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Is athletic performance affected following concussion? A systematic review and meta-analysis of literature

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ABSTRACT
Emerging research has studied in-game metrics of athletes after returning from concussion injury in an attempt to determine if performance is compromised. The aim of this meta-analysis was to quantify performance metrics in professional athletes prior to and following recovery from concussion. We conducted systematic literature searches in databases: PubMed, SCOPUS, and SPORTDiscus, between January 1990 to July 2020. Meta-analyses compared, first, pre- versus post-concussion performance within concussed athletes, and second, performance between concussed and non-concussed athletes. After thorough review, seven studies presenting pre-/post-concussion performance were retrieved. The quality of studies analysed were rated as moderate to good. Meta-analyses showed no within-group differences in performance variables in athletes following a concussion. Between group analyses showed significant differences between groups post-concussion for some variables (e.g., scoring, contribution to scoring and blocks); however, pre-concussion comparisons between groups also revealed significant differences. Collectively, our data reports no changes in athlete performance when returning to competition after suffering a concussion injury. While athletic performance appears to be affected in some variables, the retrospective nature and quasi-experimental observational designs of the studies makes interpretation difficult. However, despite study limitations, future research in this area should continue, as concussion in sport is not only a medical concern, but also a concern for high performance staff who are unsure how to work with post-concussed athletes following medical clearance to train and compete.

1. Introduction

Concussion is a growing public health and sport participation issue, particularly in contact sports where it affects individuals from youth to elite level competition (Musumeci, Ravalli, Amorini, & Lazzarino, 2019). Of particular interest is the growing understanding of the long-term changes that result from athletes sustaining repetitive head impacts during their career, including chronic neurological impairments (De Beaumont et al., 2009; Pearce et al., 2014; Pearce, Rist, Fraser, Cohen, & Maller, 2018), movement disorders (Ozolins, Aimers, Parrington, & Pearce, 2016), and neurodegenerative disease (Buckland et al., 2019; Ling et al., 2017; Mez et al., 2017; Pearce et al., 2020). To improve identification and effective return-to-play following concussion (in an attempt to minimise the long-term effects), research currently focuses on quantifying short-term changes and recovery from concussion via various neurological tests.

The neurometabolic alterations following concussion are well described (Giza & Hovda, 2001, 2014). A wide range of molecular alterations, including mitochondrial dysfunction, energy deficit, and gene and protein expression changes, are triggered by concussion and last longer than clinical symptoms (Lazzarino et al., 2019). Therefore, quantifying athlete performance post-concussion has traditionally relied on measuring various aspects of brain function. Time-course changes in saccadic eye movements and eye tracking (Galetta et al., 2016; Nguyen, King, & Pearce, 2019), vestibular and balance performance (Valovich McLeod & Hale, 2015), dual task and gait stability (Caplan et al., 2016), neurosensory processing speed (Pearce, Tommerdahl, & King, 2019; Tommerdahl et al., 2016), and neurocognitive and neurophysiological assessment (Pearce et al., 2015), all show negative effects following concussion and

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with varying rates of recovery. While research in this area has provided insights into brain dysfunction and recovery following a concussion (Giza & Hovda, 2001, 2014), allowing for clinical return-to-play decisions, translation to post-concussion on-field athletic performance remains unknown (Parrington et al., 2019). This information may play an important role in understanding the effects of concussion beyond current clinical testing and may aid in assessing recovery from concussion in applied performance settings.

While the majority of research on athlete outcomes has concentrated on clinical and neuropsychological factors, there is increased interest in post-concussion effects on subsequent injury risk and in-game performance. Some studies report that athletes are at an increased risk of musculoskeletal injury following a concussion (Brooks et al., 2016; Herman et al., 2017; McPherson, Shirley, Schilaty, Larson, & Hewett, 2020; Nordström, Nordström, & Ekstrand, 2014), although this risk has recently been challenged (Shrier, Piché, & Steele, 2019), while the effect on performance is unclear. Despite medical clearance, understanding whether players are at an increased risk of injury or potentially have poorer on-field performance, for example scoring goals, assists, disposal efficiency, becomes an important consideration for coaching and high-performance staff regarding appropriate team selection and performance monitoring practices. Other factors that contribute to a desirable performance, including technical and tactical proficiency, must be considered for coaching staff to make an informed decision on team selection. Whether these factors are influenced by concussion, and if they have the same time course for recovery as medical clearance tests, is not well established in the literature.

A growing number of studies have explored pre- and post-concussion game metrics in an attempt to determine if athlete performance is compromised after a concussion (Hardy, Jordan, Wolf, Johnson, & Brand, 2017; Kuhn, Zuckerman, Totten, & Solomon, 2016; Kumar et al., 2014; Makdissi, McCrory, Ugoni, Darby, & Brukner, 2009; Reams, Hayward, Kutcher, & Burke, 2017; Wasserman, Abar, Shah, Wasserman, & Bazarian, 2015; Yengo-Kahn et al., 2016; Zuckerman et al., 2018). For example, in soccer, Hardy et al. (2017) found a significant reduction in attempts on goal and total attempts on goal per season after concussion. Makdissi et al. (2009) quantified passing the ball (through kicks and handballs) in Australian football players after they had a concussion, showing no change post-concussion. In bat and ball sports such as baseball, Wasserman et al. (2015) has investigated batting performance pre- and post-concussion. To gain a more holistic view of performance related changes following concussion, we completed a systematic review and meta-analysis to determine whether athletes who have been cleared to return to play after their concussion perform worse compared with non-concussed athletes, and whether athletes show performance decrements after concussion compared with their pre-concussion performance. Based on traditional studies investigating neurological deficits post-concussion, and the apparent risk of musculoskeletal injury, we hypothesised that athletes who had sustained a concussion would: 1) demonstrate worse performance post-concussion when compared to their pre-concussion on-field metrics (within-group comparison), and 2) show poorer metrics following concussion when compared with non-injured (control) athletes (between group comparison).

Table 1: Medline search strategy (modified from Manley et al., 2017)

Concussion term	Sport terms	Performance terms
Brain Concussion (MeSH) OR concuss* OR sport* related concuss* OR Brain Injuries (MeSH) OR Brain Injury OR Craniocerebral Trauma (MeSH) OR mtbi OR traumatic brain injur*	Athletes (MeSH[1]) OR Sports (MeSH) OR Baseball (MeSH) OR Boxing (MeSH) OR Bicycling (MeSH) OR Diving (MeSH) OR Football (MeSH) OR Hockey (MeSH) OR Racquet Sports (MeSH) OR Martial Arts (MeSH) OR Mountaineering (MeSH) OR Skating (MeSH) OR Skiing (MeSH) OR Snow Sports (MeSH) OR Soccer (MeSH) OR Wrestling (MeSH) OR athlete* OR player* OR rider* OR cyclist* OR boxer* OR skater* OR skier* OR wrestler* OR sport* OR athletic* OR football OR hockey OR skating OR rugby OR lacrosse OR soccer OR baseball OR boxing OR bmx OR bicycling OR cycling OR biking OR diving OR equestrian OR equine OR racket sport* OR racquet sport* OR tennis OR squash OR racquetball OR martial arts OR judo OR tae kwon do OR mountaineering OR climbing OR skiing OR snowboard* OR ski jump* OR ski racing OR bobsled* OR toboggan* OR wrestling OR contact sport* OR softball OR handball	Athletic Performance (MeSH) OR Return to Sport (MeSH) OR performance or professional athletes

[1]MeSH terms were exploded to include more specific terms; MeSH terms were translated into the appropriate subject headings for other databases. Keywords were the same for each database searched.

