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The effects of repetitive head impacts on postural control:A systematic review

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Abstract

Objectives: The purpose of our study was to investigate the association between repetitive head impact (RHI) exposure and postural control.

Design: Systematic review.

Methods: PubMed, Embase and PsycInfo were searched using a self-developed search term including the keywords balance OR postural control AND repetitive OR sub-concussive head impacts. Twenty-one studies excluding non-peer reviewed studies, secondary studies, cross-sectional studies, animal studies, and studies investigating concussion were included for further analyses. We rated Level of Evidence and quality using the Centre for Evidence-Based Medicine tool, the Quality Assessment for the Systematic Review of Effectiveness, and the Sub-concussion Specific Tool.

Results: All included studies were grouped into Category I and II studies. Category I included trials investigating the effects of controlled soccer heading on postural control (n = 8) and Category II studies were cohort studies investigating on-the-field changes between preseason and postseason assessments on postural control measures (n = 13). Findings were heterogeneous, with

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Appendix A. Supplementary data
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a tendency towards no effects of RHI on clinical postural control measures. Most laboratory studies in Category I used instrumented assessments whereas on-the-field studies in Category II used both instrumented and non-instrumented assessments.

Conclusions: Due to heterogeneous findings, future studies aiming to investigate the effects of RHI on different athlete populations are needed on other participant cohorts. Furthermore, the combination of objective clinical balance measures may be a promising approach to accurately measure how, and to what degree, postural control may be affected by RHI.

Keywords

Athletes; Brain concussion; Contact sport; Postural balance; Soccer; Sub-concussion

1. Introduction

Over the past several years, increased attention has been given to the role of repetitive head impacts (RHI), also called sub-concussive impacts, on neurological function.[1] RHI are typically defined as multiple blows to the head or body that do not elicit concussion symptoms or warrant concussion diagnosis. Athletes typically do not seek medical care following RHI.[2] As a consequence, subtle impairments, if they exist, may go undetected.[3] However, using advanced neuroimaging, previous work has revealed RHI-related effects such as impaired blood-brain barrier permeability, brain regional atrophy, axonal injury, alteration in brain biochemistry, and neuroinflammation.[4]

The accumulation of head impacts over time has been hypothesized to lead to neurological deficits such as impairments in postural control, but how these impacts may manifest pathologically is not clear.[3,5] Postural control is defined as the ability to control the center of mass (CoM) in relation to the base of support.[6] Measuring postural control is especially important in the sports context, where postural control impairments after concussion are frequently reported.[7,8] For soccer players, good postural control ability is especially relevant in terms of injury prevention.[9] Following concussion, it is theorized that the required precise integration and modulation of visual, vestibular, and proprioceptive information is impaired.[10] However, whether RHI exposure affects these processes in a substantial way remains difficult to discern. Although, there are different methods available to examine potential changes, detecting postural control disruptions as they may relate to RHI is difficult.

Both instrumented and non-instrumented assessment approaches have been used to examine changes in postural control following concussion,[11] each possessing strengths and weaknesses.[12] Instrumented tools are considered to use quantifying tools to measure certain aspects of a task, whereas non-instrumented tools are used by an assessor to measure a person's whole performance. More specifically, instrumented tools have the capability to measure kinetic and/or kinematic performance using outcome variables such as postural sway or center of pressure area (CoP). While precise and objective, this approach may not be feasible in all clinical contexts due to the demands of personnel, space to administer the examination or funds to buy expensive equipment.[12] Non-instrumented tools, such as the Balance Error Scoring System (BESS) allow for the observation of postural control maintenance on different surfaces and bases of support in a clinically feasible manner.[13]

Although non-instrumented tools are less expensive and easier to implement,[14] they do not possess the same level of sensitivity to subtle neurological changes than instrumented tools due to their lack of precision and reliance on human-observers to obtain outcomes.

Currently, there is a knowledge gap investigating the relation between RHI exposure and postural control. Moreover, there is still uncertainty regarding which assessments are most sensitive to identify if changes occur as a consequence of RHI. In addition, there is a debate, if controlled lab settings are suitable to simulate real game situations or if field testing is more accurate. In order to address these open questions, the primary purpose of our systematic review was to summarize how RHI exposure affects postural control.

2. Methods

We performed a systematic review to address the above-mentioned questions. Two independent systematic literature searches and quality ratings (EB, JS) have been performed in order to ensure rigor, transparency, and reproducibility.

2.1. Data sources and searches

As illustrated in the PRISMA flow chart in Fig. 1, articles were retrieved via searching the three online databases PubMed, Embase and PsycInfo from November 11th–15th, 2019. For PubMed searches, the legacy version before the new release in early 2020 has been used. In addition, reference lists of eligible articles were screened for potentially relevant articles.

The literature search consisted of two general categories 1) repetitive head impact/sub-concussion and 2) postural control/balance. Therefore, the following search term was developed: [(subconcuss* OR sub-concuss* OR repetitive head impact* OR cumulative head impact* OR soccer heading) AND (balance OR postural control OR postur*)]. Additional single keyword, as well as MeSH term searches did not result in any further relevant articles to include. After removing duplicates, titles and abstracts of all studies were screened based on the following inclusion and exclusion criteria.

