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Review

Resting State Electroencephalography and Sports-Related Concussion: A Systematic Review

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Abstract

Sports-related concussion is associated with a range of short-term functional deficits that are commonly thought to recover within a two-week post-injury period for most, but certainly not all, persons. Resting state electroencephalography (rs-EEG) may prove to be an affordable, accessible, and sensitive method of assessing severity of brain injury and rate of recovery after a concussion. This article presents a systematic review of rs-EEG in sports-related concussion. A systematic review of articles published in the English language, up to June 2017, was retrieved via PsychINFO, Medline, Medline In Process, Embase, SportDiscus, CINAHL, and Cochrane Library, Reviews, and Trials. The following key words were used for database searches: electroencephalography, quantitative electroencephalography, qEEG, cranio-cerebral trauma, mild traumatic brain injury, mTBI, traumatic brain injury, brain concussion, concussion, brain damage, sport, athletic, and athlete. Observational, cohort, correlational, cross-sectional, and longitudinal studies were all included in the current review. Sixteen articles met inclusion criteria, which included data on 504 athletes and 367 controls. All 16 articles reported some abnormality in rs-EEG activity after a concussion; however, the cortical rhythms that were affected varied. Despite substantial methodological and analytical differences across the 16 studies, the current review suggests that rs-EEG may provide a reliable technique to identify persistent functional changes in athletes after a concussion. Because of the varied approaches, however, considerable work is needed to establish a systematic methodology to assess its efficacy as a marker of return-to-play.

Keywords: biomarker; coherence; oscillations; qEEG; return-to-play; sports-related concussion

Introduction

Electroencephalography (EEG) can be used to characterize large-scale spatial-temporal neurophysiological disturbances[1] that are associated with sports-related concussion. EEG measures electrical activity of the brain conducted from neurons and glia in the cerebral cortex. The principal generators of EEG fields are graded excitatory and inhibitory synaptic potentials of pyramidal neurons.[2] The EEG measures extracellular current flow, and it is sensitive to activity from cortical pyramidal neurons characterized by long, vertically directed apical dendrites.[2] Its measurement requires synchronous activity across a large population of regularly arranged pyramidal cells and reflects the spatial-temporal summation of excitatory and inhibitory synaptic activity arising from ensembles of cortical pyramidal cells.[1,2] Given their morphology and arrangement, however, glial cells also contribute to the EEG signal.[1,3] Glial cell involvement may be relevant based on recent animal modeling of mild traumatic brain injury (mTBI) that describe changes in functioning after injury.[4–7] As such, resting state EEG (rs-EEG) might be sensitive to microstructural, metabolic, and neurochemical changes after concussion that cause functional disruptions to cellular systems and networks.

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Historical studies have provided some evidence for EEG slowing as well as a breakdown of the expected EEG architecture in boxers[8–13] and some professional soccer players.[14,15] The evolution of quantitative or "digital EEG" was accompanied by more sophisticated mathematical algorithms, and researchers have reported elevated delta (0.5–4 Hz) and theta (4–8 Hz) activity after a single sports-related concussion.[16,17] The work of some researchers has extended well beyond the measurement of EEG amplitude variations to include studies of hemispheric asymmetries, coherence, peak frequency variation, and nonlinear indices of complexity.[16,18,19]

This systematic review focuses on rs-EEG studies of sports-related concussion. Rs-EEG can quantify the amplitude and distribution of oscillatory activity in well-defined frequency bands.[16,17] Recently, novel mathematical approaches to quantifying neural dynamics and complexity have been applied to the study of concussion.[19] Rs-EEG may prove to be a low-cost, time-efficient, portable, and direct measure of large-scale neurophysiology within the cortex, and thus has considerable potential as a biomarker of concussion-induced change in brain functioning.

Methods

The review was conducted in three stages (see Preferred Reporting Items for Systematic Reviews and Meta- Analyses [PRISMA] table, Fig. 1). In stage 1, we used a very liberal search strategy to capture all possibly relevant articles. Articles were retrieved from on-line databases, manual searches of reference lists, and cited reference searches. Online databases included PsychINFO, Medline, Medline In Process, Embase, SportDiscus, CINAHL, and Cochrane Library, Reviews, and Trials. The following key words were used for database searches: electroencephalography, quantitative electroencephalography, qEEG, cranio-cerebral trauma, mild traumatic brain injury, mTBI, traumatic brain injury, brain concussion, concussion, brain damage, sport, athletic, and athlete. Searches were limited to English-language articles published in peer-reviewed journals up to June 2017. Additional manual searches were conducted in Web of Science and Google Scholar to identify any remaining articles missed by the initial database search. This initial search was narrowed using the key words electroencephalography or EEG; concussion or sports-related concussion; sport; and athletic or athlete. This was undertaken by two reviewers (ACC and PSC) to capture the most relevant articles for further evaluation.

In stage 2, titles and abstracts of the subset were reviewed to assess eligibility for inclusion. Articles were reviewed independently by three authors (ACC, FK, and AJG) to examine whether they were specific to athletes, concussion, and EEG. There was no restriction based on timing of assessment (e.g., acute, post-acute) and use of other outcome measures (e.g., task-based EEG, conventional magnetic resonance imaging, computed tomography, symptom checklists, balance testing, inclusion of a control group or neuropsychological testing). Where there was disagreement between the reviewers about whether a study should be included based on the review of the title and abstract, the full article was reviewed.

