%$), while the certainty of evidence for both comparisons was rated as moderate. The large differences in LHA and RHA between SRC and non-concussive impacts were maintained across all sensitivity analyses, and no evidence of publication bias was observed.

Subgroup differences in SRC head acceleration

Among SRC impacts, LHA differed significantly across sports, age groups, sexes, and instrumentation types, but not between games and practices. RHA differed significantly across sports and instrumentation types, but not across age groups, sexes, or session types (Table 5).

Table 5. Subgroup differences in linear and rotational head acceleration during SRC impacts.

Subgroup	LHA findings	RHA findings
Sport	Significant overall difference ($p < 0.001$); highest in American football (83.2 g) and lowest in ice hockey (43.2 g).	Significant overall difference ($p < 0.001$); highest in rugby (7,627 rad/s ²) and lowest in ice hockey (3,695 rad/s ²).
Age group	Significant overall difference ($p = 0.010$); highest among high-school athletes (88.3 g) and lowest among youth athletes (61.4 g).	No significant overall difference ($p = 0.250$); estimates ranged from 3,637 rad/s ² in youth athletes to 7,627 rad/s ² in adult athletes.
Sex	Significantly higher in male than female athletes: 78.2 versus 44.2 g ($p < 0.001$).	No significant difference ($p = 1.000$): 4,522 versus 4,518 rad/s ² in male and female athletes, respectively.
Session type	No significant difference between games and practices ($p = 0.090$): 72.6 versus 50.4 g.	No significant difference between games and practices ($p = 0.230$): 5,537 versus 4,073 rad/s ² .
Instrumentation type	Significant overall difference ($p < 0.001$); highest with helmet-mounted sensors (79.0 g) and lowest with headband-mounted sensors (39.8 g).	Significant overall difference ($p = 0.020$); highest with skin patches (6,938 rad/s ²) and lowest with helmet-mounted sensors (4,071 rad/s ²).

Note. Values represent pooled mean peak acceleration estimates. For analyses involving more than two categories, p values refer to the overall between-group comparison and not to the displayed highest-versus-lowest comparison. *LHA*, linear head acceleration; *RHA*, rotational head acceleration; *SRC*, sport-related concussion.

Reliability of the head acceleration protocol (Paper II)

Test–retest reliability

Across movement directions and testing sessions, the protocol produced mean peak LHA values ranging from 0.18 to 0.27 g and mean peak RHA values ranging 19.31 to 41.48 rad/s². During anticipated perturbations, LHA demonstrated good test–retest reliability (ICC range 0.77–0.80; SEM% 4.17–5.56%), while RHA demonstrated good-to-excellent reliability (ICC range 0.76–0.90; SEM% 3.52–8.74%). During unanticipated perturbations, LHA demonstrated good reliability (ICC range 0.75–0.80; SEM% 4.00–7.41%), while RHA demonstrated moderate-to-good reliability (ICC range 0.72–0.85; SEM% 3.99–11.72%) (Table 6).

Table 6. Test–retest reliability of peak LHA and RHA across anticipated and unanticipated perturbations.

Condition	Direction	LHA ICC (95% CI)	LHA SEM%	RHA ICC (95% CI)	RHA SEM%
Anticipated	Flexion	0.80 (0.63–0.90)	4.35	0.76 (0.55–0.88)	8.36
	Extension	0.77 (0.56–0.89)	4.17	0.85 (0.71–0.93)	8.74
	Right lateral flexion	0.79 (0.61–0.89)	4.76	0.83 (0.67–0.91)	6.61
	Left rotation	0.80 (0.63–0.90)	5.56	0.90 (0.80–0.95)	3.52
Unanticipated	Flexion	0.77 (0.57–0.88)	4.00	0.77 (0.58–0.88)	7.17
	Extension	0.78 (0.59–0.89)	7.41	0.81 (0.64–0.90)	11.72
	Right lateral flexion	0.75 (0.54–0.87)	4.17	0.72 (0.50–0.86)	9.25
	Left rotation	0.80 (0.63–0.90)	5.00	0.85 (0.72–0.93)	3.99

Note. ICCs were calculated using a two-way mixed-effects model with absolute agreement for single measurements ($ICC_{3,1}$). *CI*, confidence interval; *ICC*, intraclass correlation coefficient; *LHA*, linear head acceleration (*g*); *RHA*, rotational head acceleration (rad/s^2); *SEM%*, standard error of measurement expressed as a percentage of the pooled mean.

Agreement & measurement variability

Across movement directions and anticipatory conditions, mean between-session differences ranged from -0.01 to 0.00 *g* for LHA and from -0.11 to 0.75 rad/s^2 for RHA, representing less than 5% of the peak values. Bland–Altman analyses indicated no systematic bias between sessions and no evidence of heteroscedasticity. Variability was generally greater for RHA than LHA and during unanticipated than anticipated perturbations.

Efficacy of exercise interventions (Paper III)

Evidence base & risk of bias

Paper III included 26 articles, of which 20 involved athletes from various sports and six involved healthy members of the general population. Sample sized ranged from 10 to 2,452 participants, with a median of 32 participants per article, and only 4% of the included participants were female. The evidence base was dominated by resistance-training interventions, while three articles evaluated neuromuscular warm-up programmes in relation to SRC incidence. Overall, 13 articles (50%) were rated as having a high risk of bias, 12 (46%) raised some concerns, and only one (4%) was rated as having low risk of bias.

Efficacy of exercise interventions

The meta-analysis of three articles involving 4,466 participants found that neuromuscular warm-up programs were not associated with a statistically significant reduction in SRC incidence (RR 0.69, 95% CI 0.39–1.23). However, there was a 59% reduction in SRC incidence among teams that implemented the program at least three times per week, indicating a possible adherence-related dose-response pattern.

No statistically significant effects of resistance training were observed for LHA (three articles; 89 participants; SMD -0.43, 95% CI -1.26 to 0.40) or RHA (two articles; 37 participants; SMD 0.08, 95% CI -0.61 to 0.77). In contrast, resistance training produced a large improvement in isometric neck strength across 20 articles involving 638 participants (SMD 0.85, 95% CI 0.57 to 1.13). The pooled estimates remained similar across all sensitivity analyses, and no evidence of publication bias was identified (Egger's test: $p = 0.160$) (Table 7).

Table 7. Effects of exercise interventions on SRC incidence, head acceleration, and isometric neck strength.

Outcome	Intervention	Evidence base	Pooled effect (95% CI)	I ²	Certainty of evidence
SRC incidence	Neuromuscular warm-up programs	3 articles; 4,466 participants	RR 0.69 (0.39–1.23)	69%	Low
LHA	Resistance training	3 articles; 89 participants	SMD -0.43 (-1.26 to 0.40)	63%	Very low
RHA	Resistance training	2 articles; 37 participants	SMD 0.08 (-0.61 to 0.77)	0%	Low
Isometric neck strength	Resistance training	20 articles; 638 participants	SMD 0.85 (0.57–1.13)	62%	High

Note. For SRC incidence, an RR below 1.00 favours the intervention. For LHA and RHA, negative SMDs favour the intervention by indicating lower head acceleration, whereas positive SMDs favour the intervention for isometric neck strength. *CI*, confidence interval; *GRADE*, Grading of Recommendations Assessment, Development and Evaluation; *LHA*, linear head acceleration; *RHA*, rotational head acceleration; *RR*, risk ratio; *SMD*, standardised mean difference; *SRC*, sport-related concussion.

Subgroup findings for isometric neck strength

Resistance training improved isometric neck strength across all examined modalities and participant groups. Large effect sizes were observed for dynamic (SMD 0.86) and multimodal resistance training (SMD 1.13), while a medium effect was observed for static resistance program (SMD 0.74). A large effect was observed among adults aged ≥ 19 years (SMD 1.19), compared with a medium effect among adolescents aged < 19 years (SMD 0.73). Similarly, the effects were large among male participants (SMD 0.89) and medium among female participants (SMD 0.65).

Reporting completeness of exercise interventions

CERT scores ranged from 4 to 16 out of a possible 19, with a median score of 11.5 (IQR 9–13). Information important for intervention replication was inconsistently reported, with rules for exercise progression described in 13 articles (50%) and exercise starting levels in 10 articles (38%).

Neck resistance training program (Paper IV)

Initial program prototype

The initial neck resistance training prototype consisted of 12 exercises organised into four sequential blocks and required approximately 10–12 minutes to complete. Each block combined one rolling static neck activation exercise with two dynamic resistance exercises targeting the same cervical movement direction. Progressive loading was incorporated through increased duration for the rolling exercises and adjustable resistance for the dynamic exercises.