2. Methods

2.1. Literature Search Strategy

A standardised search strategy used the following electronic databases: PubMed/MEDLINE, SCOPUS, and SPORTDiscus from 1 January 1990 until 31 March 2020. Medical Subject Headings (MeSH) or keywords and matching synonyms were combined (Table 1 illustrates key words and search strategy) (Manley et al., 2017). References found from previously published literature were also searched.

2.2. Inclusion and Exclusion Criteria

The inclusion and exclusion criteria followed the Population – Indicator – Comparator – Outcome (PICO) principle (Wright, Brand, Dunn, & Spindler, 2007) to identify studies relevant to our research hypothesis. Studies in English of adults (males and females ≥18 years) involved in professional sports in which data collection methods for every player during every competitive match are well established (Zuckerman et al., 2018). Non-human studies and studies involving under-age adults (<18 years) were excluded. Studies of unspecified brain injury or moderate, severe or unspecified traumatic brain injury were excluded. Studies were required to have reported data with a pre-concussion and post-concussion and/or comparison control group. Pre-concussion measurement for within-participants comparison, and between-participants comparator, was required as a comparator for inclusion. Case studies, case reports, non-peer reviewed journal papers, conference abstracts, undergraduate (e.g., honours) or post-graduate (e.g., Masters/PhD) theses, and narrative reviews and descriptive studies without presentation of data were excluded.

Figure 1 outlines the flow of studies removed following the application of each criterion according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher, Liberati, Tetzlaff, & Altman, 2009; Moher et al., 2015). While commonly used to report on randomised trials, PRISMA has been used to systematically review quasi-experimental research (Moher et al., 2009).

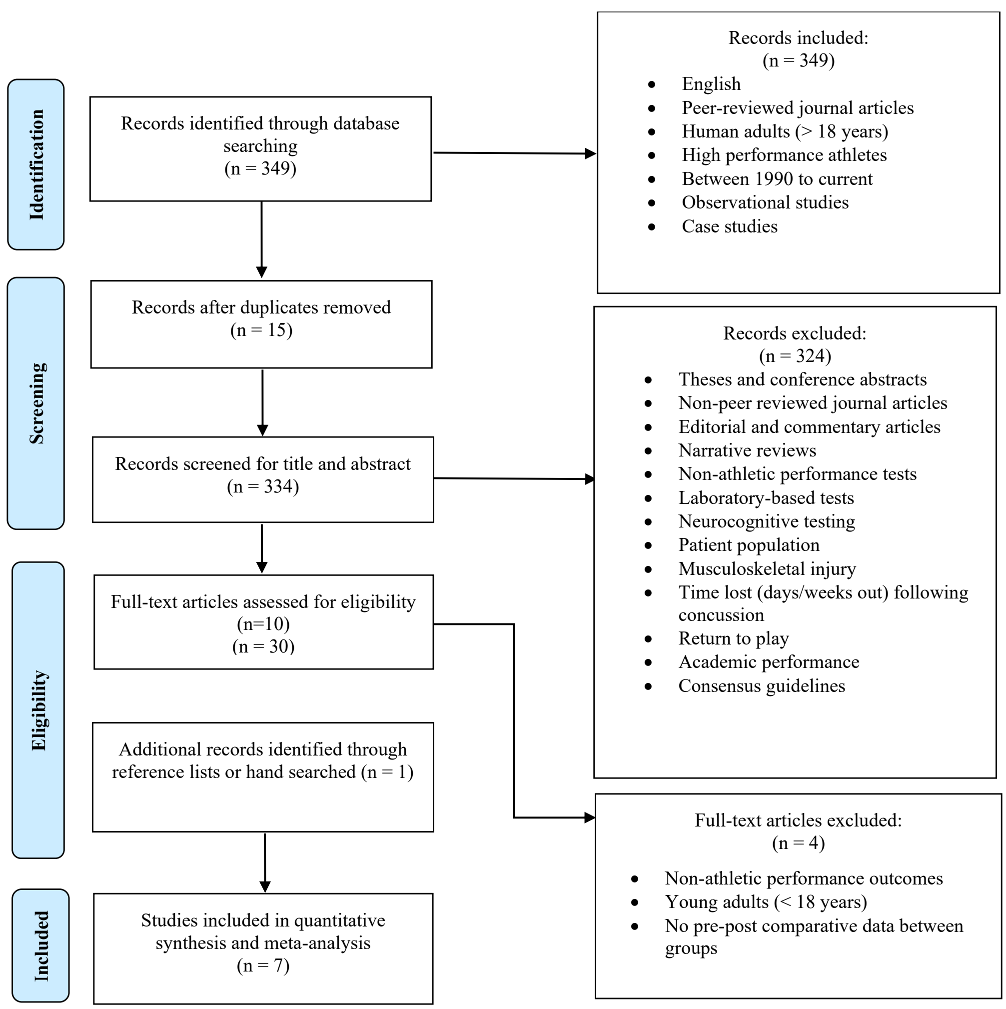


Figure 1: Flow of identification, screening, eligibility and study inclusion of previously published studies using the PRISMA guidelines

2.3. Selection of Studies and Quality Assessment

Two authors (KM and AJP) evaluated the title and abstracts of the articles against inclusion and exclusion criteria. Any titles not relating to the topic were also excluded. Lack of agreement regarding title and abstracts from the first pass of the review were resolved by mutual agreement with the third author (AC). Following duplication, article full texts were then obtained for data extraction. Study quality was assessed by two authors (AJP and KM) using a modified Downs and Black (1998) quality checklist (Pearce et al., 2012), similar to previous systematic reviews (Kidgell, Bonanno, Frazer, Howatson, & Pearce, 2017; Morris et al., 2013; Pearce et al., 2012). The Downs and Black quality checklist is specifically designed to assess the quality of both randomised and non-randomised studies. The revised checklist includes a 20-question checklist and quality is as previously reported (Hooper, Jutai, Strong, & Russell-Minda, 2008) for excellent ≥16; good (13-15); moderate (9-14); and poor ≤8 studies. Lack of agreement about inclusion of articles or grading against study quality was reconciled by mutual agreement with all other authors. Articles that satisfied the inclusion criteria were read and eligible studies were then included in the meta-analysis.

2.4. Data Extraction and Analyses

For all included articles, data extraction involved the retrieval of study characteristics (author, year, sample size, and study design), athlete demographics (age, gender), and the category of sport analysed (team, bat and ball, ice sport). This was completed by one author (AJP) with a sub sample checked by two other authors (AC and KM). Table 2 outlines the metrics extracted that were included in the meta-analysis.