In stage 3, the full-text version of the articles retained from stage 2 were independently assessed for quality by two authors (ACC and PSC). First, articles were assessed on their EEG methodology to

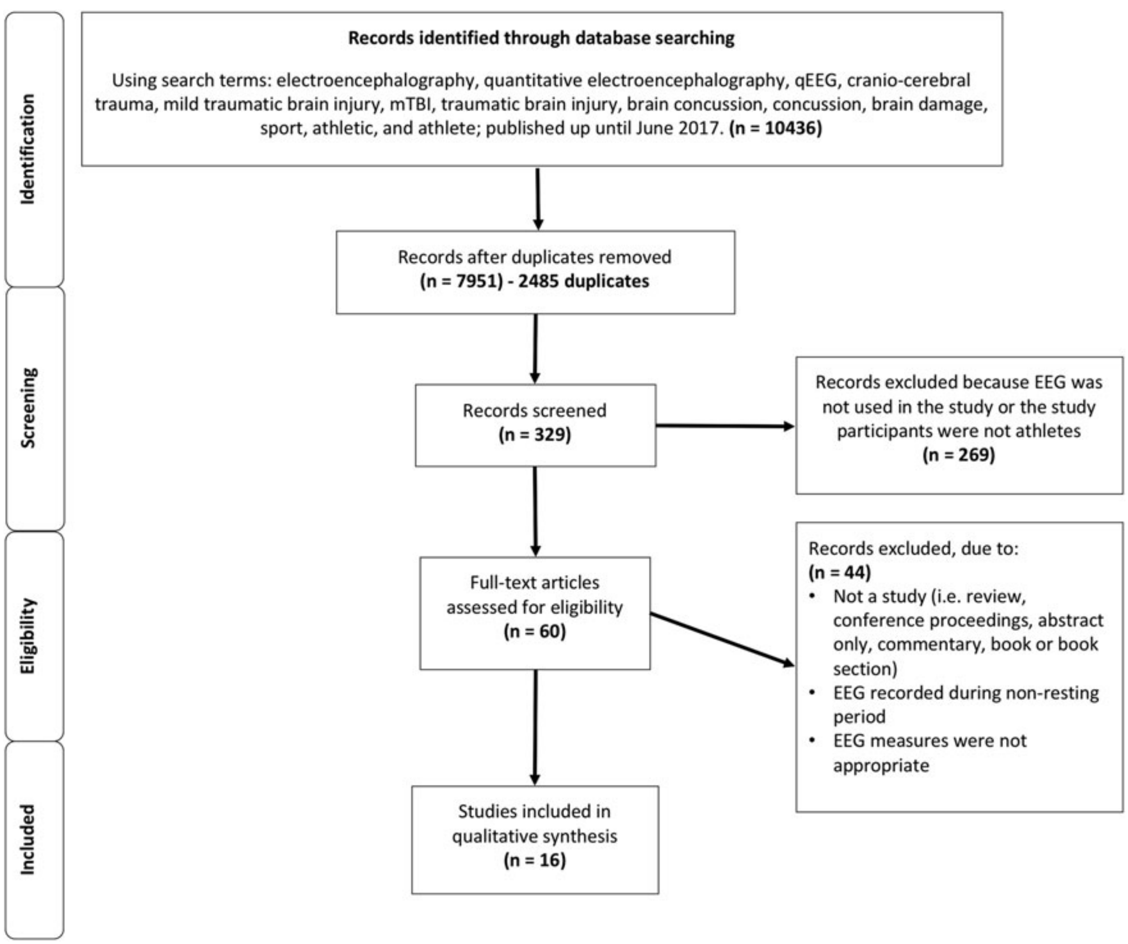

FIG. 1. Preferred Reporting Items for Systematic Reviews and Meta- Analyses table.

ensure rs-EEG was recorded. As shown in Figure 1, a number of the articles were removed before the qualitative synthesis. The final set of articles was assessed using a standardised quality assessment checklist[20] that included criteria for both study relevance and validity. This includes 10 validity criteria that address clarity of research question and aims, participant and control selection criteria, prevention or acknowledgment of potential biases, exposure and intervening factors, appropriateness of statistical analyses, and whether conclusions are supported by results (see Table 1 for details).

Each of the 10 criteria received a yes, no, or unclear rating, and these were collated into a positive, neutral, or negative overall score for the study, using criteria by Gardner and colleagues.[21] A positive score indicated that the study included appropriate selection of participants and matched controls, well-described intervention(s), and reliable and valid measures. A negative score indicated that at least six of the 10 criteria were not met. A neutral score indicated that the study did not fully meet all of the positive or all of the negative criteria. Each reviewer gave an independent assessment and, where there was discrepancy in total score, consensus was attained by deliberation.

Data extraction

One reviewer (PSC) extracted data from the final set of 16 studies, including (1) participant demographics (athletes and control participants), (2) characteristics of participants (sport, exposure to concussion, concussive history), (3) EEG recording conditions (technique and data extraction), (3) time lapsed (acute versus delayed assessment); (4) study findings, and (5) study comments (see Tables 2 and 3).

Results

Stage 1 resulted in the identification of 10,436 entries THAT represented 7951 articles after removal of duplicates (Fig. 1). Title and abstract screening reduced the number to 329 for eligibility review. In stage 2, articles were excluded if they did not fit the concussion (25) or EEG (244) criteria. Of the remaining 60 articles, 28 were excluded because they did not record rs-EEG and 16 because they were not full-text articles (i.e., conference presentation, abstract only, commentary), resulting in a final set of 16 articles for this review.

As shown in Table 1, 12 studies received a positive quality rating against the pre-specified standardized criteria.[20] Two studies[22,23] received a negative quality rating because they were given negative or neutral ratings on six or more criteria. Another two studies received a neutral quality rating.[24,25] In all 16 studies, participants who met the inclusion criteria were included, and specific exclusion criteria were not identified.