Facilitators & barriers to SRC prevention

During Workshop 1, end-users provided insights not only into the initial neck resistance training prototype but also into the implementation of SRC prevention more broadly. Using the inductive analysis, the authors identified six themes that formed three hierarchical levels: foundational alignment, practice-level alignment, and operational alignment (Figure 5).

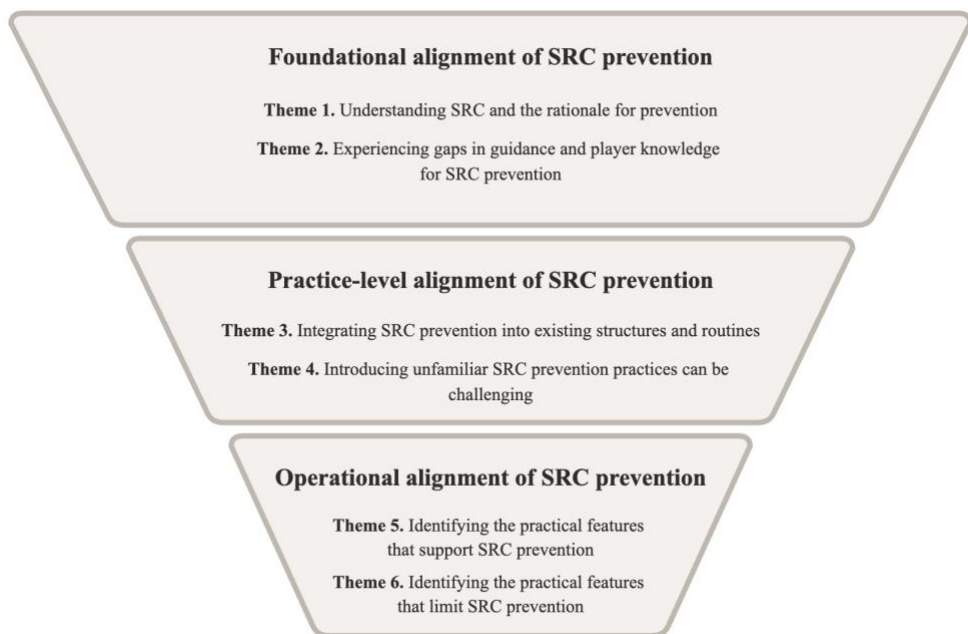


Figure 5. Funnel model illustrating the six themes across three hierarchical levels of SRC-prevention alignment identified during Workshop 1.

At the foundational level, participants emphasised the importance of understanding SRC as a serious and recurring injury and establishing a shared rationale for prevention. However, limited systematic guidance and insufficient player knowledge were identified as barriers to coordinated prevention.

“There was some frustration that more people should know more about concussions ... it feels like this is largely an education issue.”

At the practice level, participants considered SRC prevention more feasible if incorporated into established routines, such as warm-ups or prehabilitation activities, with minimal additional workload. Conversely, unfamiliar exercises and related safety concerns could create uncertainty, while influential team members and declining motivation associated with repetitive exercises could hinder wider acceptance and sustained participation.

“New exercises can feel like a red flag at first ... they work unfamiliar muscle groups, and there’s concern about doing them wrong or causing injury.”

At the operational level, simple instructions, visual guidance, athlete independence, and adaptable progression were identified as important facilitators. Implementation could be hindered by limited time, changing player availability, and insufficient access to equipment, training space, and financial resources.

“We already have circuit training with three to four stations, but we don’t really have the space for additional exercises.”

End-user feedback & program refinement

End-users generally viewed neck resistance training program as relevant to SRC prevention and perceived that improvements in neck strength could contribute to reducing SRC risk. However, they anticipated that many players might not understand why neck-specific training was relevant within football, potentially limiting initial engagement.

“They’ll probably say ... why am I training my neck? They might see it as a pointless exercise.”

The initial protocol was considered suitable because its simple and flexible design supported athlete independence and individualised progression. Nevertheless, participants anticipated hesitation around training the cervical region, including safety concerns and misconceptions that resistance training would cause excessive neck muscle growth.

“Players might be scared to train the neck ... because the neck is connected to the spine.”

The program's 10–12 minute duration was identified as the principal practical barrier.

“It would be difficult to do the full program as you present it ... 10 minutes on one muscle group is too time-consuming.”

In response, an educational component was added to explain SRC, the biomechanical rationale for neck resistance training, correct exercise execution, safety, and expected muscular adaptations. The exercise component was also condensed by removing one flexion–extension block and reducing the number of dynamic rotation exercises. These changes reduced the program from 12 to 7 exercises, from four to three blocks, and from approximately 10–12 minutes to 3–5 minutes, while retaining its multimodal structure and progressive loading (Table 8).

Table 8. End-user feedback and resulting development decisions for the neck resistance training program.

End-user feedback	Decision	Resulting development response
Players may have limited understanding of why neck resistance training is relevant to SRC prevention.	Added	An educational component explaining SRC and the biomechanical rationale for neck resistance training.
Concerns were expressed regarding exercise safety and excessive increases in neck size.	Added	Guidance on correct exercise execution, safety, and expected muscular adaptations.
Simple instructions and demonstration videos supported correct and independent exercise performance.	Retained	Concise exercise instructions and demonstration videos.
Adjustable resistance and progression were considered important for accommodating different abilities.	Retained	Team-level progression of rolling duration and individualised progression of dynamic resistance.
The 10–12-minute prototype was considered too time-consuming for integration into regular training.	Modified	One flexion–extension block was removed and the number of dynamic rotation exercises was reduced, decreasing the program from 12 to 7 exercises, from four to three blocks, and from approximately 10–12 to 3–5 minutes.

Evaluation & contextual adaptation

During Workshop 2, coaches and players reported favourable perceptions of the refined program, with questionnaire responses supporting its acceptability, relevance, applicability, and perceived effectiveness. The program was considered easy to perform and suitable for independent completion following familiarisation. The main difference between groups concerned safety-related perceptions. Coaches expressed some concern that players might feel uncomfortable training the neck, whereas players did not report any concerns about neck injury or discomfort. Both groups indicated that time would not limit implementation, suggesting that the refined duration of 3–5 minutes addressed the principal barrier identified during the initial workshop. No further modifications were made following the evaluation.

As part of the contextual adaptation, the team decided to incorporate the program into its on-field warm-up three times per week and deliver it with players divided into smaller groups. Two assistant coaches were assigned responsibility for program delivery and oversight.

Efficacy & acceptability of the program (Paper V)

Participant flow & baseline characteristics

Two of the nine female football teams approached agreed to participate. Of the 40 players invited from these teams, 30 enrolled and completed baseline testing, corresponding to a recruitment rate of 75%. Twenty-seven players completed follow-up and were included in the final analysis, representing 90% retention, with 14 players in the intervention group and 13 in the control group. The three withdrawals were unrelated to the intervention. At baseline, the intervention group was younger than the control group (16.9 ± 0.6 vs. 22.0 ± 6.4 years; $p = 0.014$), whereas the remaining participant characteristics were comparable between groups.

Intervention delivery, adherence, & safety

Across the 6-week intervention, players completed a mean of 11.2 of the 16 planned sessions, corresponding to 70% adherence. Individual participation ranged from 8 to 14 sessions, with an average of 1.9 sessions per player per week. No intervention-related adverse events occurred.

Efficacy outcomes

The intervention group showed greater reductions in LHA than the control group under both anticipatory conditions. During anticipated perturbations, significant differences were observed for flexion, extension, rotation, and the composite score (all $p \leq 0.018$; partial $\eta^2 = 0.21$ – 0.44). The difference for lateral flexion was not statistically significant ($p = 0.256$). During unanticipated perturbations, reductions favouring the intervention were found across all tested directions and for the composite score (all $p \leq 0.037$; partial $\eta^2 = 0.17$ – 0.49) (Table 9).

A similar pattern was observed for RHA. Under anticipated conditions, the intervention group showed greater reductions in flexion, extension, rotation, and the composite score (all $p \leq 0.016$; partial $\eta^2 = 0.21$ – 0.25). No significant difference was found for lateral flexion ($p = 0.075$). Under unanticipated conditions, significant reductions favouring the intervention were observed across all tested directions and for the composite score (all $p \leq 0.012$; partial $\eta^2 = 0.23$ – 0.40) (Table 9).

Neck muscle strength increased to a greater extent in the intervention group across all tested directions and for the composite score (all $p \leq 0.003$), with large effect sizes (partial $\eta^2 = 0.31$ – 0.66) (Table 9).

Table 9. Summary of efficacy outcomes for head acceleration and neck muscle strength in Paper V.