Data (mean and SD) were extracted from tables presented in studies. If studies contained data in a graphical rather than in a tabulated format, Plot Digitizer (Version 2.6) was used to extract the charted data.

2.5. Statistical Analysis

Pre- and post-concussion data were compared within group (concussed athletes only) and between groups (concussed versus control athletes) for each study. As systematic influences and random error were predicted to be present between study level effect sizes, a random effects meta-analysis was performed to compare the overall pooled standardised mean differences (SMDs) for the main outcome measures (Borenstein, Hedges, Higgins, & Rothstein, 2010). SMDs with 95% confidence intervals (CIs) were used to measure concussion effects on performance as the included studies presented outcome measures in a variety of ways. The absolute SMD values of < 0.5 (small), 0.50 - 0.79 (moderate), and ≥ 0.80 (large) were used to describe the magnitude of effects (Cohen, 1988). Heterogeneity was measured using the I^2 statistic, indicating the percentage variance between studies for low (25%), moderate (50%) and high (75%) heterogeneity (Higgins, Thompson, Deeks, & Altman, 2003). All statistical analyses were conducted using RevMan (V5.3, Review Manager, The Cochrane Collaboration) using a significance level of $\alpha = 0.05$.

Table 2: Metric variables, including grouped variables (except blocks, turnovers, or fouls which were presented as individual variables), and operational definition for each metric used.

Metric		Operational Definition
Scoring/contribution to scoring	Goals	Method of scoring for the athlete or team. Includes *home run* (Wasserman et al., 2015) and *touch down* (Kumar et al., 2014; Reams et al., 2017).
	Shots on goal	Scoring chance that does not result in successful outcome.
	Assists	Attributed to teammates who passed the object prior to goal.
Player evaluation measures	Time played	The time (in minutes or seconds) when a player is involved in the match.
	Plus/minus	An athlete's impact on the game, represented by the difference between their team's total scoring versus their opponent's when the player is in the game.
	Player ratings	Arbitrary score, calculated through sport specific characteristics of the individual's performance in each match.
Ungrouped measures	Blocks	Halting or impeding the progress or movement of the object (e.g., ball or puck) by the opposing player.
	Turnovers	Player or team loses possession of the object (e.g., ball or puck) to the opposing team.
	Fouls	Inappropriate or unfair act by a player as deemed by a referee, usually violating the rules of a sport or game.

Table 3: Characteristics of studies meeting inclusion criteria, Downs and Black (1998) score and NHMRC level of evidence.

Author(s)	Country	Sport	Sample size and athlete characteristics	Mean age (± SD)	Key findings	Downs and Black (1998) Score	% of max score
Hardy et al. 2017	USA	MLS	Concussion: 37 males Controls: 73 males	n/a	Players who were diagnosed with concussion showed reduced performance, defined as decreased shots on goal and reduced time played compared to non-concussed controls.	13	65
Kuhn et al. 2016	USA	NHL	Concussion: 94 males Controls: 58 males	25.5 ± 5.0 years 27.5 ± 3.8 years	No difference in performance or time on ice between concussed players who returned to play versus controls.	13	65
Kumar et al. 2014	USA	NFL	Concussion: 59 males Controls: 72 males	25.9 ± 4.2 years 27.2 ± 3.2 years	No difference in performance between concussed players who returned to play versus controls. Playing experience and timing of injury within the course of the season showed strong associations with return to play within 7 d after concussion.	14	70
Reams et al. 2017	USA	NFL	Concussion: 140 males Controls: 57 males	n/a	Concussed players performed at their baseline level of performance suggesting that players had recovered from concussion. However, comparison between groups pre concussion, showed concussed players' performance was worse than controls,	11	55
Wasserman et al. 2015	USA	MLB	Concussion: 66 males Controls: 68 males	n/a	Compared to control athletes, concussed players showed reduced performance measures for batting.	14	70
Yengo-Kahn et al. 2016	USA	NBA	Concussion: 51 males Controls: 51 males	25.6 ± 3.9 years 28.6 ± 3.7 years	No difference between concussed players versus controls. No change in performance in concussed players prior to, versus post concussion injury.	14	70
Buckley et al. 2019	USA	NHL	Concussion: 93 males Controls: 51 males	27.5 ± 5.0 years 27.5 ± 3.8 years	No significant differences between concussed players vs controls across all measures.	14	70

MLS: Major League Soccer; NHL: National Hockey League; NFL: National Football League; MLB: Major League Baseball; NBA: National Basketball League; N/a: mean age/SD age not presented in paper. * Modified form of quality assessment employed to account for observational studies (maximum score 20).

3. Results

3.1. Summary of Included Studies

The initial search yielded 349 records based on title and abstract. Following removal of duplicates (n = 15), the remaining 334 records were screened with 324 removed because they did not meet the inclusion criteria. Ten full-text papers were assessed for eligibility, with four of these being removed for reasons including presenting laboratory-based cognitive outcomes only, non-adult sample, and no pre-post comparative data presented (Figure 1). Further searching of reference lists and hand searching revealed one record meeting the inclusion criteria, making the final total of seven studies.

Included studies are shown in Table 3. Quality assessment scores for studies ranged from 11 to 14 (Downs & Black, 1998). It should be noted that as retrospective observational case-control studies, several criteria were not applicable, such as randomisation of study participants, likely affecting the already modified criteria. All participants included in the data were male.

3.2. Within Group Comparison for Pre- versus Post-concussion

The overall pooled data for *scoring/contribution to scoring* (Figure 2, n = 1008) showed small changes following a concussion (overall SMD = 0.07 [CI: -0.03 - 0.17]; I^2 = 27%; *P* = 0.19). Subgroup analyses showed small effects but non-significant differences for *goals* (SMD = 0.03; *P* = 0.80), *shots on goal* (SMD = 0.11; *P* = 0.17), and *assists* (SMD = 0.09; *P* = 0.43). Heterogeneity ranged from low (0%) for *shots on goal* to moderate (48%) for *assists* and *goals*.

Within group comparison data for *player evaluation* are shown in Figure 3. Overall pooled data (n = 824) showed no significant change (SMD = -0.02 [CI: -0.12 - 0.08]; *P* = 0.68) and low heterogeneity (0%). Subgroup analyses similarly showed no change for *player ratings* (SMD = -0.07; *P* = 0.42), *time played* (SMD = 0.08; *P* = 0.27), or *plus/minus* (SMD = -0.11; *P* = 0.29). Heterogeneity ranged from low (0%) to moderate (19%).

Figure 4(a-c) illustrates the separate variables of *blocks* (n = 145), *turnovers* (n = 145), and *fouls* (n = 238) respectively. No changes were observed for any of the variables and heterogeneity was small (0%).

3.3. Between Groups Comparison for Concussed Players versus Controls

Between group data for *scoring/contributing to scoring* are illustrated in Figure 5 (a and b). Overall pooled data showed a small difference between the concussed (n = 1008) and control (n = 888) groups in both pre (Figure 5a; SMD = -0.15 [CI:-0.26 – -0.05]; *P* = 0.005) and post (Figure 5b; SMD = -0.18 [-0.32 – -0.04]; *P* = 0.01) concussion. Heterogeneity ranged from low (24%) to moderate (55%) for pre- and post-concussion respectively.