2.2. Inclusion and exclusion criteria

Using predefined inclusion and exclusion criteria, only primary studies published in English were considered. Exclusion criteria were 1) studies with no full-text or non-peer reviewed studies, 2)secondary studies, 3) cross-sectional studies, 4) animal studies, 3) studies with other contents (focusing on completely different topics or involving only individuals with a diagnosed concussion, rather than RHI exposure). See Supplementary Table 1 for a protocol of included and excluded studies. Finally, 21 studies remained. After reading all full-texts of considered studies, all 21 were included for qualitative analysis.

2.3. Data extraction

The following data were extracted from each included study: author(s), year of publication, population (sample size, sex, age), control group, purpose of the study, main postural control assessment tools, results, and if present: heading intervention. The included studies were grouped into Category I (Intervention studies investigating the effects of controlled soccer heading on postural control) and Category II (Cohort studies investigating preseason-postseason changes in postural control after RHI exposure: Table 1).

2.4. Quality assessment

Quality of all included studies has been addressed by rating the Level of Evidence (LoE) using the Centre for Evidence-Based Medicine tool (CEBM).[15] Additionally, the Quality Assessment for the Systematic Review of Effectiveness[16] and the Sub-concussion Specific Tool (SST) adapted from Comper et al. were used.[17] The rationale for using these three tools include their widespread use (CEBM LoE), its appropriateness of rating scheme (Quality Assessment for the Systematic Review of Effectiveness) and specificity for the addressed topic (SST).

Using the LoE rating approach, randomized-controlled trials (RCT) were rated as level 2 and non-RCT and non-consecutive studies as level 3. Using the Quality Assessment for the Systematic Review of Effectiveness, the categories *Selection Bias, Study Design, Confounders, Blinding, Data Collection, and Withdrawals & Drop-outs* were rated as A (low quality), B (medium quality), or C (low quality). To ensure transparency of the quality ratings, it should be mentioned that for the section Confounders, the best rating A was only given for studies correcting for at least two of the following key variables: sex, age, concussion history, weight, height and soccer experience. Moreover, because of the focus of our review, for the section *Data Collection* we only considered the quality of tools to assess postural control. Because of its uniqueness and specificity within research on sub-concussion, we refer to Mainwaring et al. (2018) describing the SST in more detail. Using the SST, all studies were classified as A or B, based on five criteria.[18] An overview of all quality ratings is summarized in Table 2. More information on the specific subscale ratings of the Quality Assessment for the Systematic Review of Effectiveness and the SST is attached in Supplementary Tables 2 and 3.

2.4.1. Category I studies—

Eight studies investigating the effects of controlled soccer heading on postural control were rated for its quality. According to the CEBM, the LoE of six of the eight studies were rated as level 2, representing RCT, and two studies as level 3 representing prospective cohort studies without a control group (Table 2). Using the Quality Assessment for the Systematic Review of Effectiveness, six studies have been rated as B and two studies as C. Noticeably, all studies (Category I and II) did not report a baseline response rate (Selection Bias: C), neither blinded participants, nor outcome assessors (Blinding: C). All studies used well-established tools which have evidence to be reliable/ valid to assess postural control (Data Collection: A). More detailed information is listed in Supplementary Table 2. Using the SST, seven out of the eight studies were rated the highest category A. The only study being rated as B already has shown lacking quality in the other quality ratings (Supplementary Table 3).

2.4.2. Category II studies—

Thirteen studies investigating preseason-postseason changes in postural control after being exposed to RHI were rated for its quality. According to the CEBM, the LoE of all studies was rated as level 3, exclusively including prospective cohort studies (Table 2). Using the Quality Assessment for the Systematic Review of

Effectiveness, two studies have been rated as B and eleven as C. More detailed information is listed in Supplementary Table 2. Using the SST, eight out of the thirteen studies were rated as A and five studies as B (Supplementary Table 3).

2.5. Inter-rater reliability

Inter-rater reliability between the two raters (EB, JS) was calculated with Cohen's Kappa.[19] A third reviewer was consulted in cases of disagreement (DH). Cohen's Kappa can be categorized by strength of agreement from poor (κ = 0.0) to almost perfect (κ = 0.81–1.00).[20] The average Cohen's Kappa of all ratings was almost perfect (κ = 0.889) with an inter-rater agreement of 92.87% (Supplementary Table 4). More information on sub-scale ratings is attached in the supplementary material (Supplementary Table 5 and Supplementary Table 6).

3. Results

3.1. Category I studies

3.1.1. Sample characteristics—Sex and age were similar in the studies included in Category I. Apart from one study only investigating female athletes, the other seven investigated both male and female soccer players. In Category I, a total of 155 males (40%) and 228 females (60%) were included. Apart from one study, all investigated collegiate soccer players between 18.8 and 23 years of age on average. Caccese et al. however, investigated different cohorts including youth, high school and college players aged between 12.8 and 20.8[21] (Table 1).