Outcome	Condition	Significant findings	Difference in change	p values	partial η^2	Exception
LHA (g)	Anticipated	Flexion, Extension, Rotation, Composite	-0.06; -0.03	≤ 0.018	0.21; 0.44	Lateral flexion ($p = 0.256$)
	Unanticipated	All directions, Composite	-0.05; -0.03	≤ 0.037	0.17; 0.49	None
RHA (rad/s ²)	Anticipated	Flexion, Extension, Rotation, Composite	-6.32; -3.66	≤ 0.016	0.21; 0.25	Lateral flexion ($p = 0.075$)
	Unanticipated	All directions, Composite	-9.20; -4.25	≤ 0.012	0.23; 0.40	None
Neck strength (N·m)	–	All directions, Composite	3.24; 4.01	≤ 0.003	0.31; 0.66	None

Note. Negative between-group differences indicate greater reductions in head acceleration in the intervention group, whereas positive differences indicate greater increases in neck muscle strength. *LHA*, linear head acceleration; *RHA*, rotational head acceleration; η^2 , partial eta squared.

Acceptability and implementation feedback

Both players and coaches reported favourable perceptions of the program. Median player ratings across the questionnaire items ranged from 4 to 5 (scale range: 1–5), indicating that the program was considered relevant, understandable, manageable, and easy to perform. Median coach ratings ranged from 3.5 to 4.5, reflecting similarly positive perceptions of delivering and supervising the program.

In the open-ended responses, players primarily reported discomfort when performing the rolling exercises on natural grass and suggested using thin exercise mats. Coaches identified maintaining the program's frequency throughout the competitive season as the main implementation challenge. They suggested performing it at every training session during preseason, followed by once-weekly maintenance during the season, or twice weekly when considered appropriate for players with a history of SRC.

Discussion

Across five studies, this thesis progressed from characterising the biomechanical features of SRC to developing and evaluating an exercise-based prevention strategy. The findings established LHA and RHA as relevant components of SRC biomechanics, while also demonstrating considerable variability in real-world impacts across sporting contexts. In response to this variability, a reliable laboratory-based protocol was established, allowing head acceleration to be assessed with greater control under anticipated and unanticipated conditions. The subsequent review of exercise interventions suggested potential to reduce SRC incidence and showed that resistance training improved neck muscle strength, but evidence of effects on head acceleration remains limited. To address this gap, an end-user-informed neck resistance training program was developed for female football players, a population historically underrepresented in SRC prevention research. Preliminary evaluation of the resulting program demonstrated reductions in LHA and RHA during controlled laboratory perturbations, improvements in neck muscle strength, and favourable acceptability among players and coaches.

Collectively, these findings do not demonstrate that the program reduces SRC incidence. Rather, the thesis connects biomechanical characterisation, reliable outcome measurement, evidence synthesis, end-user-informed intervention development, and preliminary evaluation within one coherent pathway. In doing so, it provides a foundation for future research to determine whether an acceptable and contextually feasible neck resistance training program can contribute to a multicomponent approach to SRC prevention in real-world sport.

Head acceleration as a biomechanical target (Papers I & II)

Paper I demonstrated that, at the group level, impacts associated with SRC involved substantially greater LHA and RHA than non-concussive impacts in team sports. These findings reinforce the central role of head acceleration in the biomechanical processes underlying SRC (88, 89). LHA and RHA are distinct but related components of head motion that contribute to different aspects of the brain's mechanical response to impact (21, 88). Their measurement may therefore help

characterise SRC impacts and evaluate whether preventive strategies modify head kinematics (34, 88).

However, the distribution of LHA and RHA for SRC and non-concussive impacts overlapped considerably, with some SRC impacts occurring at lower magnitudes than some non-concussive impacts. This overlap indicates that greater head acceleration reflects greater inertial loading but does not invariably result in SRC, as injury tolerance appears to vary between individuals and according to impact-specific characteristics (89, 90). Consequently, no universal acceleration threshold can reliably determine whether an individual impact will result in SRC (20, 89). LHA and RHA should instead be interpreted as biomechanical outcomes that contribute to understanding SRC risk rather than as stand-alone diagnostic indicators (20, 88).

Paper I also identified considerable variation in head acceleration across sports and measurement systems, with additional differences in LHA according to age group and sex. Between-sport differences may partly reflect distinct collision demands, but comparisons are complicated because sport and sensor systems were often closely linked across included studies. For example, American football studies predominantly used helmet-mounted sensors, which may be affected by helmet motion relative to the head, whereas studies in non-helmeted sports more commonly used instrumented mouthguards, which can provide closer coupling to the skull (31, 91). Variation in device placement, event-verification procedures, filtering approaches, and recording thresholds could therefore contribute to differences observed between sports and studies (33, 92). The sex-specific findings also require cautious interpretation because female athletes were markedly underrepresented in the available evidence. Although pooled LHA was higher among male athletes, no significant differences were found for RHA. Nevertheless, given the limited female data and differences in the sports and measurement systems represented in each group, the LHA finding should not be interpreted as evidence of a biological sex difference.

These challenges illustrate the value of complementing field-based measurements with controlled laboratory assessment. Within such settings, the applied perturbation, movement direction, anticipatory condition, equipment setup, and testing procedures can be standardised, reducing sources of variation that are difficult to control during sport participation (93). Paper II demonstrated good-to-excellent test-retest reliability for LHA and RHA under anticipated conditions and moderate-to-good reliability under unanticipated conditions. This is encouraging, as previous research demonstrated excellent reliability of head-acceleration measurements obtained using an instrumented mouthguard under pendulum impactor conditions (94), Paper II showed that reproducible measurements can also be obtained from active human participants exposed to controlled perturbations.

Variability was slightly greater during unanticipated than anticipated perturbations, possibly reflecting the stabilising influence of preparatory cervical activation when participants have time to brace for the perturbation (32). In contrast, unanticipated perturbations rely more heavily on reflexive responses initiated after loading begins, the observed variability of these responses across individuals and perturbation directions may contribute to lower consistency across testing sessions (29, 95). RHA was also somewhat more variable than LHA, potentially reflecting the asymmetric and direction-specific patterns of cervical activation involved in controlling rotational motion (96, 97). Nevertheless, LHA and RHA demonstrated sufficient reliability under both anticipated and unanticipated conditions to support their use as outcomes in the subsequent intervention evaluation (Paper V). The protocol does not reproduce the magnitude or complexity of real-world sporting impacts, but it provides a safe and controlled method for examining whether an intervention modifies the head's response to a standardised external perturbation.

Exercise interventions: evidence & gaps (Paper III)

Paper III found no statistically significant pooled effect of neuromuscular warm-up programs on SRC incidence. However, differences in participant age, intervention duration, and SRC definitions, together with substantial statistical heterogeneity, limited confidence in the pooled estimate. Findings from the individual trials nevertheless indicated possible preventive effects. One trial reported a 60% reduction in SRC incidence, while another reported a 59% reduction among teams averaging at least three sessions per week (98, 99). Both trials incorporated neck resistance training exercises, which the trial authors proposed may have contributed to the observed reductions (98, 99). However, because these exercises formed part of broader neuromuscular programs, their independent contribution could not be established. The findings therefore suggest that neuromuscular warm-up programs may have preventive potential when delivered at a sufficient dose.

Resistance training did not produce statistically significant pooled effects on either LHA or RHA. However, the analyses included only three articles and 89 participants for LHA and two articles and 37 participants for RHA. The nonsignificant findings should therefore be interpreted as reflecting insufficient evidence to determine whether resistance training influences head acceleration, rather than evidence of no effect.

In contrast to findings for head acceleration, resistance training produced large improvements in isometric neck strength across different exercise prescriptions. These improvements are consistent with established neuromuscular and muscular adaptations to resistance training, including enhanced motor-unit activation and muscle hypertrophy (100, 101). The consistency of the strength gains despite

substantial variation in training modality, frequency, duration, and intensity further supports isometric neck strength as a modifiable outcome. However, increased neck strength represents a proximal physiological adaptation and cannot, by itself, be interpreted as evidence of reduced head acceleration or SRC risk. Female athletes were also severely underrepresented, accounting for less than 5% of all included participants. Although female athletes can achieve meaningful strength adaptations following resistance training, their limited representation restricts the precision of sex-specific conclusions and the applicability of the available evidence (102).

Paper III also showed that descriptions of exercise interventions were generally insufficient to permit accurate replication. None of the included articles reported motivational strategies; most did not adequately describe participants' starting levels; and only half clearly reported rules for exercise progression. These elements are important as motivation can influence adherence, whereas appropriate starting levels and progression rules help ensure that training is matched to participants' capacity and adjusted as they adapt (103, 104). Incomplete reporting therefore limits both the interpretation of intervention efficacy and efforts to reproduce and implement promising programs in real-world sport settings (77).