Subgroup analyses for *goals* revealed a significant difference between groups pre (SMD = -0.21 [CI: -0.43 – 0.00]; I^2 = 43%; *P* = 0.05) and post (SMD = -0.22 [CI: -0.38 – -0.06]; I^2 = 0%; *P* = 0.008) concussion. No significant differences were observed between the concussed and control groups for pre- or post-concussion SMD for *shots on goals* or *assists* (Figures 5a and b).

Between groups data for *player evaluation* are presented in Figure 6 (a and b). Overall pooled data showed non-significant differences between the concussed (n = 824) and control (n = 636) groups in both pre (Figure 6a; SMD = 0.06 [CI: -0.05 – 0.16]; *P* = 0.28) and post (Figure 6b; SMD = 0.10 [-0.06 – 0.26]; *P* = 0.21) concussion outcomes. Heterogeneity ranged from low (0%) to moderate (55%) for pre- and post-concussion respectively.

Subgroup analyses for *player ratings and plus/minus* revealed no differences between groups pre- or post-concussion. Concussed players were observed to have a greater amount of time played pre-concussion compared to controls (SMD = 0.17; *P* = 0.04). Conversely, comparison on time played between groups was not significantly different post-concussion (SMD = 0.06; *P* = 0.56).

Due to disparity in metrics, *blocks*, *turnovers* and *fouls* are presented as separate variables, comparing the concussed (n = 145) and control groups (n = 109), in Figures 7 – 9.

Blocks (Figure 7a and b) showed small differences between groups in both pre (SMD = 0.39 [CI: 0.13 – 0.64]; I^2 = 0%; *P* = 0.003) and post (SMD = 0.43 [CI: 0.18 – 0.69]; I^2 = 0%; *P* < 0.001) concussion. *Turnovers* (Figure 8a and b) showed no differences between groups for pre (SMD = 0.07 [CI: -0.18 – 0.32]; I^2 = 0%; *P* = 0.58) or post (SMD = 0.23 [CI: -0.02 – 0.48]; I^2 = 0%; *P* = 0.07) concussion. Similarly, *fouls* (Figure 9a and b) showed no differences between groups (concussed n = 238; control n = 160) pre- or post-concussion, with moderate to large heterogeneity (pre: SMD = 0.08 [CI: -0.19 – 0.36]; I^2 = 45%; *P* = 0.56; post: SMD = 0.42 [CI: -0.49 – 1.32]; I^2 = 95%; *P* = 0.37).

4. Discussion

This systematic review and meta-analysis aimed to assess the literature relating to the question of whether athletic performance was affected following a concussion. In the past five years, a number of studies have reported increased musculoskeletal injury risk in athletes following a concussion injury (Brooks et al., 2016; Herman et al., 2017; McPherson et al., 2020; Nordström et al., 2014). Similarly, studies over the same time period have aimed to determine if concussion injury affects an athlete's subsequent on-field performance; yet this aspect of concussion has been less widely discussed, and is the *raison d'etre* for this meta-analysis.

Our study findings, while needing to take into account that data was analysed independent of contextual factors such as playing environment, opposition traits, and phase of season, showed that while within-group comparison of pre and post-concussion metrics did not change, there were differences between groups. Interestingly, between group differences were found in both pre- and post-concussion metrics.

Study or Subgroup	Pre Mean	Pre SD	Pre Total	Post Mean	Post SD	Post Total	Weight	Std. Mean Difference IV, Random, 95% CI
Goals								
Buckley et al	0.08	0.14	93	0.1	0.2	93	8.6%	-0.12 [-0.40, 0.17]
Hardy et al - goals	2.73	4.33	37	1.78	2.92	37	4.3%	0.25 [-0.20, 0.71]
Kuhn et al - goals	0.55	0.88	94	0.71	1.3	94	8.6%	-0.14 [-0.43, 0.14]
Wasserman et al - goals	3.06	3.28	61	1.86	2.84	61	6.3%	0.39 [0.03, 0.75]
Yengo-Kahn et al - goals	10.16	5.1	51	10.84	5.73	51	5.6%	-0.12 [-0.51, 0.26]
Subtotal (95% CI)			**336**			**336**	**33.3%**	**0.03 [-0.19, 0.24]**
Heterogeneity: $Tau^2 = 0.03$; $Chi^2 = 7.68$, df = 4 (P = 0.10); $I^2 = 48\%$								
Test for overall effect: Z = 0.25 (P = 0.80)								
Shots on goals								
Buckley et al	1.33	0.74	93	1.32	0.75	93	8.6%	0.01 [-0.27, 0.30]
Hardy et al - shots on goal	9.46	11.74	37	6.52	8.95	37	4.3%	0.28 [-0.18, 0.74]
Kuhn et al - shots on goal	8.6	5	94	8.5	5.2	94	8.7%	0.02 [-0.27, 0.31]
Wasserman et al - shots on goal	0.71	0.24	61	0.63	0.24	61	6.3%	0.33 [-0.03, 0.69]
Yengo-Kahn et al - shots on goal	5.32	3.01	51	5.19	3.05	51	5.6%	0.04 [-0.35, 0.43]
Subtotal (95% CI)			**336**			**336**	**33.4%**	**0.11 [-0.05, 0.26]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 2.92$, df = 4 (P = 0.57); $I^2 = 0\%$								
Test for overall effect: Z = 1.37 (P = 0.17)								
Assists								
Buckley et al	0.18	0.2	93	0.21	0.21	93	8.6%	-0.15 [-0.43, 0.14]
Hardy et al - assists	1.99	1.55	37	1.48	1.9	37	4.3%	0.29 [-0.17, 0.75]
Kuhn et al - assists	1.4	1.4	94	1.4	1.3	94	8.7%	0.00 [-0.29, 0.29]
Wasserman et al - assists	0.32	0.09	61	0.28	0.09	61	6.3%	0.44 [0.08, 0.80]
Yengo-Kahn et al - assists	2.26	2.34	51	2.35	2.65	51	5.6%	-0.04 [-0.42, 0.35]
Subtotal (95% CI)			**336**			**336**	**33.3%**	**0.09 [-0.13, 0.30]**
Heterogeneity: $Tau^2 = 0.03$; $Chi^2 = 7.67$, df = 4 (P = 0.10); $I^2 = 48\%$								
Test for overall effect: Z = 0.79 (P = 0.43)								
Total (95% CI)			**1008**			**1008**	**100.0%**	**0.07 [-0.03, 0.17]**
Heterogeneity: $Tau^2 = 0.01$; $Chi^2 = 19.11$, df = 14 (P = 0.16); $I^2 = 27\%$								
Test for overall effect: Z = 1.32 (P = 0.19)								
Test for subgroup differences: $Chi^2 = 0.34$, df = 2 (P = 0.84), $I^2 = 0\%$								