Sample characteristics are listed in Table 2. The 16 studies included a total of 504 concussed athletes. Thirteen studies included nonconcussed healthy athletes as controls ($n = 367$), and 10 of these articles identified the controls as participating either in the same sport or in a noncontact sport, such as swimming or cycling.[17–19,22,24,26–30] Three studies either used controls who did not play sports, or they did not report the type of sport played.[15,23,25] The final three studies did not include controls.[16,31,32] Ten of the studies compared concussed athletes with controls, without a pre-concussion baseline.[15,17,18,22,23,25,28–30,33] Four of the studies compared baseline and post-concussion recordings with controls.[19,26,27,32] The last two studies only assessed recordings from athletes after concussion.[16,31]

Nine studies examined athletes after a single Grade 1 mTBI,[34] or after the designation of a concussion by a physician or certified athletic trainer, but did not look at athletes who had multiple concussions.[16,18,19,22,24–27,31] Four studies examined athletes who had multiple concussions.[17,28,29,32] Two studies examined athletes after concussions of differing severity.[25,30] The final study assessed former professional and semi-professional athletes, against non-athletes, but did not include athletes with a history of concussion.[23] Seven studies included only males.[16,18,23,28–31] Another five either did not disclose sex information or did not specify the demographic information of the subset of participants drawn from a larger sample.[15,19,22,24,32] Of the four studies that included participants of both sexes, one study[17] included a 2:1 ratio of males to females. In total, across all studies, sex was reported for only 560 participants and, of these, only 11% were female. Hence, sex differences were not evaluated.

Athletes participated in a number of contact sports including American and Canadian football, soccer, field and ice hockey, rugby, and lacrosse (see Table 2). Half of the studies were cross-sectional, whereas the other half included repeated measurements. Six studies examined the effects of concussion within eight days, and all but one of these also included repeated measurements at varying intervals.[16,24,25,27,31,32] Two studies did not identify the delay between injury and EEG recordings.[15,22] All but one study[17] reported concussion characteristics (e.g., concussion severity, concussion history, or post-concussion symptoms) at the group level.

EEG results

EEG recording characteristics (system, number of channels used), data acquisition parameters (e.g., sampling frequency, length of recording session), and post-processing procedures varied considerably across studies (see Tables 2 [characteristics] and 3 [methods and results]), and this may have contributed to the heterogeneity of results. The main findings are also reported in Table 3. Below, we summarize briefly the EEG findings by analysis method. The largest number of studies used power-based analysis, which examined the differences in magnitudes of different EEG frequencies between controls and injured athletes.[17,18,22,23,25,28,29] Another three studies examined the differences in connectivity patterns between the two groups.[25,27,30] One study examined the differences in waveform features from continuous recordings.[15] The other studies used a number of nonstandard processing techniques to assess EEG changes after a concussion. These measures include a machine-learning algorithm to classify abnormalities,[26] entropy-based transformations of the EEG,[19,32] and composite scores derived from a number of different EEG features.[16,24,31]

Power-based analyses

The EEG signal can be decomposed into oscillatory activity in different frequency bands (i.e., delta = 0.5–4 Hz; theta = 4–8 Hz; alpha = 8–13 Hz; beta = 13–30 Hz; gamma = 30+ Hz) that are associated with distinct arousal and/or cognitive states. Power-based analyses characterize the strength or magnitude of activity within each EEG frequency band.[35,36] Changes in EEG power have been linked to deficits in cognitive functioning in a number of pathologies.[37] Seven studies examined differences in EEG power between concussed athletes and controls for distinct frequencies and spatial regions; however, none of these studies compared the same athletes before and after concussion.[17,18,22,23,25,28,29] Two of these studies compared EEG power across different postural conditions during rest.[18,25] Another two examined EEG before, during, and after a hyperventilation challenge, during which participants briefly performed intense activity to induce a hyperventilated state.[22,23]

Thompson and associates[18] reported that, compared with controls, concussed athletes had significantly reduced power across

Table 1. Quality Assessment

Study	*1.Research question clearly stated?*	*2. Selection of study participants free from bias?*	*3. Study groups comparable?*	*4. Method of handling withdrawals described?*	*5. Blinding used to prevent introduction of bias?*	*6. Procedures and intervening factors described?*	*7. Outcomes clearly defined; measurements valid and reliable?*	*8. Statistical analysis appropriate?*	*9. Conclusions supported by results; biases and limitations considered?*	*10. Is bias due to study's funding or sponsorship unlikely?*	*Overall quality rating*
Barr 2012	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Unclear	P
Cao 2010	Yes	Yes	Unclear	No	Unclear	Yes	Yes	Yes	Yes	Yes	P
Cao 2011	Yes	Yes	Yes	No	Unclear	Yes	Yes	Yes	Yes	Yes	P
Cao 2008	Yes	Yes	Yes	No	Unclear	Yes	Yes	Yes	Yes	Yes	P
Gay 2015	Yes	Yes	Yes	No	Unclear	No	No	No	No	Unclear	N
Gosselin 2009	Yes	Yes	Yes	No	Unclear	Yes	Yes	Yes	Yes	Yes	P
McCrea 2010	Yes	Yes	Yes	Yes	No	Yes	Unclear	Yes	Yes	Unclear	O
Moore 2016	Yes	Yes	Yes	No	Unclear	Yes	Yes	Yes	Yes	Yes	P
Munia 2016	Yes	Yes	Yes	No	Unclear	Yes	Yes	Yes	Yes	Yes	P
Prichep 2013	Yes	Yes	Yes	No	Unclear	Yes	Yes	Yes	Yes	Unclear	P
Radic 2015	Yes	Yes	Unclear	No	Unclear	Unclear	No	No	No	Unclear	N
Slobounov 2009	Yes	Yes	Yes	No	Unclear	Yes	Yes	Yes	Yes	Yes	P
Teel 2014	Yes	Yes	Unclear	No	Unclear	Yes	Unclear	Yes	Yes	Yes	O
Thompson 2005	Yes	Yes	Yes	No	Unclear	Yes	Unclear	Yes	Yes	Yes	P
Tysvaer 1989	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Unclear	P
Virji-Babul 2014	Yes	Yes	Yes	No	Unclear	Yes	Yes	Unclear	Yes	Yes	P

P, positive; N, negative; O, neutral; EEG, electroencephalography; mTBI, mild traumatic brain injury.