Together, the uncertain evidence regarding effects on head acceleration, the severe underrepresentation of female athletes, and incomplete intervention reporting provided the rationale for the next stage of the thesis.

Developing an end-user-informed program (Paper IV)

Paper IV addressed the gap between identifying a potentially beneficial exercise strategy and developing a program suitable for delivery within routine football practice. Rather than assuming that an evidence-informed prototype would be suitable in its original form, intended users were involved in examining how its content and delivery aligned with their knowledge, experience, established routines, and available resources. This approach is important because intervention developers may not fully anticipate the priorities and constraints of those expected to deliver or undertake a program (105, 106). End-user feedback indicated that implementation was shaped by considerations at three interconnected levels: understanding the rationale for prevention, integrating the program into established football practice, and ensuring that its practical demands were manageable.

At foundational level, coaches, athletic trainers, and physiotherapists described substantial variation in SRC knowledge, which was often shaped by personal experience rather than systematic guidance. Limited knowledge among players was also perceived as a barrier because exercises may be undervalued when their purpose and relationship to SRC prevention are unclear, consistent with previously reported gaps in injury-prevention knowledge and awareness in football (107, 108).

Consequently, an educational package was introduced to explain SRC, the biomechanical rationale for neck resistance training, correct performance of the exercises, and common misconceptions about resistance training. Education therefore became a component of the intervention itself, intended to support understanding and engagement before players were asked to adopt an unfamiliar prevention practice.

At the practice level, end-users emphasised that the program should be embedded within existing training structures rather than delivered as an additional, isolated activity. Integration into familiar routines is a recognised facilitator of implementation, whereas additional time demands and viewing injury prevention as a low priority are common barriers (56). A particularly important finding was the discrepancy between the coaches' expectations and players' experiences. Coaches anticipated that players might be uncomfortable training the cervical region because of concerns about injury or excessive muscular development, whereas the players themselves expressed no such concerns and did not find the exercises uncomfortable. This discrepancy indicated that the perceptions of one end-user group should not be assumed to represent those of another. Involving players alongside coaches and medical or performance staff therefore allowed both delivery-related concerns and first-hand experiences of performing the program to inform its development, consistent with previous football research (109). Coaches also identified influential players as potential role models, highlighting how social relationships may influence self-efficacy and the adoption of unfamiliar injury-prevention practices (110).

Operationally, the program needed to be simple, supported by clear instructions, and sufficiently flexible to be performed by players with increasing independence. Instructional videos were retained to support correct execution without continuous supervision, while manageable starting levels and individual progression were incorporated to accommodate variation in ability and fatigue. These features may support autonomous motivation and perceived behavioural control, which has been associated with stronger intentions to engage in injury-prevention behaviours (111). However, the clearest constraint was time. The original 12-exercise program required approximately 10–12 minutes and was considered difficult to accommodate alongside existing warm-up and prehabilitation activities. End-user feedback therefore led to the program being reduced to seven exercises, shortening its duration to approximately 3–5 minutes. This refinement was not simply intended to make the program easier; it balanced reducing the delivery burden with retaining the training principles required to promote cervical strength adaptations. Equipment requirements were similarly kept to a minimum, although resistance tubing was retained because removing all equipment would have limited the scope for individual progression.

End-user involvement therefore changed the program and the conditions surrounding its delivery, rather than serving only as a final assessment of an already

completed intervention. Importantly, Paper IV established the relevance and perceived feasibility of the program but did not determine whether these adaptations preserved sufficient training stimulus to modify neck strength or head acceleration. This provided the basis for evaluating the program's preliminary efficacy and acceptability during team-based implementation in Paper V.

Efficacy and acceptability of the program (Paper V)

Paper V brought together the preceding stages of the thesis by evaluating the end-user-informed neck resistance training program in a team-based female football setting. Compared with the control group, the intervention group demonstrated greater reductions in both LHA and RHA across anticipated and unanticipated conditions. The observed changes therefore encompassed both components of head motion, which is biomechanically relevant because on-field impacts generally produce concurrent linear and rotational acceleration (23). The intervention group also demonstrated greater improvements in neck strength across all tested directions and in overall strength. Collectively, these findings provide promising preliminary evidence that a short, progressive, and multidirectional neck resistance training program may increase cervical force-generating capacity and modify the response of the head to a standardised external perturbation.

These results began to address an important gap identified in Paper III. Although resistance training consistently improved neck muscle strength, evidence concerning LHA and RHA was derived from only a small number of studies and participants, limiting statistical power and the precision of the pooled estimates (Paper III). Paper V extends this evidence by showing that gains in neck muscle strength occurred alongside reductions in laboratory-measured head acceleration. One plausible interpretation is that increased cervical force-generating capacity contributed to greater control of head motion during perturbation, consistent with previous associations between neck strength and smaller kinematic responses to impulsive loading (32, 45). This mechanism may be particularly relevant during anticipated trials, in which players could activate the cervical musculature before loading. In addition, reductions also occurred during unanticipated trials, indicating that a training-related change was detectable in the absence of planned pre-impact bracing.

The program was rated favourably by both players and coaches, providing preliminary support for its acceptability and aligning with the end-user-informed development approach used in Paper IV. No intervention-related adverse events were reported, indicating that the program was well tolerated within the intervention cohort. Feedback nevertheless identified context-specific challenges. Players reported discomfort when performing the rolling exercises on natural grass, whereas

coaches focused primarily on how delivery could be maintained throughout the competitive season. These distinct perspectives reinforce the value of seeking feedback from multiple end-user groups involved in performing and delivering an injury-prevention intervention (57).

Taken together, Study V completes the progression of the thesis from characterising head acceleration and establishing its reliable assessment to identifying limitations of existing exercise evidence, developing an end-user-informed intervention, and conducting its preliminary evaluation. The combined findings establish a coherent foundation for neck resistance training as an acceptable and testable strategy targeting outcomes relevant to SRC prevention. While improvements in laboratory-based surrogate outcomes remain distinct from direct evidence of reduced SRC risk, they provide a basis for progressing to larger studies that directly evaluate whether the program can reduce head acceleration during real-world impacts and SRC incidence.

Methodological considerations

The five papers used complementary methods that provided methodological breadth, but their findings must be interpreted in relation to the limitations of each design. Both systematic reviews demonstrated moderate-to-substantial heterogeneity in most analyses (Papers I and III). This variability reduced comparability between studies and increased uncertainty around the pooled estimates. Moreover, heterogeneity could not be fully explored because potentially relevant study characteristics were frequently unavailable or inadequately reported. This was particularly important in Paper I, where SRC history, playing position, and athlete experience could not be considered consistently, despite their potential influence on impact exposure and biomechanical responses. In Paper III, incomplete descriptions of the interventions similarly limited the identification of characteristics that might explain differences in efficacy.

Papers II and V relied on laboratory-induced head perturbations as their principal method of assessing LHA and RHA. The accelerations generated by the apparatus were considerably smaller than those occurring during real-world football impacts. The protocol was not intended to reproduce a football collision; rather, the low-intensity perturbations were deliberately selected to prioritise participant safety while still producing measurable head motion. Although this limits direct transfer to the field, the controlled setting reduced variation in impact exposure and enabled specific variables to be examined in relative isolation.

Paper IV included nine end-users across two workshops, which potentially limited the breadth of perspectives that could be captured. However, the sample was selected purposively, as all participants had direct roles as players, coaches, athletic

trainers, or physiotherapists across Divisions 1–3 of Swedish female football, resulting in a contextually relevant and information-rich sample. The design therefore prioritised depth of discussion and practical knowledge over broad generalisability. Nevertheless, perspectives from other competitive levels, geographical areas, or organisational settings may not have been represented.

Paper V purposively evaluated a neck resistance training strategy to establish whether this specific approach showed sufficient potential for further investigation. Although this increased the specificity of the intervention, neck muscle strength represents only one component of the broader SRC-prevention puzzle. End-user education and training in appropriate heading technique should therefore be investigated alongside neck resistance training as complementary components of a multimodal approach to SRC prevention in female football.

Finally, the effect of the developed neck resistance training program on SRC incidence was not evaluated. A sufficiently powered trial evaluating SRC incidence would require substantially larger athlete samples, detailed exposure monitoring, and follow-up across one or more competitive seasons, which was not feasible within the scope and timeframe of this thesis. Consequently, the thesis provides foundational evidence concerning biomechanical modifiability and the acceptability of the intervention, but it does not demonstrate that the program reduces SRC incidence.