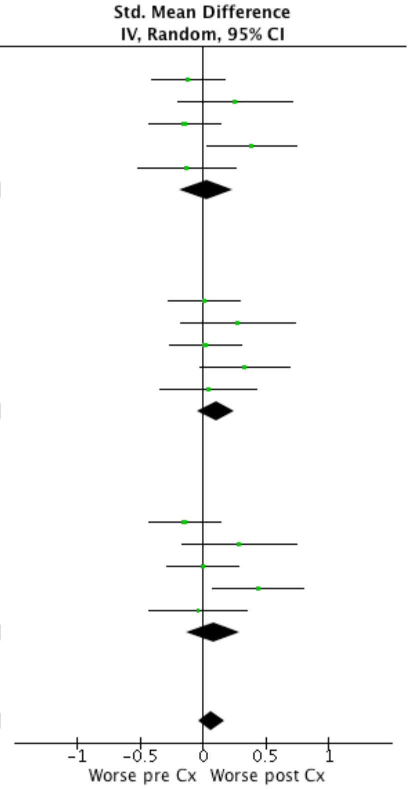


Figure 2: Scoring/contribution to scoring variables for concussed athletes' pre and post injury

Study or Subgroup	Pre Mean	Pre SD	Pre Total	Post Mean	Post SD	Post Total	Weight	Std. Mean Difference IV, Random, 95% CI
Player ratings								
Kumar et al - player ratings	-0.06	2.2	59	0.1	0.09	59	7.2%	-0.10 [-0.46, 0.26]
Reams et al - DYAR	0.26	7.55	140	0.76	4.06	140	17.0%	-0.08 [-0.32, 0.15]
Yengo-Kahn et al - player impact	8.54	4.52	51	8.59	4.87	51	6.2%	-0.01 [-0.40, 0.38]
Subtotal (95% CI)			**250**			**250**	**30.4%**	**-0.07 [-0.25, 0.10]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 0.13$, df = 2 (P = 0.94); $I^2 = 0\%$								
Test for overall effect: Z = 0.81 (P = 0.42)								
Time played								
Buckley et al	13.65	2.87	93	13.55	2.84	93	11.3%	0.03 [-0.25, 0.32]
Hardy et al - time played	1,503	554.04	37	1,203	820.61	37	4.4%	0.42 [-0.04, 0.89]
Kuhn et al - time played	5,193.3	1,321.9	94	5,085	1,260.8	94	11.4%	0.08 [-0.20, 0.37]
Wasserman et al - plate appearances	40.72	14.37	61	38.64	15.67	61	7.4%	0.14 [-0.22, 0.49]
Yengo-Kahn et al - time played	27.02	8.14	51	28.04	7.82	51	6.2%	-0.13 [-0.52, 0.26]
Subtotal (95% CI)			**336**			**336**	**40.8%**	**0.08 [-0.07, 0.24]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 3.42$, df = 4 (P = 0.49); $I^2 = 0\%$								
Test for overall effect: Z = 1.09 (P = 0.27)								
Plus/minus								
Buckley et al	0.09	1.98	93	0.3	2.14	93	11.3%	-0.10 [-0.39, 0.19]
Kuhn et al - plus/minus	-0.07	2.6	94	0.57	2.3	94	11.3%	-0.26 [-0.55, 0.03]
Yengo-Kahn et al - plus/minus	-0.01	4.77	51	-0.68	5.73	51	6.2%	0.13 [-0.26, 0.51]
Subtotal (95% CI)			**238**			**238**	**28.8%**	**-0.11 [-0.31, 0.09]**
Heterogeneity: $Tau^2 = 0.01$; $Chi^2 = 2.46$, df = 2 (P = 0.29); $I^2 = 19\%$								
Test for overall effect: Z = 1.06 (P = 0.29)								
Total (95% CI)			**824**			**824**	**100.0%**	**-0.02 [-0.12, 0.08]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 9.25$, df = 10 (P = 0.51); $I^2 = 0\%$								
Test for overall effect: Z = 0.42 (P = 0.68)								
Test for subgroup differences: $Chi^2 = 2.91$, df = 2 (P = 0.23), $I^2 = 31.2\%$								