3.1.2. Study design—Six out of the eight studies are considered a RCT,[21–26] defined as a prospective random assignment to a group performing/not performing a soccer heading protocol. Whereas in five of those six studies, the control group did nothing, in one study, the control group performed the same protocol kicking the ball with the foot, respectively.[26] Moreover, one study did not only randomly assign athletes to a heading and simulation group, but additionally investigated the effects of concussion history.[23] Two studies considered as a cohort study did not include a control group.[27,28] Large sample size differences between studies existed, ranging from 10[27] to 160 included participants.[21]

3.1.3. Heading intervention—Heading interventions typically consisted of heading a soccer ball 10−12 times within 10−12 min from around 10−12 m distance at a speed of 11.2 m/s. However, in some studies heading interventions included higher numbers of headers (20,[22,27,28] 18,[26] 15[23]) and less time (12[27] or 30 s[28]) between headers. Moreover, some interventions were performed from a more distant location of around 25 m,[22,26,27] a closer distance of 10 m,[24] 6 m,[28] at a higher speed of 24 m/s[22] or not controlled speed.[27] Except for one study, investigating linear and rotational heading,[22] all other studies did not investigate different types of headers.

3.1.4. Postural control assessment tools—In the studies in Category I, primarily instrumented tools have been used to investigate postural control before and after a soccer heading paradigm (n = 6[21,22,24,26–28]). One study used both instrumented and non-instrumented[25] and one study used non-instrumented tools only[23] (Supplementary Fig. 1). For instrumented tools mostly kinetic devices such as force plates or pressure mats, calculating CoP, sway velocity and sample entropy as dependent variables, were used. For non-instrumented tools the BESS was the most commonly used.

3.1.5. Findings—

Findings are heterogeneous including three out of eight studies (37.5%) reporting significant worse postural control performance in the heading than in the control group for at least one of the investigated parameters (Table 1; Supplementary Figure 2). All three studies found these effects using instrumented tools. Caccese et al. reported higher sway velocities after the intervention in the soccer heading compared to the control group. However, they did not find significant group differences in postural control for 95% area, nor approximate entropy.[21] Haran et al. found higher CoM root mean square values at 24 h after the intervention in the heading compared to the control group.[24] Hwang et al. showed significant decrease in trunk angle, leg angle gain, and CoM gain relative to galvanic vestibular stimulation for the heading compared with the control group.[25] One study also reported statistically significant worse BESS scores in a heading group with one or two previous concussions, but not in a very small heading group with more than three concussions compared to a simulated heading group.[23] While an interesting finding, it was outside the scope of our primary research question to investigate the effects of previous concussion history. Four studies did not report any significant outcome regarding the association of soccer heading and postural control. Concluding, most studies did not detect significant effects, and if so, only using instrumented tools assessing postural control.

3.2. Category II studies

3.2.1. Sample characteristics—

Most studies in Category II involved male athletes only (n = 9[29–37]). Of the other four studies in Category II, one investigated females only,[38] and the other three investigated males and females.[2,39,40] In total, in the studies in Category II a total of 453 (91%) male and 45 (9%) female pre-post longitudinal data were investigated. The most common average age of athletes included in these studies was 19–23 (n = 9[2,29,31,32,34,35,38–40]). The other four studies investigated younger athletes in the ages of 13 (n = 2[36,37]) and 10 years (n = 2[30,33]). Most commonly, only one type of contact sport was investigated within each study (n = 11). In one study two types[39] and in another study three types of contact-sports[31] were included. Ten studies investigated American football players as one of their groups, two investigated lacrosse,[34,35] and two soccer players.[38] In five studies contact sport athletes were compared with matched non-contact sport athletes[2,29,31,33,38] and in one study with non-athlete controls.[40] All other studies did not include control groups (Table 1).

3.2.2. Study design—

All thirteen studies are considered as prospective longitudinal cohort studies investigating preseason-postseason (n = 12), or preseason-postseason-6 months after postseason changes (n = 1[29]). Sample size differences existed, ranging from 10[36] to 87[33] included participants at baseline.

3.2.3. Head impact exposure—

Eleven out of thirteen studies reported the number of head impacts. Most of them used sensors (n = 10) such as the well-known Head Impact

Telemetry system (HITS: n = 7[2,29,30,32,37,39,40]) and other sensors (n = 3[31,34,35]). One study used a tally system (n = 1[38]).

3.2.4. Postural control assessment tools—
Compared to the intervention studies in Category I, these studies used a variety of approaches, including non-instrumented (n = 5[2,33,34,38,39]), instrumented (n = 4[31,36,37,40]), or a combination of both types of tools (n = 4[29,30,32,35]; Supplementary Fig. 1). The most often used instrumented tools were force plates and the most often non-instrumented tools the BESS and tandem gait test.