Clinical relevance and future perspectives

The findings of this thesis have several implications for SRC prevention research and practice. First, LHA and RHA are relevant biomechanical outcomes, but their magnitudes vary considerably with sporting context and measurement methods. They should therefore not be interpreted in isolation as indicators of SRC occurrence. Instead, they may serve as intermediate outcomes for examining whether a preventive strategy modifies the mechanical response of the head before progressing to larger injury-incidence studies. The reliable laboratory protocol established in Paper II provides a controlled method for such early-stage evaluations, particularly when the variability in field-based head-impact measurements would make intervention effects difficult to isolate.

The end-user-informed neck resistance training program developed and evaluated in Papers IV and V provides a practical example of this progression. Requiring only 3–5 minutes, the program was incorporated into an existing football warm-up and was considered acceptable to players and coaches. Preliminary reductions in laboratory-measured LHA and RHA occurred alongside improvements in neck muscle strength, while no intervention-related adverse events were reported during the six-week evaluation. These findings indicate that neck resistance training can be delivered within a team-based female football setting and may modify outcomes relevant to SRC prevention. However, the program should currently be regarded as a promising component rather than an established SRC-prevention intervention because its effects on head acceleration during sport-specific impacts and SRC incidence remain unknown.

Future research should improve the consistency and transparency of head acceleration measurement through greater adherence to the Consensus Head Acceleration Measurement Practices (CHAMP) guidelines (33). This would improve comparisons between studies and help distinguish genuine biomechanical differences from variation introduced by instrumentation or analytical procedures. Similar improvements are needed in the reporting of exercise-based interventions. Consistent use of the Consensus on Exercise Reporting Template (CERT) would facilitate interpretation and replication while enabling clearer examination of which program characteristics are associated with meaningful effects (77).

Future research should examine neck resistance training alongside complementary components, such as training in appropriate heading technique, and evaluate their effects on head acceleration during controlled, sport-specific heading tasks. This would help determine whether improvements observed during low-intensity laboratory perturbations transfer to more representative football situations, thereby bridging the gap between standardised laboratory testing and the demands of the sport. Ultimately, adequately powered randomised trials with SRC incidence as the primary outcome and sufficient representation of female athletes are needed. This staged pathway from laboratory-based biomechanical testing through controlled sport-specific task evaluation to incidence-based trials provides a clear framework for translating the foundational findings of this thesis into evidence of real-world SRC prevention.

Conclusion

This thesis followed a stepwise progression, with each paper addressing gaps identified by the preceding work. Paper I established head acceleration as a relevant but context-dependent feature of SRC biomechanics, showing greater LHA and RHA during SRC than non-concussive impacts but considerable variation across sporting and measurement contexts. This variability highlighted the value of controlled assessment, which Paper II addressed by demonstrating the test–retest reliability of a laboratory protocol for measuring head acceleration. Building on this biomechanical foundation, Paper III examined whether exercise interventions could influence SRC incidence, head acceleration, and neck muscle strength. Resistance training produced large improvements in neck strength, but evidence concerning head acceleration and SRC incidence was limited, heterogeneous, and predominantly based on male participants.

These gaps directly informed the development of an end-user-informed neck resistance training program for female football in Paper IV, translating the available evidence into a brief, contextually adapted intervention. Paper V subsequently provided the first evaluation of this program, showing preliminary reductions in laboratory-measured LHA and RHA alongside improvements in neck muscle strength and favourable ratings of acceptability from players and coaches. Collectively, the five papers trace a progression from identifying a relevant biomechanical outcome to demonstrating that it can be assessed reliably under controlled conditions, synthesising the available intervention evidence, developing a population-specific program, and examining its preliminary efficacy and acceptability. Although this thesis does not demonstrate a reduction in SRC incidence, it provides a coherent foundation for future research to determine whether this acceptable and feasible neck resistance training strategy can ultimately contribute to SRC prevention.

Acknowledgements

The journey leading to this thesis was not three years in the making. It was 29. Throughout those years, so many people crossed my path and, in ways both large and small, helped me reach the point where I can write these final words of gratitude. I cannot acknowledge everyone who has supported me along the way, but you are all in my thoughts as I write this. Some people, however, have made an especially profound impact on this journey, and they deserve to be recognised here.

To my main supervisor, **Eva Ageberg**, thank you for having the courage to give me this incredible opportunity and for placing your trust in me. For that alone, I will always be grateful. Thank you for your patience and guidance throughout these three years. You have turned every experience into an opportunity for me to learn and grow. Thank you for being an exceptional supervisor, but, even more importantly, an incredible human being. As we bring this PhD project to a close, one thing is clear to me. This is not the end of our work together, but simply the closing of one chapter in what I hope will be a long and productive collaboration.

To my co-supervisor, **Anna Cronström**, thank you for being so flexible in how you supported me and for always adapting to what I needed. Thoughtful feedback? Anna was there. A fresh perspective? Ask Anna. A calm approach when things felt stressful, or simply a bit of laughter? Co-supervisor to the rescue! I could always count on you, and you have been everything I could have hoped for in a co-supervisor. I am deeply grateful that you have been part of this journey.

To my co-authors, **Kajsa Johansson**, **Arlind Reuter**, **Mana Rasi**, **James T. Eckner**, and **Nicholas Ryan**, thank you for sharing the fascinating world of science and research with me and for so generously passing on your knowledge and experience. Together, we put an enormous amount of hard work into these papers. I learned so much from each of you, and I can only hope that, somewhere along the way, you may also have learned something from me. I will carry these lessons with me throughout my career and hope to pass them on to others in the same generous spirit.

To my colleagues in the Sport Sciences research group, **Anders Pålsson**, **Anna Cronström**, **August Estberger**, **Eva Ageberg**, **Humberto Moreira Carvalho**, **Jenny Älmqvist Nae**, **Karolina Lucander**, **Maria Biesért**, **Niklas Cederström**, **Simon Granér**, and **Thérèse Jönsson** thank you for three incredible years. You welcomed me with support and genuine care, and I never once felt like an outsider.

Thank you for all the laughter, conversations, and countless lessons along the way. Each of you has taught me far more than you probably realise, both about research and about what it means to be part of a truly supportive group.

To the Eliasson family, **Marina**, **Anders**, and **Lucas**, thank you for opening the doors of your home and welcoming a young man with big dreams and aspirations into your family. You have supported me throughout my years in Sweden, and the love and kindness you have shown me mean more than I can express.

To the Pijaca family, **Anna** and **Mirko**, thank you for treating me like your own grandson from the very beginning. Thank you for bringing a piece of Croatia into my life in Sweden and for the countless dinners filled with delicious food and wonderful conversations. Your home has always been a place of warmth, and I am deeply grateful for every moment we have shared.

To the Lovric family, **Meri**, **Stipe**, and **Jerko**, thank you for being there for me during my years in Zagreb. You helped me in every way imaginable and never once asked for anything in return. Your generosity and support carried me through those years, and I will remain forever grateful for everything you did for me.

To the Kera family, **Elizabeth**, **Ivan**, **Nila**, and **Kristian**, thank you for your love and support throughout the years. The encouragement I have received from you have been invaluable to me, and I hope to give Nila and Kristian the same love and support as they follow their own paths through life.

To the Ivanic family, **Josip**, **Nina**, and **Noa**, thank you for your support, particularly during my years in Zagreb. I will always appreciate all the moments we have shared over the years. Thank you also for visiting us in Sweden, taking the time to experience the life we have built here, and giving us more precious time with our little nephew. I am grateful that you have been part of this journey and look forward to the memories that the years ahead will bring.

To my mother, **Anita**, if this journey was 29 years in the making, you were there from its very first day. Watching me move so far away could not have been easy, yet you understood and supported my need to find my own place in the world. For that, I will always be grateful. Thank you for your love, for every sacrifice you made, and for believing in my dreams long before any of this became reality.

To my beloved wife, **Maja**, no words could ever capture the dept of love and support you have given me throughout these years. Completely selfless and endlessly understanding, you have never treated this as my journey alone but have walked beside me every step of the way. Every sacrifice we made was for our family and the future we were building together, and for that reason, this thesis may carry my name, but it belongs to you as well. As we finish this chapter together, we can look ahead to our greatest adventure, already waiting for us on the horizon.