Table 2. Study Characteristics

Refs author (Yr)	*N CA:NC M:F*	*Age mean SD range (yrs)*	*Delay (days) mean SD range*	*Concussion severity rating scale*	*Diagnosis of concussion*	*Concussion symptoms*	*Concussion history*	*Level of play*	*Sports involved*
Barr et al. (2012)	59:31 90:0	NR	8 1 45	CSI, SAC, BESS ANAM, LOC, PTA, RGA	Occurrence during sport, presence of altered mental state + one or more American Academy of Neurology (AAN) symptoms	Described in the article	NR	High school or collegiate	Football
Cao et al. (2008)	30:31 27:34	20 NR 18–25	30 NR	CARS	Suffered Grade 1 MTBI within six months after baseline testing	Clinically asymptomatic at time of testing	No prior concussions	Collegiate	Rugby and football
Cao & Slobounov (2010)	29:131 84:76	21 NR 18–25	7 NR	CARS	NR	Clinically symptomatic at the time of testing	No prior concussions	Collegiate	Rugby, football, and ice hockey
Cao & Slobounov (2011)	30:30 NR	21 NR 18–25	30 3 NR	Cantu Grade 1 mTBI, LOC	On field by certified athletic trainers based on clinical symptoms such as complaints of loss of concentration, dizziness, fatigue, headache, irritability, visual disturbances, and light sensitivity	Clinically asymptomatic at time of testing	Nil	Collegiate	Rugby, football, soccer, and ice hockey
Gay et al. (2015)	9:9 NR	NR	NR	NR	Diagnosed by certified athletic trainer of physician	Clinically asymptomatic at time of testing	NR	Amateur	NR
Gosselin et al. (2009)	10:11 14:7	23.5 4.2 NR	3.78 months NR 1–11 months	GCS between 13–15; LOC, PTA, PCS Scale	Team physicians based on presence of one or more of the following: confusion or disorientation, LOC for 30 mins or less, PTA for less than 24 h, and/or other transient neurological abnormalities such as focal signs, seizure, and intracranial lesions	Clinically asymptomatic at time of testing	2 or more	Professional (3), university/ semi-professional (7)	Hockey, football, rugby, soccer, and skate
McCrea et al. (2010)	28:28 56:0	NR	1 5 45	LOC, PTA, RGA, CSI, SAC, BESS, ANAM	Observed mechanism of injury, symptoms reported or exhibited by player reports by medical staff or witnesses regarding player condition	Described in the article	NR	High school or collegiate	Football

(*continued*)

Table 2. (Continued)

Refs author (Yr)	*N CA:NC M:F*	*Age mean SD range (yrs)*	*Delay (days) mean SD range*	*Concussion severity rating scale*	*Diagnosis of concussion*	*Concussion symptoms*	*Concussion history*	*Level of play*	*Sports involved*
Moore et al. (2016)	52:29 81:0	21 NR NR	22 months 2 months 11–50 months	LOC, PTA, RGA	All concussions were identified on the field by the team medical staff and confirmed by an attending physician	Clinically asymptomatic at time of testing	1–3	Collegiate	Football and soccer
Munia et al. (2016)	4:2 6:0	16 0.3 NR	190 NR 118–267	PTA, RGA, PCS	Positive concussion incidents	Clinically asymptomatic at time of testing	1–3	High school	Football
Prichep et al. (2013)	65:0 65:0	17.9 NR 15.1–23.2	1 NR 45	LOC, PTA, RGA, CSI, SAC, BESS, ANAM	Injury resulting from a blow to the head leading to an alteration in mental status and 1 or more or the following AAN Guideline for Management of Sports Concussion symptoms	Described in the article	NR	High school or collegiate	Football
Radic (2015)	70:70 140:0	41.4 4.5 33–50	NR	NR	NR	NR	None	Amateur	Soccer
Slobounov et al. (2009)	21:0 NR	21 NR 18–25	7 after each concussion	Headache, light sensitivity, dizziness, memory and concentration problems, disorientation	Suffered two concussive episodes within an athletic season, suffered the first within 12 months of baseline testing, both concussions were grade 1 MTBI and did not occur within 21 days of each other	Clinically asymptomatic at time of testing	No prior to baseline, each subject suffered 2	Collegiate	Rugby, football, soccer, and ice hockey
Teel et al. (2014)	7:12 12:7	21 1 NR	5 1 8	NR	Diagnosed by certified athletic trainer of physician.	NR	NR	NR	NR
Thompson et al. (2005)	12:12 24:0	20.95 NR 18–25	89.4 NR 70–131	NR	Grade 1–2 MTBI assessed by team physician	Clinically asymptomatic at time of testing.	NR	Collegiate	Rugby, football, and ice hockey
Tysvaer (1989)	69:69 138:0	NR NR 15–34	NR	LOC	NR	NR	1	Professional	Soccer
Virji-Babul et al. (2014)	9:33 42:0	16 1 NR	26 35 ≤ 90	PCSS	NR	Significantly higher PCSS score for athletes compared with controls	1.8	Residency soccer program and minor league ice hockey	Soccer and ice hockey

N, number of participants; CA, concussed athletes; NC, nonconcussed participants; M, male; F, Female; SD, standard deviation; PCS, post-concussion symptoms; GCS, Glasgow Coma Scale; PTA, post-traumatic amnesia; RGA, retrograde amnesia; LOC, loss of consciousness; TBI, traumatic brain injury; mTBI, mild traumatic brain injury; S, subject group; C, control group; F/U, follow-up; conc., concussion; Ax, assessment; h, hours; yr, year; CIS, Concussion in Sport; N/A, not applicable; NR, not reported; ANAM, Automated Neuropsychological Assessment Metrics; BESS, Balance Error Scoring System; CARS, Co-operative Ataxia Rating Scale; CGS, Cantu Grading System; CSI, Concussion Symptom Inventory; SAC, Standardised Assessment of Concussion; PCSS, Post Concussion Symptom Scale.