3.3. Findings

In total, three of the thirteen included studies (23%) found a change from preseason to postseason for at least one postural control parameter (Table 1; Supplementary Figure 2). Whereas two studies found a decrease,[34,35] one study found an increase in performance in women's soccer players between preseason and postseason.[39] Two of the three studies found pre-post changes using non-instrumented[34,39] and one study found effects using instrumented tools.[35] Significantly worse postural control performance was found over time, but not between groups. Among those changes, researchers observed significant increased sway velocity and an increase in errors using the BESS in three out of six stances.[34,35] However, no pre-post difference for the overall composite score of all stances was found.[35] Another study found faster time in the tandem gait test in women's soccer players from preseason to postseason. Furthermore, they found soccer players with impacts >=98 g to improve less than the other players.[39] No study investigating American football players, but the other three studies investigating lacrosse (n = 2) and soccer players (n = 1) found significant changes in postural control performance over time.[34,35,38]

4. Discussion

The findings from this systematic review are heterogeneous, with a tendency towards RHI having no effect on clinical postural control measures. In total, three out of eight soccer heading intervention studies in Category I and three out of thirteen cohort studies in Category II found a statistically significant association between RHI and altered postural control. Therefore, a clear understanding of our primary aim concerning the effects of RHI exposure on postural control is not evident based on existing evidence.

4.1. Differences between Category I and II studies

In general, instrumented tools are more likely to detect subtle impairments in postural control after concussions than non-instrumented.[11] The same is expected after sub-concussive head impacts. Clear differences can also be seen in the frequency of using instrumented versus non-instrumented tools between Category I and II studies. Among the soccer heading intervention studies in Category I, instrumented tools were used in a majority of studies, whereas the cohort studies in Category II used either instrumented, non-instrumented approaches, or a mixed approach. This reflects the assumption that a proper balance of cost, time and added value often dictates the management practices within each setting.[41] Consequently, the applicability and the low-cost burden of non-instrumented tools such as the BESS leads to a higher likelihood of adapting this approach for measurements obtained on the field, rather than in the laboratory. On the contrary, instrumented tools are likely placed in laboratories because of the high equipment needs. Another difference between the two categories of studies resulting from the different settings depicts the variability in sample size and completeness of pre-post data. Compared to laboratory experiments with pre-post testing on the same day, for testing preseason-postseason changes, athletes need to return back to the second testing. This can be challenging due to injury risks or organizational reasons and can result in lower attrition rates. Even though the BESS is known to be limited by practice, environmental and equipment effects,[13,42,43] it is often used for preseason-postseason studies, because baseline data often already exists as part of a pre-participation assessment of athletes. Although, it might not be sensitive enough to detect changes in postural control after RHI, it seems suited to detect acute impairments following concussion when overt postural control deficits are more apparent.

Only limited RHI pathological research has been performed related to exposure. Therefore, it is important to consider both approaches, while weighing their relative strengths and weaknesses, and interpreting findings accordingly. By doing so, both subtle pathologies which might be only detectable using instrumented tools and more overt deficits may be detected.

Interpretation of the clinical relevance of the included studies should be done with caution, particularly because some studies only found significant differences for one out of several investigated parameters,[21] but not for the whole overall composite score.[35] Moreover, all Category II studies only showed significant changes after RHI over time, but not compared to non-exposed groups.[34,35,39] Based on the literature, other potential influences such as daily performance,[44] sleep deprivation[45] and fatigue[46] might have caused changes in postural control performance to a similar extent as RHI exposure. Taking into account all the potential influences the detected effects of RHI exposure on postural control performance seem to be rather small.

4.2. Quality of included studies

Addressing the quality of the included studies, it is noticeable that no single study reported a baseline response rate, nor blinded the participants and outcome assessors. Although blinding of athletes in the context of exposure is almost impossible, blinding the outcome assessor may be feasible in future studies. *Data Collection* was rated as high quality, because all studies used widespread tools known to be reliable/valid to assess postural control. No clear conclusions between the quality of the studies and the finding of results can be drawn. However, these very similar ratings indicate that most studies are conducted quite similarly and are showing equal deficits, which should be addressed in future studies.

4.3. Category I studies

Addressing the soccer heading intervention studies in Category I specifically, significant changes were identified especially when the participants stood close to the machine - approximately 10−12 m apart - from where the ball was projected,[21,24,25] but not when standing far away from the machine - approximately 25 m apart,[22,26,27] independent from ball velocity. Moreover, changes have particularly been found when balance has been perturbed using a visual[24] or vestibular stimulus[25] compared to quiet stance assessments.

To date, researchers have not established an appropriate number of headers across a specific period best simulating a typical game situation, nor any sort of cutoff for the number of headers needed to identify any effects on postural control. Some of the included studies based their number of applied headers on data suggesting that athletes undergo 1–16 headers during a collegiate soccer practice[26] or a study[47] reporting a median of 16 headers per match in professional soccer.[27] However, most of the headers done during study participation likely happened within a shorter time frame than headers sustained during a game. Another important aspect to consider is that in such lab-controlled experiments, athletes are prepared for heading the ball. In comparison, RHI exposure on the field often includes unanticipated hits without activating neck muscles to prepare for the impact. A study on collegiate female soccer players showed purposeful headers result in lower mean linear accelerations compared to non-header impacts and unintentional deflections.[48] Therefore, the question of whether controlled lab settings are comparable with real situations requires further investigation.[22]