References

1. Patricios JS, Schneider KJ, Dvorak J, Ahmed OH, Blauwet C, Cantu RC, et al. Consensus statement on concussion in sport: the 6th International Conference on Concussion in Sport-Amsterdam, October 2022. *Br J Sports Med.* 2023;57(11):695-711.
2. Rowson S, Bland ML, Campolettano ET, Press JN, Rowson B, Smith JA, et al. Biomechanical Perspectives on Concussion in Sport. *Sports Med Arthrosc Rev.* 2016;24(3):100-7.
3. Giza CC, Hovda DA. The new neurometabolic cascade of concussion. *Neurosurgery.* 2014;75 Suppl 4(0 4):S24-33.
4. McCrea M, Hammeke T, Olsen G, Leo P, Guskiewicz K. Unreported concussion in high school football players: implications for prevention. *Clin J Sport Med.* 2004;14(1):13-7.
5. Williamson IJ, Goodman D. Converging evidence for the under-reporting of concussions in youth ice hockey. *Br J Sports Med.* 2006;40(2):128-32; discussion -32.
6. Lincoln AE, Caswell SV, Almquist JL, Dunn RE, Norris JB, Hinton RY. Trends in concussion incidence in high school sports: a prospective 11-year study. *Am J Sports Med.* 2011;39(5):958-63.
7. Bretzin AC, Anderson M, Bhandari N, Schmitt AJ, Beidler E. Concussion Nondisclosure in Youth Sports. *J Athl Train.* 2022;57(7):688-95.
8. Ingram V, Fielding M, Dunne LAM, Piantella S, Weakley J, Johnston RD, McGuckian TB. The Incidence of Sports-Related Concussion in Children and Adolescents: A Systematic Review and Meta-Analysis. *Sports Med Open.* 2025;11(1):36.
9. Prien A, Grafe A, Rossler R, Junge A, Verhagen E. Epidemiology of Head Injuries Focusing on Concussions in Team Contact Sports: A Systematic Review. *Sports Med.* 2018;48(4):953-69.
10. Chandran A, Boltz AJ, Morris SN, Robison HJ, Nedimyer AK, Collins CL, Register-Mihalik JK. Epidemiology of Concussions in National Collegiate Athletic Association (NCAA) Sports: 2014/15-2018/19. *Am J Sports Med.* 2022;50(2):526-36.
11. Cheng J, Ammerman B, Santiago K, Jivanelli B, Lin E, Casey E, Ling D. Sex-Based Differences in the Incidence of Sports-Related Concussion: Systematic Review and Meta-analysis. *Sports Health.* 2019;11(6):486-91.
12. Echemendia RJ, Brett BL, Broglio S, Davis GA, Giza CC, Guskiewicz KM, et al. Sport concussion assessment tool - 6 (SCAT6). *Br J Sports Med.* 2023;57(11):622-31.

13. Putukian M, Purcell L, Schneider KJ, Black AM, Burma JS, Chandran A, et al. Clinical recovery from concussion-return to school and sport: a systematic review and meta-analysis. *Br J Sports Med.* 2023;57(12):798-809.
14. Davis GA, Schneider KJ, Anderson V, Babl FE, Barlow KM, Blauwet CA, et al. Pediatric Sport-Related Concussion: Recommendations From the Amsterdam Consensus Statement 2023. *Pediatrics.* 2024;153(1).
15. Caccese JB, Master CL, Buckley TA, Chrisman SPD, Clugston JR, Eckner JT, et al. Sex Differences in Recovery Trajectories of Assessments for Sport-Related Concussion Among NCAA Athletes: A CARE Consortium Study. *Sports Med.* 2024;54(6):1707-21.
16. van Ierssel J, Osmond M, Hamid J, Sampson M, Zemek R. What is the risk of recurrent concussion in children and adolescents aged 5-18 years? A systematic review and meta-analysis. *Br J Sports Med.* 2021;55(12):663-9.
17. Iverson GL, Castellani RJ, Cassidy JD, Schneider GM, Schneider KJ, Echemendia RJ, et al. Examining later-in-life health risks associated with sport-related concussion and repetitive head impacts: a systematic review of case-control and cohort studies. *Br J Sports Med.* 2023;57(12):810-21.
18. Meaney DF, Smith DH. Biomechanics of concussion. *Clin Sports Med.* 2011;30(1):19-31, vii.
19. Ji S, Ghajari M, Mao H, Kraft RH, Hajiaghamemar M, Panzer MB, et al. Use of Brain Biomechanical Models for Monitoring Impact Exposure in Contact Sports. *Ann Biomed Eng.* 2022;50(11):1389-408.
20. O'Connor KL, Rowson S, Duma SM, Broglio SP. Head-Impact-Measurement Devices: A Systematic Review. *J Athl Train.* 2017;52(3):206-27.
21. Rowson S, Duma SM. Brain injury prediction: assessing the combined probability of concussion using linear and rotational head acceleration. *Ann Biomed Eng.* 2013;41(5):873-82.
22. Guskiewicz KM, Mihalik JP, Shankar V, Marshall SW, Crowell DH, Oliaro SM, et al. Measurement of head impacts in collegiate football players: relationship between head impact biomechanics and acute clinical outcome after concussion. *Neurosurgery.* 2007;61(6):1244-52; discussion 52-3.
23. Rowson S, Brolinson G, Goforth M, Dietter D, Duma S. Linear and angular head acceleration measurements in collegiate football. *J Biomech Eng.* 2009;131(6):061016.
24. Ji S, Zhao W, Li Z, McAllister TW. Head impact accelerations for brain strain-related responses in contact sports: a model-based investigation. *Biomech Model Mechanobiol.* 2014;13(5):1121-36.
25. Zhao W, Ruan S, Ji S. Brain pressure responses in translational head impact: a dimensional analysis and a further computational study. *Biomech Model Mechanobiol.* 2015;14(4):753-66.

26. Siegmund GP, Guskiewicz KM, Marshall SW, DeMarco AL, Bonin SJ. Laboratory Validation of Two Wearable Sensor Systems for Measuring Head Impact Severity in Football Players. *Ann Biomed Eng.* 2016;44(4):1257-74.
27. Kuo C, Patton D, Rooks T, Tierney G, McIntosh A, Lynall R, et al. On-Field Deployment and Validation for Wearable Devices. *Ann Biomed Eng.* 2022;50(11):1372-88.
28. Le Flao E, Siegmund GP, Borotkanics R. Head Impact Research Using Inertial Sensors in Sport: A Systematic Review of Methods, Demographics, and Factors Contributing to Exposure. *Sports Med.* 2022;52(3):481-504.
29. Le Flao E, Brughelli M, Hume PA, King D. Assessing Head/Neck Dynamic Response to Head Perturbation: A Systematic Review. *Sports Med.* 2018;48(11):2641-58.
30. Gabler L, Patton D, Begonia M, Daniel R, Rezaei A, Huber C, et al. Consensus Head Acceleration Measurement Practices (CHAMP): Laboratory Validation of Wearable Head Kinematic Devices. *Ann Biomed Eng.* 2022;50(11):1356-71.
31. Wu LC, Nangia V, Bui K, Hammor B, Kurt M, Hernandez F, et al. In Vivo Evaluation of Wearable Head Impact Sensors. *Ann Biomed Eng.* 2016;44(4):1234-45.
32. Eckner JT, Oh YK, Joshi MS, Richardson JK, Ashton-Miller JA. Effect of neck muscle strength and anticipatory cervical muscle activation on the kinematic response of the head to impulsive loads. *Am J Sports Med.* 2014;42(3):566-76.
33. Arbogast KB, Caccese JB, Buckley TA, McIntosh AS, Henderson K, Stemper BD, et al. Consensus Head Acceleration Measurement Practices (CHAMP): Origins, Methods, Transparency and Disclosure. *Ann Biomed Eng.* 2022;50(11):1317-45.
34. Eliason PH, Galarneau JM, Kolstad AT, Pankow MP, West SW, Bailey S, et al. Prevention strategies and modifiable risk factors for sport-related concussions and head impacts: a systematic review and meta-analysis. *Br J Sports Med.* 2023;57(12):749-61.
35. Gornall H, Truscott H, Shill IJ, Ashford M, Palmer D. Evaluating the Use of In-Game Rule Changes as a Primary Prevention Approach to Reduce Injury Risk in Invasion Team Sports: A Scoping Review. *Sports Med.* 2026;56(4):927-39.
36. Williamson RA, Kolstad AT, Krolkowski M, Nadeau L, Goulet C, Hagel BE, Emery CA. Incidence of Head Contacts, Penalties, and Player Contact Behaviors in Youth Ice Hockey: Evaluating the "Zero Tolerance for Head Contact" Policy Change. *Orthop J Sports Med.* 2021;9(3):2325967121992375.
37. Beaudouin F, Aus der Funten K, Tross T, Reinsberger C, Meyer T. Head injuries in professional male football (soccer) over 13 years: 29% lower incidence rates after a rule change (red card). *Br J Sports Med.* 2019;53(15):948-52.
38. Shill IJ, Shepherd HA, Eliason PH, Kolstad AT, Heyward O, Martens G, et al. Prevention strategies and modifiable risk factors for concussion: a systematic review and meta-analysis for the Female, woman and girl/or Athlete Injury pRevention (FAIR) consensus. *Br J Sports Med.* 2025;59(22):1599-616.