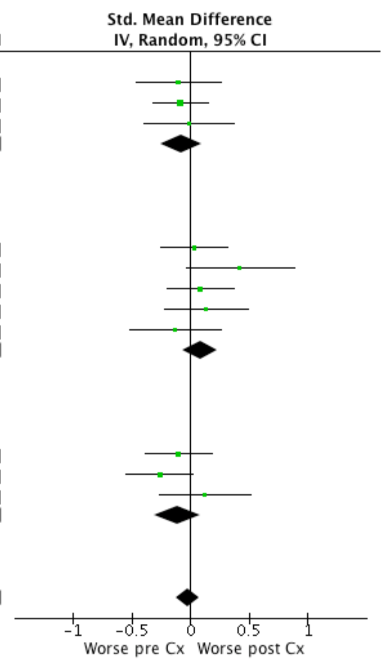
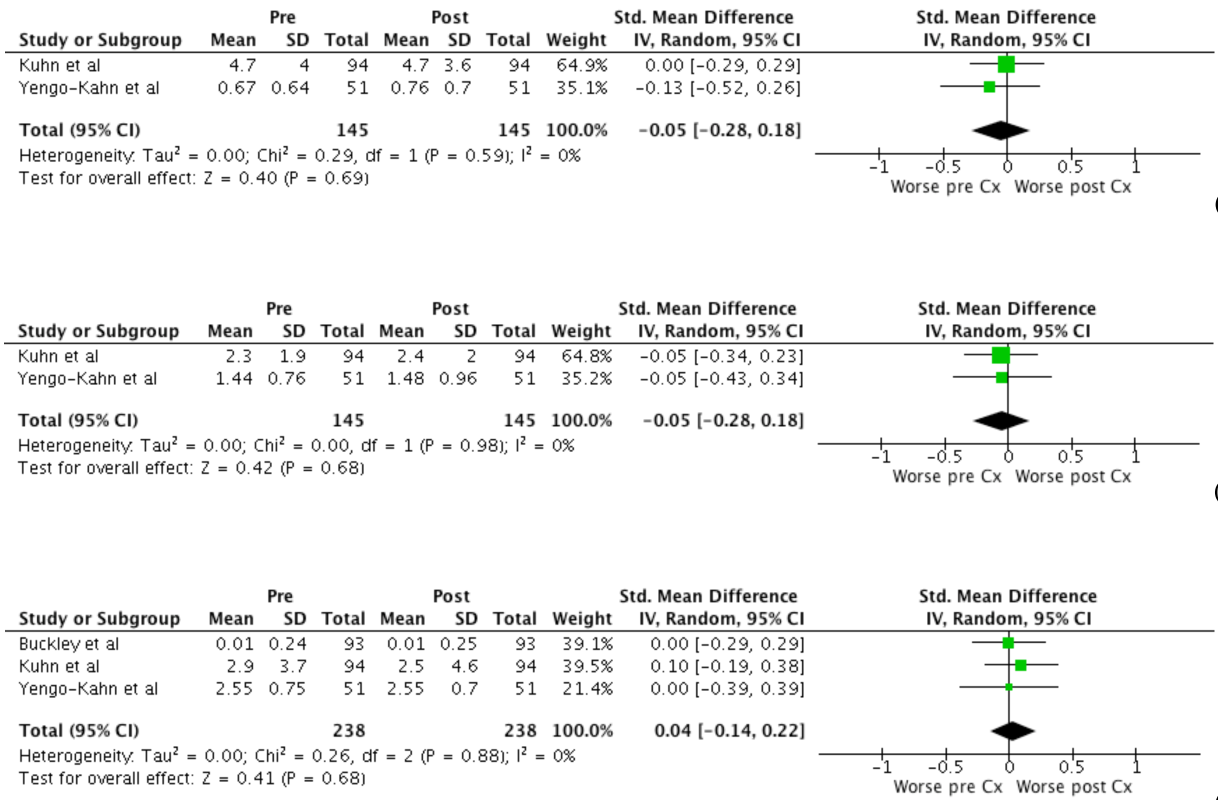
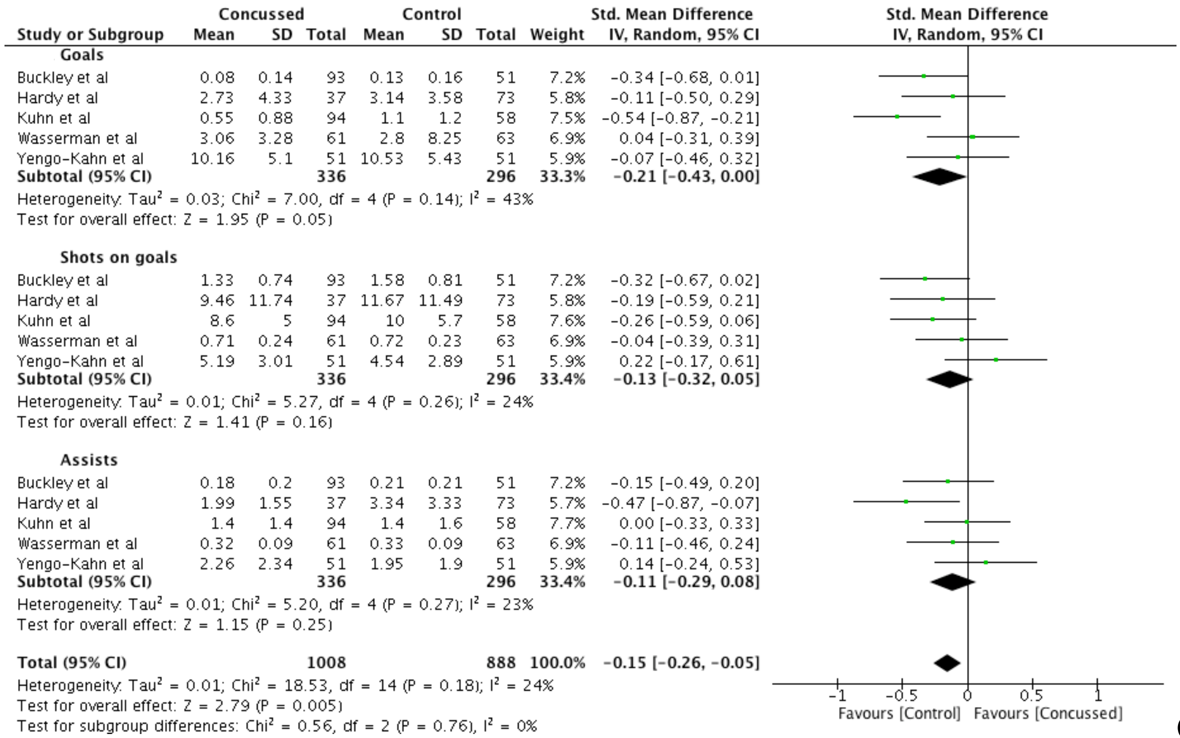


Figure 3: Player evaluation measures for concussed athletes pre and post injury

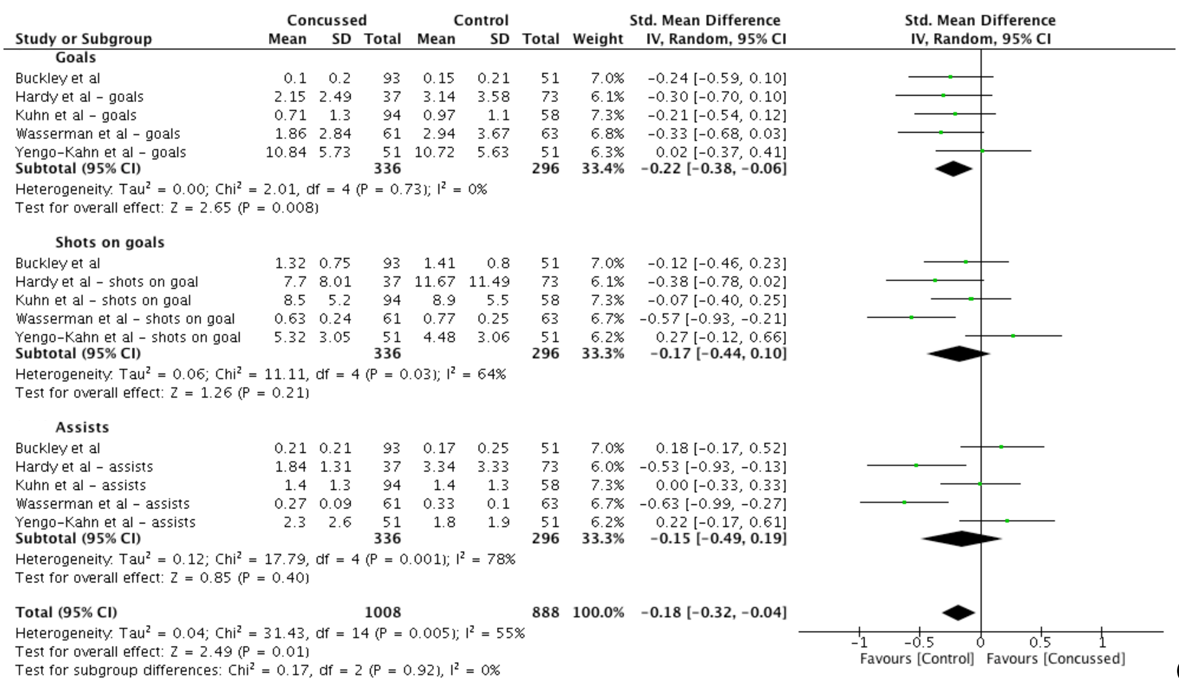


(a) (b) (c)

Figure 4a-c: Within-group comparison for concussed athletes' pre and post injury for blocks (a), turnover (b), fouls (c)



(a)



(b)

Figure 5: Scoring/contribution to scoring variables for between groups pre (a) and post (b) concussion