4.4. Category II studies

Addressing the cohort studies in Category II specifically, three reported significant alterations in postural control from preseason to postseason, and none of the studies reported significant differences between contact-sport athletes and non-contact sport athletes. One potential explanation for the reported decrease in performance from preseason to postseason in both groups, but not between groups, could result from other reasons than head impact exposure such as fatigue after an intense season of sports. The increase in performance in the tandem gait test from preseason to postseason in the study by Caccese et al. could be a result of a moderate practice effect or other determinants not yet identified.[39] Practice effects for the tandem gait test have previously been shown in a study by Howell et al.[49]

Five out of eleven studies quantifying head impact exposure reported a positive association between at least one variable of head impact exposure measures, such as impacts > = 98 g or linear acceleration, and one variable measuring postural control performance.[2,32,34,35,39] However, in most studies only a few out of several investigated associations have reached significance. Furthermore, none of ten studies investigating American football players identified significant differences between preseason and postseason whereas two out of two studies in lacrosse players found differences. So far, published studies mostly focused on the impact of RHI in American football, because of the prevalence of potential head trauma during gameplay.[50] However, relatively few studies have examined RHI among other contact sports such as lacrosse, rugby, and ice hockey which is making between-sport comparisons within the existing literature difficult.

5. Limitations

The results of our systematic review should be treated with caution given the relatively small number of studies that were eligible for inclusion. Moreover, all studies investigated a rather homogenous sample, including primarily male, young, and healthy athletes. Therefore, differences may exist among females, those of different ages or different performance levels, but we were unable to assess these aspects within our systematic review. Moreover, approximately half of the studies included did not include a control group, limiting the utility of our results. For example, potential learning effects on the BESS may be responsible for changes over time. Without a control group, it is difficult to distinguish between the effects of RHI versus learning.[25] Also, the difference in sensitivity and frequency of used tools to assess postural control between categories raises the question whether significant findings, especially in Category II studies, might have been missed because of the tendency to use less sensitive tools.

6. Conclusion and outlook

In conclusion, the influence of RHI on postural control outcomes is likely complex and multifactorial. Several factors likely influence observed performance, such as the test battery used, sport assessed, characteristics of head exposure, and the reflection of real-game scenarios. Existing studies report heterogeneous results on the association between RHI exposure and altered postural control among athletes.

Around one third of the included studies investigating soccer heading interventions (Category I) found differences between the heading and the control group. However, factors such as the distance from where the header is performed seem to affect outcome. Therefore, it should be assessed more thoroughly in prospective studies. In addition, the fact that the included studies only investigated anticipated rather than unanticipated headers, potentially led to different results than what is experienced on the field. In contrast, only three out of thirteen cohort studies (Category II) reported differences between preseason and postseason and none of the studies reported differences between the groups. The lack of consistent differences between groups across the included studies suggests that the effects of RHI on postural control are likely small, cumulative, multifactorial, or difficult to measure using clinically viable assessments.

The findings from our systematic review also demonstrate the lack of consistent research in the field of RHI and the sensitivity of clinical measures assessing these impairments. Recommendations on the further study of RHI including a set of common data elements and measures for the quantification of head impact exposure. These will help researchers and clinicians to better identify potential dose-response relationships related to RHI in sports. We have attempted to provide a comprehensive summary of an important research question in a field that contains mostly negative results, in the hope of avoiding publication bias. According to our synthesis, it appears that RHI exposure is not likely to cause overt postural control impairments.

Nevertheless, future studies should investigate more heterogeneous samples including more females, different levels of performance and expertise, athletes of different ages, and different kinds of sports. Additionally, other, more sensitive non-instrumented clinical tools such as tandem gait analyses should be considered for use. Furthermore, several of the included studies recommend the use of neuroimaging, because especially advanced imaging methods such as diffusion tensor imaging have demonstrated sensitivity to detect subtle changes resulting from RHI exposure, which was not visible in clinical performance measures.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Abbreviations:

BESS	Balance Error Scoring System
CEBM	Centre for Evidence-Based-Medicine
CoM	center of mass
CoP	center of pressure
LoE	Level of Evidence
RCT	randomized-controlled trial
RHI	repetitive head impacts
SST	Sub-concussion Specific Tool

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Practical implications

- The influence of repetitive head impact exposure on postural control performance is likely complex, multifactorial and not likely to cause overt postural control impairments.
- Instrumented tools are more likely to detect subtle impairments in postural control performance than non-instrumented tools, but the utility is dictated by a proper balance of cost, time and added value.
- The investigated type of sports, the extent of naturalistic head impact exposure and the study design play a major role in determining postural control outcome.