Table 3. Study Methods and Results

Author (Yr)	*Recording characteristics and analysis used*	*Other outcomes measured*	*Major findings*	*Study strengths and comments*
Barr (2012)	Data recorded from 5 frontal electrodes with linked ears reference Sampled at 8 kHz & filtered between 0.5 & 70 Hz Power analysis filtered between 1.5 & 45 Hz Analyzed a composite Z-score of 7 qEEG features	BESS, ANAM	Concussed athletes scored significantly worse than controls on the EEG discriminant score at the time of injury, and also at 8 days post-injury. This difference was not present at 45 days post-injury. EEG abnormalities persist beyond observed clinical recovery by neuropsychological measures.	Large samples of both control and concussed athletes. Serial design of the study allowed the comparison between groups at multiple time-points.
Cao (2008)	Data recorded 19-channels with linked earlobes reference Power analysis on data was filtered between 0.5 & 30 Hz Feature selection and classification methods of EEG data	TMT	Using a novel classification algorithm, EEG abnormalities were observed in concussed athletes following a concussive episode compared with baseline. EEG abnormalities were located over temporal and occipital regions in the theta, alpha, and beta frequency bands. Posture of the subject during recording resulted in changes to EEG rhythms, with more abnormalities observed when participants were standing compared with when seated.	The study used a large sample of baseline data for comparisons against the post-concussive recordings. Different postural conditions used for the continuous recordings allowed for greater investigation of disturbances within the population. Combination of all 60 participants from the baseline data as a comparison against the half that suffered concussions meant that the study was not a true serial design. Classification algorithm used, the support vector model, allowed a more paradigmatic way of classifying abnormalities in the EEG recordings
Cao (2010)	Data recorded 19-channels with linked earlobes reference Sampled at 1000 Hz & filtered between DC & 70 Hz Connectivity analysis using 19 ROIs to define sources of independent components.	NR	Using a source localization algorithm (sLORETA), changes in connectivity were observed in athletes following an mTBI. MTBI resulted in a decrease in frontal connectivity, and an increase in occipital connectivity. Connectivity patterns following mTBI were less small-world like compared with baseline recordings.	First study to examine connectivity pattern changes in athletes following concussion.
Cao (2011)	Data recorded 19-channels with linked earlobes reference Sampled at 1000 Hz & filtered between DC & 70 Hz Power analysis performed between 2 & 40 Hz, before entropy calculation performed on transformed data.	Neuropsychological battery	Using a Shannon's entropy-based algorithm, the stability of EEG signals were observed following an mTBI. EEG stationarity decreased following mTBI over occipital and temporal areas. The stability of EEG signals across a continuous recording may be effective measure of dysfunction following mTBI.	The study used a large sample of baseline data, as well as follow-up data in a matched group of controls.

(*continued*)

Table 3. (Continued)

Author (Yr)	*Recording characteristics and analysis used*	*Other outcomes measured*	*Major findings*	*Study strengths and comments*
Gay (2015)	128-channel Reference NR Differences in global power assessed, analysis NR	Heart rate monitoring	EEG abnormalities in continuous recordings were observed between controls and athletes during light exercise, but not during resting EEG. EEG abnormalities were observed despite all concussed athletes being cleared for return-to-play.	The inclusion of a 30-min post-intervention survey allowed for a stronger comparison with baseline. Limited information on EEG settings, data processing, and analysis methods used.
Gosselin (2009)	Data recorded 19-channels with linked earlobes reference Power analysis between 0.5 & 32 Hz of REM, NREM and resting data Assessed over frontal, central, parietal, & occipital clusters		Concussion resulted in alterations to waking EEG abnormalities, but did not affect sleeping characteristics or sleeping EEG. In the waking EEG, participants displayed increased delta power and decreased alpha power. EEG abnormalities were present across most regions of the scalp.	Concussed and control groups were well matched in age, sex, and education. Only study examined to provide individual concussion history.
McCrea (2010)	5-frontal electrodes with linked ears reference Sampled at 8 kHz & filtered between 0.5 & 70 Hz Power analysis filtered between 1.5 & 45 Hz Analyzed a composite Z-score of 7 qEEG features	BESS, ANAM	Concussion significantly altered resting EEG activity from baseline. EEG abnormalities in injured athletes compared with controls persisted beyond 8 days post-injury, unlike neuropsychological measures which showed no difference at 8 days post-injury.	Baseline testing of all athletes allowed for a stronger comparison to controls post-injury.
Moore (2016)	128 channel net with a vertex reference Data sampled at 250 Hz, filtered between 0.1–100 Hz Power analysis between 1–40 Hz	BDI-II, POMS	Frontal asymmetry differed between concussed athletes and controls. Athletes had reduced alpha asymmetry and increased beta asymmetry. For athletes, reduced alpha activity was associated with higher scores on the BDI-II and POMS	Concussed athletes show similar asymmetry pattern to depressed patients. Results show that concussion may lead to medium to long term psycho-affective changes.
Munia (2016)	9 channels with a linked earlobes reference Sampled at 256 Hz Power analysis conducted between 1–40 Hz	ImPACT, Vigilance Task	Concussed athletes displayed increased delta power, but reduced beta and gamma compared with controls.	Preliminary stage of paper, but significant differences in groups seen with only 6 participants.
Prichep (2013)	5-frontal electrodes with linked ears reference Sampled at 8 kHz & filtered between 0.5 & 70 Hz Power analysis filtered between 1.5 & 45 Hz Analyzed a composite Z-score of 7 qEEG features	BESS, ANAM	EEG abnormalities between mild and moderate concussed athletes persisted up to 45 days post-injury, whereas there is no difference between the groups in terms of neuropsychological measures at 8 days post-injury.	Compares the severity of concussions sustained. Study groups are unbalanced, with over 3 times the number of participants in the mild compared with the moderate groups.
Radic (2015)	Recording characteristics NR Analysis consisted of power from each electrode and each activity state calculated	Behavioural data on Distributed attention test, and VAT	Former athletes displayed reduced performance on an attention task compared with controls. EEG changes were observed post-hyperventilation, with the former athletes producing greater frontotemporal theta compared with controls.	Large samples of both former athletes and controls. No data on concussion severity, frequency. Limited information on EEG settings, data processing, and analysis methods used.