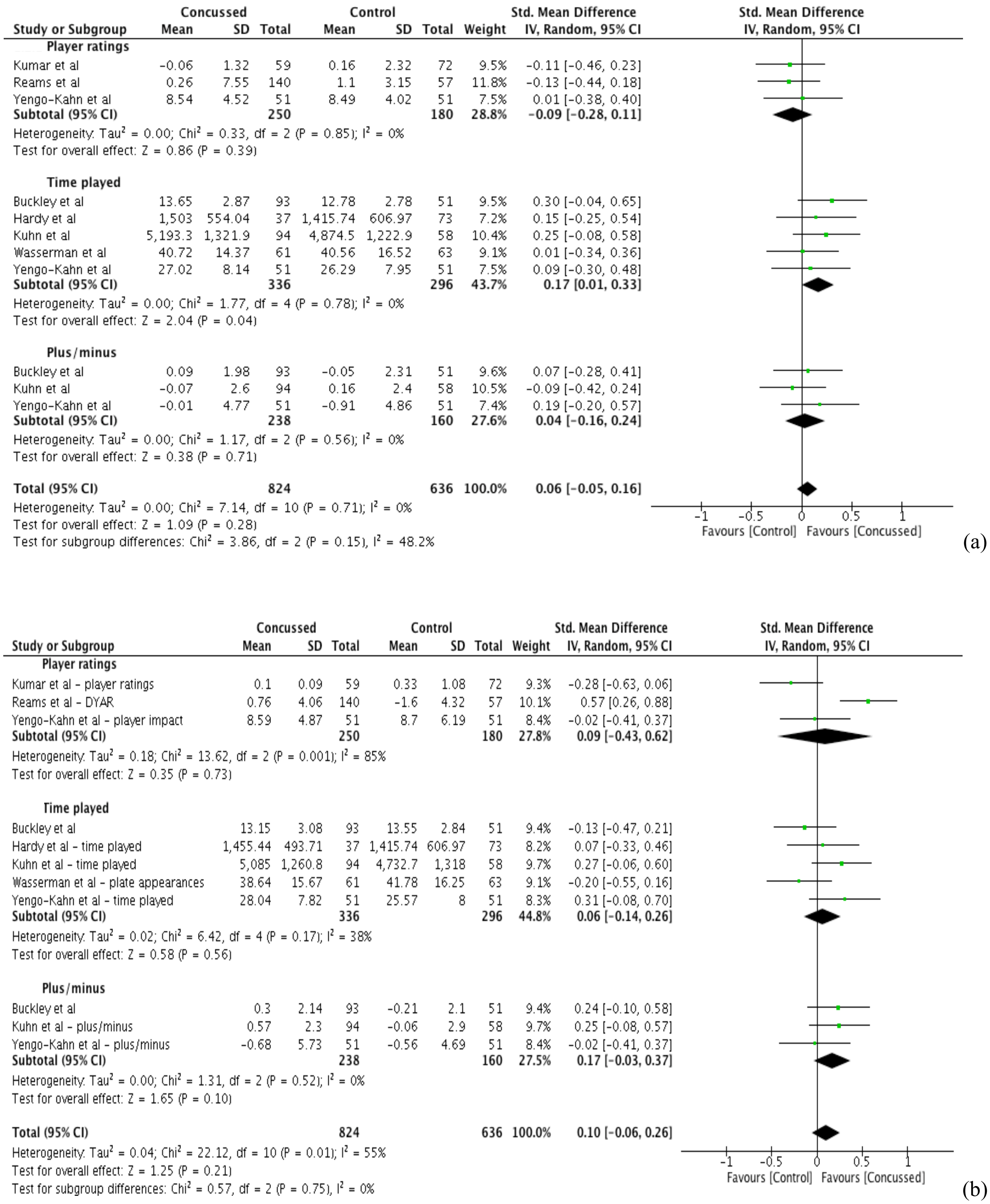


Figure 6: Player evaluation measures between groups pre (a) and post (b) concussion

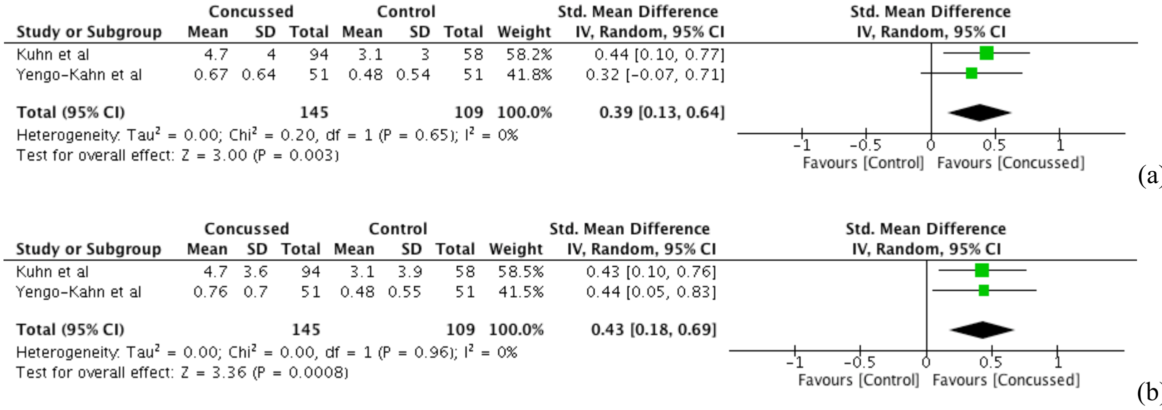


Figure 7: Blocks against player. Pre (a), post (b)

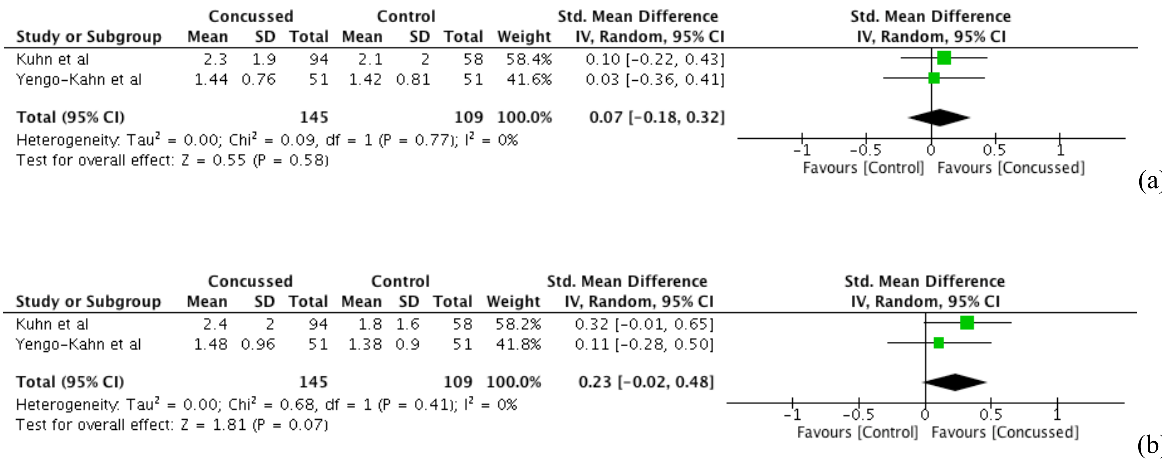


Figure 8: Turnovers against player. Pre (a), post (b)