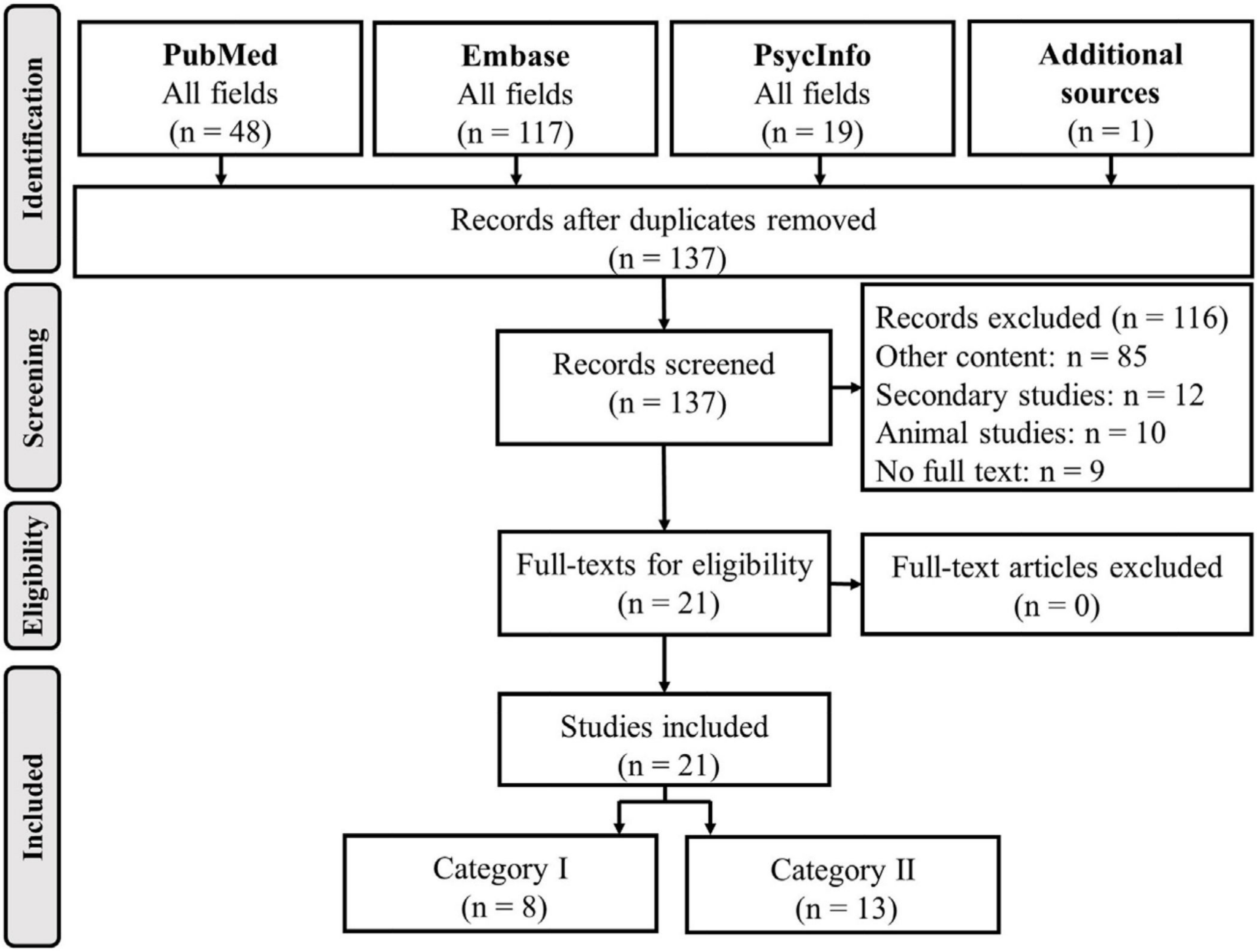

Fig. 1.
PRISMA flow diagram describing the systematic literature search process.

Table 1.

Category I intervention studies investigating the effect of controlled soccer heading on postural control and Category II cohort studies investigating preseason-postseason changes of contact sport athletes exposed to repetitive head impacts and its association with postural control.

Author, Year	Population	Control group	Primary purpose	Time of measurement	Heading intervention	Type of tool (variables/ test)	Findings in postural control
Category I Studies (n = 8)							
Broglio et al., 2004[22]	EG (all): n = 30 collegiate soccer players (♂ 14, ♀ 16; mean age 19.3) EG1: n= 10: Linear heading EG2: n = 10: Simulated rotational heading EG3: n= 10: Rotational heading	CG: n=10 collegiate soccer players (♂ 4, ♀ 6; mean age 19.90)	Investigate the acute effects of different types of soccer heading on postural control	T1: Pre-test T2: Post-test	20 headers in 20 min; distance 24.38 m; speed 24.64 m/s	IT (Total sway and CoP)	No significant findings for postural control assessments x
Caccese et al., 2018[21]	EG: n=100 soccer players (different sex and age groups)	CG: n = 60 (different sex and age groups)	Investigate the acute effects of repetitive soccer heading on postural control	T1: Pre-test T2: Post-test	12 headers in 12 min; distance 12m; speed 11.2 m/s	IT (CoP, 95% area, sway velocity, ApEn)	Higher sway velocity in soccer heading group after heading compared to controls √
Di Virgilio et al., 2016[28]	EG: n=19 healthy amateur soccer players (♂ 14, ♀ 5; mean age 22)	No	Investigate immediate alterations in brain electro-physiological and cognitive function following soccer heading	T1: Pre-test T2: Post-test after 24h T3: Post-test after 48 h T4: Post-test after 14 days	20 headers in 10 min; distance 6 m; speed 38.7 kph (~10.75m/s)	IT (stability index derived from horizontal baseline)	No significant findings for postural control assessments x
Haran et al., 2013[24]	EG: n=8 heading group (6 ♂, 2 ♀; mean age 21) minimum soccer experience of 5 years	CG: n = 8 (6 ♂ 2 ♀; mean age 23)	Investigate the effects of an acute bout of soccer heading on postural control	T1: Pre-test T2: Post-test after 1 h T3: Post-test after 24 h T4: Post-test after 48 h	10 headers in 10 min; distance 10m; speed 11.2 m/s	IT (CoM RMS)	Time series CoM RMS significantly higher in EG at 24 h post heading √
Hwang et al., 2017[25]	EG: n= 10 heading group (8♂,2 ♀; mean age 21) minimum soccer experience of 5 years	CG:n=10 (7 ♂, 3 ♀; mean age 20)	Investigate the effects of sub-concussive impacts on vestibular function and walking stability	T1:24h pre-heading T2: directly post-heading T3: 24h post-heading	10 headers in 10 min; distance 12.2m; speed 11.2 m/s	NIT and IT (mBESS, GVS)	Significant decrease in trunk angle, leg angle gain and CoM gain relative to GVS in heading group; learning effect in CG in mBESS √
Kaminski et al., 2019[23]	EG (all): n=87 intercollegiate women's soccer players (♀; mean age 18.9) EG1 1: n = 28	CG: n = 24 (♀; mean age 19)	Examine differences in BESS following an acute bout of soccer heading in a	T1: Pre-test T2: Post-test	15 headers with 1-minute rest interval in between; distance	NIT (BESS)	No significant findings for postural control assessments