(*continued*)

Table 3. (Continued)

Author (Yr)	*Recording characteristics and analysis used*	*Other outcomes measured*	*Major findings*	*Study strengths and comments*
Slobounov (2009)	19 channels with linked earlobes reference Sampled at 1000 Hz Filtered between DC & 70 Hz EEG information quality score derived from power transformed EEG data	TMT	Changes to recorded electrical activity lasts beyond 2 weeks, whereas neuropsychological tests show recovery in 7 days. EEG-IQ score was decreased following concussion compared with baseline scores. The decrease in EEG-IQ score was significantly larger following the second concussive episode compared with the first concussive episode.	Participants recorded baseline sessions and completed follow-up sessions that lasted for a substantial period post-injury.
Teel (2014)	128-channels with vertex reference Sampled at 500 Hz Power analysis filtered between 0.5 & 59 Hz EEG resting state and continuous EEG recorded during VR Testing & ImPACT EEG power and coherence defined at frontal, central and posterior clusters.	ImPACT, VR Testing	Concussed athletes showed decreased beta and theta power compared with controls across all resting EEG conditions. Concussed athletes showed increased coherence compared with controls at EEG baseline. Despite EEG abnormalities, concussed athletes completed all clinical tests at a similar level of performance compared with controls.	Compared the difference in electrophysiological performance across a wide variety of tasks, in addition to examining resting state EEG. Examined both resting EEG power and coherence. Study groups were unbalanced, with nearly double the number of controls compared with concussed participants.
Thompson (2005)	19-channels with linked earlobes reference Sampled at 250 Hz Filtered between DC & 70 Hz Spectral analysis of postural and eyes-open/closed data	N/A	Concussed participants showed decreased power compared with controls., especially in the theta and beta frequencies The power decrement seen in concussed participants was strongest during standing postures	Concussed participants were at least 70 days post-injury at the time of testing, highlighting the long-term effects of concussion on cortical functioning.
Tysvaer (1989)	16-channels, Reference NR Waveform shape analysis to define abnormalities in continuous data	Football heading exercise (only some participants)	Abnormal temporal theta activity was observed in 35% of athletes examined, compared with controls. Increased resting alpha activity following heading exercise. Repetitive minor impacts may cause substantial functional deficits.	Examines the effect of a completing an athletic technique on endogenous electrical activity. Only four players completed the EEG recording following the heading exercise.
Virji-Babul (2014)	64-channels, Reference NR Sampled at 250 Hz Filtered between 4 & 40 Hz Connectivity and graph theory analysis across 27 defined ROIs	ImPACT	Altered connectivity patterns in adolescents following concussion compared with controls. Connectivity differences were located primarily over the right prefrontal cortex.	One of the few studies examining the impact of concussion in adolescents. Study groups are unbalanced, with over 3 times the number of healthy compared with concussed participants. In addition there were a very high number (up to 27) of interpolated electrodes in a 64-channel montage.

ANAM, Automated Neuropsychological Assessment Metrics; BESS, Balance Error Scoring System; CWT, Continuous Wavelet Transform; EEG-IQ, EEG Information Quality; FFT, Fast-Fourier Transform; ImPACT, Immediate Post-Concussion Assessment Testing; mTBI-DS, Mild Traumatic Brain Injury Discriminant Score; NREM, non-REM sleep; REM, Rapid Eye Movement sleep; ROI, Region of Interest; SEPFS, Shannon entropy of the peak frequency shift; VAT, Visual Attention Test; VR, Virtual Reality; NR, not reported.

delta to beta frequency bands, with the effects being particularly pronounced in the standing position. The effects differed across the scalp: power in the alpha and beta bands showed greater reduction over frontal regions, whereas theta power was more reduced parietally. Teel and colleagues[25] also reported a significant reduction in theta and beta power within eight days of injury compared with controls across all postural conditions. Two studies examined EEG differences at rest versus physical activity. Gay and coworkers[22] reported that, compared with controls, concussed athletes showed a significant increase in EEG power across delta to beta frequency bands during, as well as 30 min after, rigorous cycling activity that induced the hyperventilation in the athletes. Radic and colleagues[23] reported that, compared with controls, soccer players had reduced alpha power over posterior regions, greater hemispheric lateralization differences in delta power, and increased left temporal theta after hyperventilation-inducing exercise. The authors do not provide statistical results on the differences between these two groups, however.

Gosselin and associates[17] examined resting EEG under an eyes closed condition as well as EEG during sleep in healthy and concussed athletes. Concussed athletes showed a statistically significant increase in delta power and reduced alpha power at several recording sites under resting conditions compared with healthy controls. Moore, Sauve, and Ellemberg[28] examined whether long-term (i.e., greater than nine months) alterations in EEG activation after a concussion were related to changes in psychological functioning measured using the Beck Depression Inventory-Second Edition[38] and the Profile of Mood States.[39] Concussed athletes showed significantly reduced frontal alpha asymmetry, as well as significantly increased frontal beta asymmetry, compared with controls. In addition, in the athletes, the pattern of alpha activity was negatively correlated with scores on both the Beck Depression Inventory and the Profile of Mood States.