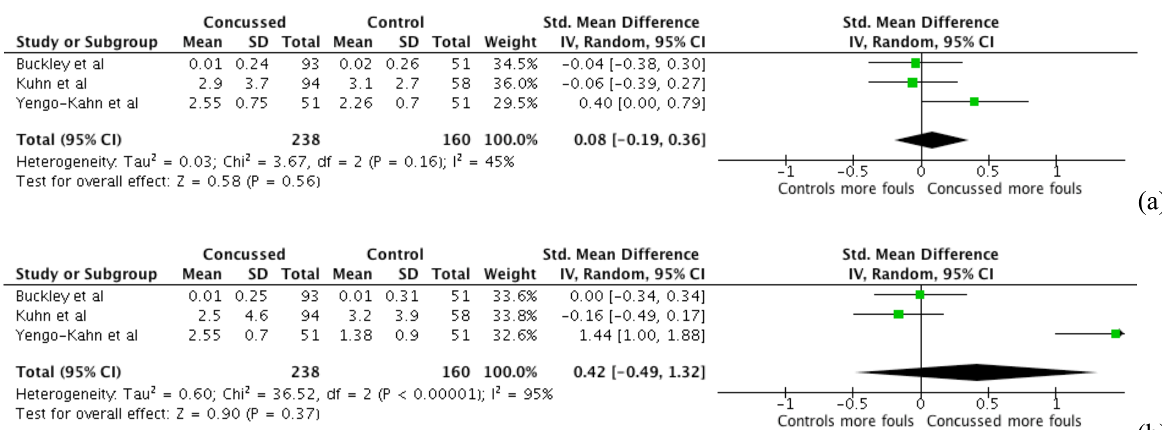


Figure 9: Fouls against player. Pre (a), post (b)

4.1. Within-groups Analysis

Analysis of within-player pre- versus post-concussion (Figures 2 – 4) showed no change in athlete performance, thereby not supporting our first hypothesis. The studies analysed presented common box score statistics specific to their sport, where there are typically more offence-related statistics compared with defense-related statistics, while only three studies reported an overall player rating metric (Kumar et al., 2014; Yengo-Kahn et al., 2016; Zuckerman et al., 2018). These findings collectively indicate that returning to competition following concussion does not have an impact on specific player statistics. However, inclusion of a wider spread of metrics that include both offensive and defensive box score statistics, in addition to an overall player rating metric, would be beneficial to gaining a greater insight into how concussion may or may not affect subsequent in-game performance. Additionally, there is the potential that upon return to play athletes may play reduced game time compared to their pre-injury state. For this reason, applying a time-normalised approach similar to Buckley et al. (2019), while also reporting over various time windows (e.g., +5 games, +10 games, full season), may assist with more meaningful comparisons pre-post concussion and within and between players and sports. It should also be noted that the included studies are relatively recent. Significant increases in concussion awareness, as well as changes in policies and improvement in concussion management procedures in recent years (Gunasekaran, Hodge, Pearce, King, & Fraser, 2019; McCrory et al., 2017) subsequently affect the return to play protocols for athletes and may explain why athlete performance was not compromised as was hypothesised. Indeed, a recent editorial has argued that risk of further concussion is not increased if athletes are managed effectively (Shrier et al., 2019). However, given that studies suggest an increased risk in musculoskeletal injuries following concussion (Brooks et al., 2016; Herman et al., 2017; McPherson et al., 2020; Nordström et al., 2014), future research that include not only sport-specific performance metrics, but also physical metrics (e.g., sprint speed, total distance covered, movement coordination etc.) are required to confirm if athletes who recover from a concussion have reduced in-game performance and physical activity demands capacities.

4.2. Between-groups Comparison

Our second hypothesis for between-group analyses was partly supported with data showing significant differences in *some* variables (e.g., *scoring/ contribution to scoring* and *blocks*) post-concussion. However, an unexpected finding was the significant differences found in pre-concussion data where the concussed group were worse than the control group for goals scored, time played, and blocks against that player. We are unable to explain why differences were found in performance *prior* to a concussion diagnosis, given that all but one study did not show pre-injury differences between groups. Reams et al. (2017), whose study did detect pre-concussion differences between groups, posited that differences in athletic performance before concussion may reflect undetected issues, such as fatigue, or non-disclosure of a concussion from the players themselves before diagnostic confirmation from the team doctor (Brown, Elsass, Miller, Reed, & Reneker, 2015; Pearce, Young, Parrington, & Aimers, 2017). However, it is more likely that our finding of significant differences between groups prior to concussion injury reflects increased sample size power. Further, differences would also reflect limitations of quasi-experimental and observational research design, particularly in applied settings such as in-competition match play. While true experimental pretest-posttest randomised-control designs would be advantageous, these research designs in professional sport are not logically feasible or indeed ethical. Therefore, despite this limitation, it is important to not diminish their contribution to our understanding of concussion in sport. Moreover, the included studies in this systematic review were of moderate-to-good quality. Consequently, we assert that despite limitations in pre-concussion data showing differences between groups, the data reported has value to applied sports science practice.

Further limitations of this study include disparities between team sports differing in characteristics. For example, baseball analyses focused on pitcher versus batter compared to invasion team sports where all players are involved in game play (Yengo-Kahn et al., 2016). Also, this systematic review and meta-analysis only provided data in males, and previous research has shown women have a higher incidence of concussion and a longer recovery time (Agel & Harvey, 2010; Colvin et al., 2009; Howell, Stracciolini, Geminiani, & Meehan III, 2017). Therefore, research that observes any performance changes in female team sport athletes is also required and may differ in presentation of symptoms and outcomes to male athletes. Finally, limitations of these team sports studies confined at the elite level suggest caution in generalising these findings to athletic performance across all sports, including individual sports (specifically combative sports such as martial arts and boxing), and to non-elite levels of participation. Variation in performance metrics can also be considerable from game to game, due to external contextual factors such as opposition strength, travel, time in season, and game outcome (Kempton, Sullivan, Bilsborough, Cordy, & Coutts, 2015; Liu, Gómez, Gonçalves, & Sampaio, 2016). This variation can also make the observation of any concussion-related changes in performance metrics more difficult to observe and should be considered within future work in this area.

5. Conclusion

Understanding the effects of concussion on athletic performance should be as important as understanding the medical effects. While previous research has focused on clinical outcomes that can affect athletes, such as neurological functions, cognition, motor control (e.g., balance), behaviour (e.g., irritability) and sleep/wake disturbances (McCrory et al., 2017) this is the first review to investigate athletic performance. Despite anecdotal concerns from high performance staff members and published studies suggesting concussion-affected performance (Hardy et al., 2017; Wasserman et al., 2015), the pooled data in our meta-analysis does not indicate that concussion affects the on-field performance of elite team sport athletes following return to play. While study methods were determined to be moderate to good in quality (Downs & Black, 1998) the limitation of retrospective designs and disparity in metrics are likely to have contributed to our findings. Prospective studies that report consistent time-normalised metrics, and are conducted in a greater spread of sports and across both sexes will improve the identification of any subtle changes in athletic performance following concussion. For sports science and high performance staff who are accountable for the preparation athlete optimal performance, any effect of concussion on performance will be of importance in athlete preparation and team success, given a small percentage change in performance may be the difference between winning and losing.

Conflict of Interest

The authors declare no conflict of interests.

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