Category I Studies (n = 8)

Author, Year	Population	Control group	Primary purpose	Time of measurement	Heading intervention	Type of tool (variables/ test)	Findings in postural control
	no concussions and heading EG 2: n = 26 1–2 previous concussions and heading EG 3: n=9 3 or more previous concussions and heading		group of female collegiate players with and without history of concussion		9.1–13.7 m; speed 11.2 m/s		x, but effect of concussion history
Mangus et al., 2004[27]	EG: n= 10 Division I university soccer players (8♂, 2 ♀; mean age 21.4)	No	Investigate the effects of a specially designed heading session on postural control	T1: Pre-test T2: Post-test	20 headers in 4 min; distance 25 m; no controlled speed	IT (SOT)	No significant findings for postural control assessments x
Schmitt et al., 2004[26]	EG1: n= 16 college soccer players heading group (8♂, 8 ♀; no information on mean age in the two groups, but aged ~20 and ~ 12 years of soccer experience)	CG:n=15 kicking group (8♂, 7 ♀)	Investigate the effect of an acute bout of heading on postural control	T1: Pre-test T2: directly post-heading T3: 24 h post-heading	18 headers in 40 min; distance 25 m; speed 13.41 m/s	IT; Kinetic (CoP velocity and CoP area)	No significant findings for postural control assessments x, but significantly more concussion symptoms in heading group immediately after heading

Category II Studies (n= 13)

Author, Year	Population	Control group	Primary purpose	Time of measurement	Type of tool (variables/ test)	Findings in postural control
Bazarian et al., 2014[29]	EG: n= 10 Division III collegiate American football players (♂; mean age 20.4)	CG: n = 5 non-athlete controls (♂; mean age 20.6)	Investigate magnitude of WM changes, postural control and clinical relevance	T1: Preseason T2: Postseason T3: after 6 months of no contact	NIT and IT (BESS and Wii Balance Board)	No significant findings for postural control assessments x
Buckley et al., 2018[2]	EG: n = 34 American football NCAA Division I (♂; mean age 20.2)	CG : n= 13 cheerleaders (♂ 2, ♀11; mean age 19.8)	Investigate the effect of RHI on dynamic postural control	T1: Preseason T2: Postseason	NIT (ST and DT TG, gait initiation and termination)	No significant findings for postural control assessments x
Caccese et al., 2019[39]	EG1: n= 15 American football NCAA Division I (♂; mean age 19.5) EG2: n = 23 women's soccer players (♀; mean age 19.7)	No	Determine the relationship between RHI and clinical concussion assessments	T1: Preseason T2: Postseason	NIT (BESS and TG)	Faster time in TG test in preseason compared to postseason test for women's soccer players → Increase in performance √

Category I Studies (n = 8)