Munia and colleagues[29] examined changes in rs-EEG power at eight, 10, and 12 months after a concussion. Compared with controls, the concussed athletes displayed increased frontal delta as well as reduced beta and gamma power across the cortex. These differences were significant between eight and 10 months after injury, but only the differences in frontal delta were significant out to 12 months (it should be noted that this was a small dataset, with only six participants completed at the time of the preliminary analysis).

In sum, three of the seven studies showed a reduction in theta, alpha, or beta power in concussed athletes compared with controls.[17,18,25] There is also some evidence of changes in delta and gamma activity after a concussion[29]; however, the direction of the changes varied. Undergoing hyperventilation changed the observed power dramatically,[22,23] but the direction of effects was not consistent between the two studies.

Coherence-based analyses

In EEG, coherency is a measure of associative strength (i.e., a correlation) between activity at two or more recording sites. If two time series co-vary together, they are said to have strong coherence versus two that do not correlate.[40] Depending on the aspect of the signal that is probed (e.g., amplitude or phase), distinct types of coherence measures can be extracted.[41] Regardless of the specific measure, if two sites have strong coherence, this is thought to indicate evidence of neural communication, and thus coherence provides a measure of network dynamics.

Three studies examined the impact of concussion on rs-EEG coherence.[25,27,30] Teel and colleagues[25] reported that, despite reduced theta and beta power, concussed athletes showed significantly increased coherence across the scalp in theta, alpha, and beta bands, relative to controls. Cao and Slobounov[27] and Virji-Babul and coworkers[30] both used graph theory to quantify coherence-defined network properties, but produced inconsistent results. Cao and Slobounov[27] found that, compared with controls, concussed athletes had significantly *decreased* frontocentral connectivity and increased parieto-occipital connectivity. In contrast, Virji-Babul and colleagues[30] found that concussed athletes showed *increased* connectivity over the right pre-frontal cortex and *reduced* parieto-occipital connectivity, compared with controls.

The graph theory measures also differed between the two studies. Cao and Slobounov[27] showed that concussed athletes exhibited more random connections between nodes, while control athletes displayed a ''small-world'' network with separate hubs of nodes interconnected with each other (small-world networks indicate an optimal trade-off between wiring cost and information propagation speed).[42] In contrast, Virji-Babul and coworkers[30] reported substantial differences in local but not global networks in concussed versus control athletes. Compared with controls, concussed athletes had a significantly higher level of network connectivity over the right frontotemporal area, with reduced right parietal connectivity. The studies differed in sample age (college students vs. adolescents, respectively) as well as processing and analyses approaches. For instance, Cao and Slobounov[27] used a source localization technique to transform the recording montage into regions of interest (ROIs) before constructing the graphical networks based on interactions of these ROIs. Virji-Babul and colleagues[30] used a Bayesian network learning algorithm to compute a probabilistic network from which to construct the graphs.

Continuous EEG monitoring

Continuous EEG monitoring refers to reviewing the entire EEG recording for abnormal patterns of activity. This type of analysis is used commonly in diagnostic evaluations and involves looking for specific waveforms or components among the entire trace.[43] A study in the late 1980s by Tysvaer and associates[15] reported that significantly more active professional soccer players had some form of abnormal theta bursts in the continuous EEG recording, compared with the control group (35% vs. 13%).

Other measures

A number of the studies use non-traditional approaches to analyze resting EEG. Cao, Tutwiler, and Slobounov[26] used a machine-learning algorithm (support vector machine) to identify features that could be used to classify EEG abnormalities after a concussion. The classifier identified reduced power across theta, alpha, and beta frequencies at the parietal and temporal areas for concussed athletes compared with controls. Both Slobounov, Cao, and Sesbastianelli[32] and Cao and Slobounov[19] examined entropy-based transformations of resting EEG data.

Slobounov, Cao, and Sesbastianelli[32] measured EEG wavelet information quality (EEG-IQ) at baseline and at seven, 14, and 21 days after an athlete's first and second concussions. EEG-IQ scores across the occipital, parietal, and temporal scalp recovered over a two-week period after the first concussion, but this recovery was significantly slower after the second concussion. In contrast, performance on the Trails B version of the Trail Making Test recovered to near baseline levels, for both the first and second concussion. Cao and Slobounov[19] examined neuropsychological test performance and entropy in the nonstationarity of EEG oscillations in athletes 30 days post-injury compared with controls. Although there were no group differences in neuropsychological performance, athletes showed significant reduction in entropy over posterior scalp compared with controls.

Other studies have computed a composite score derived from a number of linear and nonlinear metrics on EEG recorded from five frontal electrodes.[16,24,31] This composite score was derived using changes in total and frequency-specific power across spatial locations, connectivity, and coherence changes in specific regions, as well as specific abnormalities present in the recording, and is used as a discriminant score of electrical activity after an mTBI. This discriminant score was higher in concussed athletes compared with controls,[16,24] and in severely versus mildly concussed athletes.[31] In all three studies, neuropsychological tests and clinical observations showed no effect one week post-concussion, whereas significant differences in the EEG discriminate score persisted and continued to be present up to 45 days after injury in moderately severe concussions.

Discussion

Current guidelines for return-to-play after a concussion rely heavily on clinical judgment based primarily on self-reported symptoms, neurological soft signs, and/or neuropsychological assessment. These measures may not be sensitive to subtle, protracted changes in brain physiology and, as a result, players return to the field too early, making them more vulnerable to re-injury. In this systematic review, we examine the evidence for the use of rs-EEG to assess changes in brain functioning after sports-related concussion. rs-EEG is an affordable, fast, and accessible measure of brain functioning.