39. Benson BW, Hamilton GM, Meeuwisse WH, McCrory P, Dvorak J. Is protective equipment useful in preventing concussion? A systematic review of the literature. *Br J Sports Med.* 2009;43 Suppl 1:i56-67.
40. Rowson S, Duma SM, Greenwald RM, Beckwith JG, Chu JJ, Guskiewicz KM, et al. Can helmet design reduce the risk of concussion in football? *J Neurosurg.* 2014;120(4):919-22.
41. Knapik JJ, Hoedebecke BL, Rogers GG, Sharp MA, Marshall SW. Effectiveness of Mouthguards for the Prevention of Orofacial Injuries and Concussions in Sports: Systematic Review and Meta-Analysis. *Sports Med.* 2019;49(8):1217-32.
42. Al Attar WSA, Mahmoud H, Alfadel A, Faude O. Does Headgear Prevent Sport-Related Concussion? A Systematic Review and Meta-Analysis of Randomized Controlled Trials Including 6311 Players and 173,383 Exposure Hours. *Sports Health.* 2024;16(3):473-80.
43. Schneider DK, Grandhi RK, Bansal P, Kuntz G, Webster KE, Logan K, et al. Current state of concussion prevention strategies: a systematic review and meta-analysis of prospective, controlled studies. *Br J Sports Med.* 2017;51(20):1473-82.
44. Fownes-Walpole M, Heyward O, Till K, Mackay L, Stodter A, Al-Dawoud M, et al. Combining evidence and practice to optimise neck training aimed at reducing head acceleration events in sport: a systematic review and Delphi-consensus study. *Br J Sports Med.* 2025;59(15):1027-42.
45. Streifer M, Brown AM, Porfido T, Anderson EZ, Buckman JF, Esopenko C. The Potential Role of the Cervical Spine in Sports-Related Concussion: Clinical Perspectives and Considerations for Risk Reduction. *J Orthop Sports Phys Ther.* 2019;49(3):202-8.
46. Kung SM, Suksreephaisan TK, Perry BG, Palmer BR, Page RA. The Effects of Anticipation and Visual and Sensory Performance on Concussion Risk in Sport: A Review. *Sports Med Open.* 2020;6(1):54.
47. Peek K, Elliott JM, Orr R. Higher neck strength is associated with lower head acceleration during purposeful heading in soccer: A systematic review. *J Sci Med Sport.* 2020;23(5):453-62.
48. Schmidt JD, Guskiewicz KM, Blackburn JT, Mihalik JP, Siegmund GP, Marshall SW. The influence of cervical muscle characteristics on head impact biomechanics in football. *Am J Sports Med.* 2014;42(9):2056-66.
49. Collins CL, Fletcher EN, Fields SK, Kluchurosky L, Rohrkemper MK, Comstock RD, Cantu RC. Neck strength: a protective factor reducing risk for concussion in high school sports. *J Prim Prev.* 2014;35(5):309-19.
50. Farley T, Barry E, Sylvester R, Medici A, Wilson MG. Poor isometric neck extension strength as a risk factor for concussion in male professional Rugby Union players. *Br J Sports Med.* 2022;56(11):616-21.

51. Leung FT, Brown DA, Warner E, Shamim S, Harris S, Hides JA. Neck strength deficit is a risk factor for concussion in high school rugby union and rugby league players. *J Sci Med Sport*. 2025;28(5):370-6.
52. Liston M, Leckey C, Whale A, van Dyk N. Neck Strength Assessment Offers No Clinical Value in Predicting Concussion in Male Professional Rugby Players: A Prospective Cohort Study. *J Orthop Sports Phys Ther*. 2023;53(5):317-23.
53. Donaldson A, Lloyd DG, Gabbe BJ, Cook J, Young W, White P, Finch CF. Scientific evidence is just the starting point: A generalizable process for developing sports injury prevention interventions. *J Sport Health Sci*. 2016;5(3):334-41.
54. Root HJ, Lininger MR, DiStefano LJ. Hybrid effectiveness-implementation study designs in sports injury prevention research. *Front Sports Act Living*. 2022;4:981656.
55. Nauta J, Haugg J, Nemeth R, Verhagen E, McKay CD, van Nassau F. Implementing sports injury prevention programmes during and beyond effectiveness trials: a mixed methodologies study. *BMJ Open Sport Exerc Med*. 2026;12(1):e002931.
56. Minnig MC, Hawkinson L, Root HJ, Driban J, DiStefano LJ, Callahan L, et al. Barriers and facilitators to the adoption and implementation of evidence-based injury prevention training programmes: a narrative review. *BMJ Open Sport Exerc Med*. 2022;8(3):e001374.
57. Ageberg E, Bunke S, Linnell J, Moesch K. Co-creating holistic injury prevention training for youth handball: Development of an intervention targeting end-users at the individual, team, and organizational levels. *BMC Sports Sci Med Rehabil*. 2024;16(1):10.
58. Lindblom H, Carljford S, Hagglund M. Adoption and use of an injury prevention exercise program in female football: A qualitative study among coaches. *Scand J Med Sci Sports*. 2018;28(3):1295-303.
59. Petrie FJ, Williams EMP, Mackintosh KA, Starbuck C, McNarry MA. Assessing the feasibility of a neck-strength training intervention in university women's rugby. *European Journal of Sport Science*. 2024;24(4):466-73.
60. Proctor E, Silmere H, Raghavan R, Hovmand P, Aarons G, Bunger A, et al. Outcomes for implementation research: conceptual distinctions, measurement challenges, and research agenda. *Adm Policy Ment Health*. 2011;38(2):65-76.
61. Crossley KM, Whittaker JL, Patterson B, Shill IJ, Heming EE, Bullock GS, et al. Female, woman and/or girl Athlete Injury pRevention (FAIR) practical recommendations: International Olympic Committee (IOC) consensus meeting held in Lausanne, Switzerland, 2025. *Br J Sports Med*. 2025;59(22):1546-59.
62. Patterson BE, McKay CD, Critchley ML, Lutz D, Cowan SM, Kolesky N, et al. Dissemination and implementation of injury prevention interventions: a scoping review for the Female, woman and/or girl Athlete Injury pRevention (FAIR) consensus. *Br J Sports Med*. 2025;59(22):1618-32.

63. D'Lauro C, Jones ER, Swope LM, Anderson MN, Broglio S, Schmidt JD. Underrepresentation of female athletes in research informing influential concussion consensus and position statements: an evidence review and synthesis. *Br J Sports Med*. 2022.
64. Asselstine S, Krystofiak J, Gorbonosov M, Toto D. Progress of Female Athlete Representation in Research Influencing International Conference on Concussion in Sport Consensus Statements: An Evidence Review. *Women Sport Phys Act*. 2024;32(1):13-.
65. Heidari S, Babor TF, De Castro P, Tort S, Curno M. Sex and Gender Equity in Research: rationale for the SAGER guidelines and recommended use. *Res Integr Peer Rev*. 2016;1:2.
66. Bretzin AC, Covassin T, Wiebe DJ, Stewart W. Association of Sex With Adolescent Soccer Concussion Incidence and Characteristics. *JAMA Netw Open*. 2021;4(4):e218191.
67. Fahr J, Kraff O, Deuschl C, Dodel R. Concussion in Female Athletes of Contact Sports: A Scoping Review. *Orthop J Sports Med*. 2024;12(10):23259671241276447.
68. Huber CM, Patton DA, McDonald CC, Jain D, Simms K, Lallo VA, et al. Sport- and Gender-Based Differences in Head Impact Exposure and Mechanism in High School Sports. *Orthop J Sports Med*. 2021;9(3):2325967120984423.
69. Page MJ, Moher D, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews. *BMJ*. 2021;372:n160.
70. Arden CL, Buttner F, Andrade R, Weir A, Ashe MC, Holden S, et al. Implementing the 27 PRISMA 2020 Statement items for systematic reviews in the sport and exercise medicine, musculoskeletal rehabilitation and sports science fields: the PERSiST (implementing Prisma in Exercise, Rehabilitation, Sport medicine and SporTs science) guidance. *Br J Sports Med*. 2022;56(4):175-95.
71. Veritas Health Innovation. Covidence systematic review software [computer program]. Melbourne, Australia: Veritas Health Innovation; 2025 Available from: <https://www.covidence.org>.
72. National Heart L, and Blood Institute,. Study quality assessment tools [Internet]. Bethesda (MD): National Institutes of Health; 2025 Available from: <https://www.nhlbi.nih.gov/health-topics/study-quality-assessment-tools>.
73. Sterne JAC, Savovic J, Page MJ, Elbers RG, Blencowe NS, Boutron I, et al. RoB 2: a revised tool for assessing risk of bias in randomised trials. *BMJ*. 2019;366:l4898.
74. Cohen J. Statistical power analysis for the behavioral sciences. 2nd ed. Hillsdale (NJ): Lawrence Erlbaum Associates; 1988.
75. Deeks JJ, Higgins JPT, Altman DG. Analysing data and undertaking meta-analyses. In: Higgins JPT, Thomas J, Chandler J, Cumpston M, Li T, Page MJ, Welch VA, editors. *Cochrane handbook for systematic reviews of interventions*. 2nd ed. Chichester (UK): John Wiley & Sons; 2019. p. 241-84.