Author, Year	Population	Control group	Primary purpose	Time of measurement	Heading intervention	Type of tool (variables/ test)	Findings in postural control
Campolettano et al., 2018[30]	EG: n = 34 youth American football athletes (♂; mean age 9.9)	No	Compare performance on BESS with force plate measures		T1: Preseason T2: Postseason	NIT and IT (BESS, CoP)	No significant findings for postural control assessments x
Dierijck et al., 201 8[31]	EG: n= 135 contact sport athletes (American football, hockey, rugby); n = 48 with only RHI and returning back at postseason (♂; total mean age 19.28)	CG: n= 15 control athletes (♂; mean age 20.2)	Investigate the effects of sub-concussive head impacts on quiet stance postural control		T1: Preseason T2: Postseason	IT (CoP, RMS)	No significant findings for postural control assessments x
Gysland et al., 2012[32]	EG: n = 46 collegiate American football players (♂; mean age 19.65)	No	Investigate the relation- ship between RHI and concussion history on neurological functioning		T1: Preseason T2: Postseason	NIT and IT (SOT, BESS)	No significant findings for postural control assessments x
Jennings et al., 2015[33]	EG: preseason: n = 59; youth American football players (♂; mean age 10.3), postseason: n = 44	CG: preseason: n = 28 Little League baseball players (♂; mean age 10), postseason: n=13	Investigate the effect of sub-concussions over one season of youth American football compared to baseball		T1: Preseason T2: Postseason	NIT (mBESS)	No significant findings for postural control assessments x
Kaminski et al., 20 07[38]	EG: 21 collegiate soccer players (♀; mean age 19.1) EG: 26 high school soccer players (♀; mean age 15.1)	CG: 24 collegiate controls (♀; mean age 21.3)	Investigate relationship between number of headers in one season and performance in postural stability		T1: Preseason T2: Postseason	NIT (modified Romberg test, BESS)	No findings on association between number ofheaders and postural control; adjusted BESS scores at T2 worse than high school soccer players and CG x
Miyashita et al., 2017[34]	EG: n = 34 Division I lacrosse players (♂; mean age 19.59)	No	Investigate the effect of cumulative head impacts on balance in lacrosse players		T1: Preseason T2: Postseason	NIT (BESS)	Number of errors from pre- to postseason increased on a firm and foam surface; explicitly in dual leg stance and tandem stance on foam → Decrease in performance √

Category I Studies (n = 8)							
Author, Year	**Population**	**Control group**	**Primary purpose**	**Time of measurement**	**Heading intervention**	**Type of tool (variables/ test)**	**Findings in postural control**
Miyashita et al., 2018[35]	EG: n = 33 Division I lacrosse players (♂; mean age 19.52)	No	Investigate if RHI overone season lacrosse effects sway velocity	T1: Preseason T2: Postseason		NIT and IT (BESS, sway velocity)	Postseason increase in sway velocity on dual leg stance and tandem stance firm surface and dual leg stance foam surface → Decrease in performance √
Munce et al., 2014[36]	EG:n=10 adolescent American football players (♂; mean age 13.4)	No	Investigate the effects of one season of American football in adolescents on clinical measures		T1: Preseason T2: Postseason	IT (CoP)	No significant findings for postural control assessments x
Munce et al., 2015[37]	EG: n = 22 adolescent American football players (♂; mean age 12.9)	No	Investigate RHI exposure ofyouth American football players and clinical measures		T1: Preseason T2: Postseason	IT (SOT, CoP, 95% ellipse area)	No significant findings for postural control assessments x
Murray et al., 2018[40]	EG: n=14 Division I American football players (♂; mean age 20.4)	CG:n=14 non-contact athletes (3 ♂, 11 ♀; mean age 19.85)	Investigate changes in static postural control in American football		T1: Preseason T2: Postseason	IT (RMS, PEV, SampEn)	No significant findings for postural control assessments x

Abbreviations. *ApEn* approximate entropy, *BESS* Balance Error Scoring System, *CG* control group, *CoM* center of mass, *CoP* center of pressure, *DT* dual task, *EG* experimental group, *GVS* galvanic vestibular stimulation, *IT* instrumented tool, *mBESS* modified Balance Error Scoring System, *NCAA* National Collegiate Athletic Association, *NIT* non-instrumented tool, *PEV* peak excursion velocity, *RHI* repetitive head impacts, *RMS* root mean square, *SampEn* sample entropy, *SOT* Sensory Organization Test, *ST* single task, *T* test time point, *TG* tandem gait, *WM* white matter.

Note. √ indicates statistically significant findings in postural control outcomes; x indicates no statistically significant findings in postural control outcomes.

Table 2

E rating and the final scores of the Quality Assessment for the Systematic Review of Effectiveness and the Sub-concussion

	cese l., 8[21]	Di Virgilio et al., 2016[28]	Haran et al., 2013[24]	Hwang et al., 2017[25]	Kaminski et al., 2019[23]	Mangus et al., 2004[27]	Schmitt et al., 2004[26]	Bazarian et al., 2014[29]	Buckley et al., 2018[2]	Caccese et al., 2019[39]	Campolettano et al., 2018[30]	Dierijck et al., 2018[31]	Gysland et al., 2012[32]	Jennings et al., 2015[33]	Kaminski et al., 2007[38]	Miyashita et al., 2017[34]	Miyashita, et al., 2018[35]	Munce et al., 20 14[36]	Munce et al., 2015[37]	Murray et al., 2018[40]
		3	2	2	2	3	2	3	3	3	3	3	3	3	3	3	3	3	3	3
		C	B	B	B	C	B	B	C	C	C	B	C	C	C	C	C	C	C	C
		A	A	A	A	B	A	A	A	A	B	A	A	B	B	A	A	B	B	A

or Evidence-Based Medicine, *LoE* Level of Evidence, *SST* Sub-concussion Specific Tool *Note*. For the quality rating, the CEBM, Quality Assessment for the Systematic ST have been used.

controlled trials; Level 3: Longitudinal cohort studies or controlled trials without a control group

tematic Review of Effectiveness: A = high quality, B = medium quality; C = low quality; SST: A = high quality, B = low quality.