76. Schünemann H, Brożek J, Guyatt G, Oxman A. GRADE handbook for grading quality of evidence and strength of recommendations: The GRADE Working Group; 2013.
77. Slade SC, Dionne CE, Underwood M, Buchbinder R. Consensus on Exercise Reporting Template (CERT): Explanation and Elaboration Statement. *Br J Sports Med*. 2016;50(23):1428-37.
78. Ivanic B, Cronstrom A, Ryan N, Eckner JT, Ageberg E. Test-retest reliability of a laboratory-based head acceleration testing protocol. *J Sci Med Sport*. 2026;29(6):578-86.
79. Koo TK, Li MY. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *J Chiropr Med*. 2016;15(2):155-63.
80. Lexell JE, Downham DY. How to assess the reliability of measurements in rehabilitation. *Am J Phys Med Rehabil*. 2005;84(9):719-23.
81. Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *J Strength Cond Res*. 2005;19(1):231-40.
82. Peterson MD, Rhea MR, Alvar BA. Maximizing strength development in athletes: a meta-analysis to determine the dose-response relationship. *J Strength Cond Res*. 2004;18(2):377-82.
83. Braun V, Clarke V. Thematic analysis: A practical guide. Los Angeles: SAGE; 2022.
84. Weiner BJ, Lewis CC, Stanick C, Powell BJ, Dorsey CN, Clary AS, et al. Psychometric assessment of three newly developed implementation outcome measures. *Implement Sci*. 2017;12(1):108.
85. Peek K. The measurement of neck strength: A guide for sports medicine clinicians. *Phys Ther Sport*. 2022;55:282-8.
86. Sekhon M, Cartwright M, Francis JJ. Acceptability of healthcare interventions: an overview of reviews and development of a theoretical framework. *BMC Health Serv Res*. 2017;17(1):88.
87. World Medical A. World Medical Association Declaration of Helsinki: Ethical Principles for Medical Research Involving Human Participants. *JAMA*. 2025;333(1):71-4.
88. Tierney G. Concussion biomechanics, head acceleration exposure and brain injury criteria in sport: a review. *Sports Biomech*. 2024;23(11):1888-916.
89. Guskiewicz KM, Mihalik JP. Biomechanics of sport concussion: quest for the elusive injury threshold. *Exerc Sport Sci Rev*. 2011;39(1):4-11.
90. Rowson S, Duma SM, Stemper BD, Shah A, Mihalik JP, Harezlak J, et al. Correlation of Concussion Symptom Profile with Head Impact Biomechanics: A Case for Individual-Specific Injury Tolerance. *J Neurotrauma*. 2018;35(4):681-90.
91. Beckwith JG, Greenwald RM, Chu JJ. Measuring head kinematics in football: correlation between the head impact telemetry system and Hybrid III headform. *Ann Biomed Eng*. 2012;40(1):237-48.

92. Patton DA, Huber CM, Jain D, Myers RK, McDonald CC, Margulies SS, et al. Head Impact Sensor Studies In Sports: A Systematic Review Of Exposure Confirmation Methods. *Ann Biomed Eng.* 2020;48(11):2497-507.
93. Verheul J, Nedergaard NJ, Vanrenterghem J, Robinson MA. Measuring biomechanical loads in team sports - from lab to field. *Sci Med Football.* 2020;4(3):246-52.
94. Austin K, Nicholas KJ, Jones CM, Loosemore M. Criterion validity and reliability of an instrumented mouthguard under pendulum impactor conditions. *Sports Eng.* 2023;26(1).
95. Wochner I, Nolle LV, Martynenko OV, Schmitt S. 'Falling heads': investigating reflexive responses to head-neck perturbations. *Biomed Eng Online.* 2022;21(1):25.
96. Keshner EA, Campbell D, Katz RT, Peterson BW. Neck muscle activation patterns in humans during isometric head stabilization. *Exp Brain Res.* 1989;75(2):335-44.
97. Kumar S, Ferrari R, Narayan Y. Analysis of right anterolateral impacts: the effect of head rotation on the cervical muscle whiplash response. *J Neuroeng Rehabil.* 2005;2:11.
98. Attwood MJ, Roberts SP, Trewartha G, England ME, Stokes KA. Efficacy of a movement control injury prevention programme in adult men's community rugby union: a cluster randomised controlled trial. *Br J Sports Med.* 2018;52(6):368-74.
99. Hislop MD, Stokes KA, Williams S, McKay CD, England ME, Kemp SPT, Trewartha G. Reducing musculoskeletal injury and concussion risk in schoolboy rugby players with a pre-activity movement control exercise programme: a cluster randomised controlled trial. *Br J Sports Med.* 2017;51(15):1140-6.
100. Bandy WD, Lovelace-Chandler V, McKittrick-Bandy B. Adaptation of skeletal muscle to resistance training. *J Orthop Sports Phys Ther.* 1990;12(6):248-55.
101. Currier BS, McLeod JC, Banfield L, Beyene J, Welton NJ, D'Souza AC, et al. Resistance training prescription for muscle strength and hypertrophy in healthy adults: a systematic review and Bayesian network meta-analysis. *Br J Sports Med.* 2023;57(18):1211-20.
102. Zouita A, Darragi M, Bousselmi M, Sghaier Z, Clark CCT, Hackney AC, et al. The Effects of Resistance Training on Muscular Fitness, Muscle Morphology, and Body Composition in Elite Female Athletes: A Systematic Review. *Sports Med.* 2023;53(9):1709-35.
103. Kraemer WJ, Adams K, Cafarelli E, Dudley GA, Dooly C, Feigenbaum MS, et al. American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. *Med Sci Sports Exerc.* 2002;34(2):364-80.
104. Way A, Jones MV, Slater MJ. Exploring training adherence in elite school-age athletes. *Qual Res Sport Exerc.* 2012;4(1):154-71.
105. Donaldson A, Finch CF. Planning for implementation and translation: seek first to understand the end-users' perspectives. *Br J Sports Med.* 2012;46(5):306-7.
106. O'Cathain A, Croot L, Duncan E, Rousseau N, Sworn K, Turner KM, et al. Guidance on how to develop complex interventions to improve health and healthcare. *BMJ Open.* 2019;9(8):e029954.

107. McKay CD, Steffen K, Romiti M, Finch CF, Emery CA. The effect of coach and player injury knowledge, attitudes and beliefs on adherence to the FIFA 11+ programme in female youth soccer. *Br J Sports Med.* 2014;48(17):1281-6.
108. O'Brien J, Finch CF. Injury prevention exercise programmes in professional youth soccer: understanding the perceptions of programme deliverers. *BMJ Open Sport Exerc Med.* 2016;2(1):e000075.
109. Winstanley C, Reid D, Fulcher ML. Suggested improvements to the 11+ as identified by coaches, players, strength and conditioning staff and medical staff in New Zealand Football. *BMJ Open Sport Exerc Med.* 2023;9(2):e001463.
110. White P, Donaldson A, Finch CF. But can someone like me do it? The importance of appropriate role modelling for safety behaviours in sports injury prevention. *Brit J Sport Med.* 2016;50(10):569-70.
111. Chan DK, Hagger MS. Self-determined forms of motivation predict sport injury prevention and rehabilitation intentions. *J Sci Med Sport.* 2012;15(5):398-406.

About the Author



Branimir Ivanic received a Bachelor of Coaching Profession from the Faculty of Kinesiology, University of Zagreb, in 2019, followed by a Bachelor of Physiotherapy from the University of Applied Health Sciences in Zagreb in 2020. In 2023, he completed a Master of Medical Science at the Faculty of Medicine, Lund University. That same year, he began his doctoral studies within the Sport Sciences Research Group at the Department of Health Sciences, Faculty of Medicine, Lund University.