What aspects of the EEG signal are affected by concussion?

Of the 16 studies included in this review, only half provided sufficient information to identify specific frequency bands affected by concussion. [15,17,18,23,25,26,28,29] Six of these studies reported changes in theta rhythms; however, the measures used and the direction of effects were not consistent across studies. Concussed athletes had lower theta power, [15,17,22,26] abnormal theta oscillations,[15] increased theta coherence,[25] or increased frontotemporal theta power [23] relative to pre-injury baseline or controls. While most studies identified these changes at rest, Radic and colleagues[23] found theta changes after only hyperventilation conditions. Less consistent changes are also reported in other frequency bands. Concussion was associated with enhanced delta power,[17,29] reduced alpha power,[17,26,28] and both increased frontal beta asymmetry[28] and reduced beta power.[18,25,26,29]

Thus, the existing studies most consistently report changes in theta oscillations after concussion. Theta oscillations are enhanced typically during internally guided attention (such as meditation or introspection), [44–46] greater in patients with anxiety,[47] altered in individuals experiencing suicidal ideation,[48] reduced in athletes experiencing a downturn in performance (i.e., a ''slump''),[49] critical for memory processes,[50,51] and increased with longer durations of wakefulness.[52] Given that concussion is associated with an increase in confusion as well as a decline in mood, sleep quality, concentration, and memory, post-concussion changes in theta oscillatory activity are consistent with neurophysiological changes. Importantly, theta oscillations are also associated with goal-directed cognition and decision-making.[53,54] Thus, abnormal theta activity post-concussion may influence the speed and accuracy of decision making processes that are important on field and thereby increase the risk of further injury.

Comparatively, the results of the other studies did not present a consistent story of how concussion altered recorded electrophysiological activity. The connectivity analyses showed that concussion altered the nature of functional networks; however, the two studies reported opposite effects of concussion on the structure of pre-frontal connectivity.[27,30] The use of composite analyses to derive discriminant scores to represent a number of factors of recorded EEG activity consistently showed a delayed recovery of functional activity compared with the neuropsychological measures used in most studies.[16,19,31–33] This collapsing of the data, however, removed the ability to effectively identify the source of this abnormality. There are other issues with this methodology discussed below.

Recommendations for future rs-EEG studies

A major limitation in the strength of conclusions that can be drawn from the studies reviewed here is the lack of consistency in (1) the measures used to assess rs-EEG (e.g., power, coherence, nonstandard entropy-based measures), (2) the information provided about how these measured were derived and analysed (e.g., recording system, analysis approach), and (3) the time and number of testing sessions relative to the concussive event.

Different measures of the EEG signal characterize distinct physiological mechanisms. For instance, power is sensitive to regional properties of the EEG signal, whereas coherence is sensitive to the similarity of wave features between sites. Changes in theta power may be because of neurophysiological changes in region-specific activity in, say, frontal or temporal brain regions, whereas changes in theta coherence may represent a disruption of the efficacy of communication between these regions. To identify the mechanisms that are most sensitive to concussion, studies need to report both power and coherence measures in multiple frequency bands.

Novel metrics of brain activity, derived by combining information from power and coherence measures,[16,24] may prove to be sensitive summative measures of disrupted brain activity post-concussion. It is necessary to first standardize their measurement, however, and establish their psychometric properties. Currently, studies provide insufficient information about how these measures are derived, and what little information is provided indicates a lack of consistency across studies. Unfortunately, many studies lack sufficient details regarding basic EEG recording parameters, processing, and power/coherence calculations, let alone details of nonstandard analysis techniques.

Most of the studies included here compared EEG measures between groups of concussed and nonconcussed athletes. Although the EEG signal recorded at the scalp can vary as a function of individual (e.g., scalp thickness, age) and situational (e.g., fatigue, diurnal patterns) variables, cross-sectional designs may be sensitive enough to produce statistically significant mean differences between groups. For EEG to be a sensitive diagnostic measure of post-concussion changes and recovery in brain neurophysiology, however, it is likely to require multiple measurements, including one or more pre-concussion baseline and multiple post-concussion measures in the same individual. These individual trajectories would then need to be compared with norms derived from both healthy nonconcussed and concussed athletes. Below we provide some recommendations for performing rs-EEG analyses.

Appropriate details of recording parameters and processing pipelines

There are a number of issues to consider when setting up EEG recording parameters for time-frequency analyses,[55] including the system's fundamental limits on how information is gathered—e.g., the number of electrodes that it can record from and the sampling rate capability. Recordings from a sparse electrode array do not provide sufficient topographical representation to support inter-site–clustering analyses. The sampling rate directly influences the frequency bands that can be analyzed (i.e., the Nyquist-sampling limit; >2/sampling frequency). It is also important to consider approaches to EEG pre-processing, such as the choice of reference montage,[56] the number and length of epochs extracted from the continuous EEG, and how to remove or correct for artefacts. The number and duration of epochs can also impact signal-to-noise and have a large impact on phase-based measures (i.e., artificially inflating effects). Slow frequencies are particularly susceptible to drift, movement, and ocular artefacts, which have different impact on eyes open versus eyes closed recordings. Finally, the criteria used to select frequency band limits and the methods used to quantify the signal must be considered and choices clearly reported.

Conclusions and Future Directions

All 16 studies reviewed here report some effects of concussion on rs-EEG. Given large differences in methodology and measurement parameters, however, it is not possible to draw a clear conclusion regarding the effects of concussion on rs-EEG. Nevertheless, given concerns that current practice does not sufficiently support clinicians in making return-to-play assessments, and the promising findings shown in the studies reviewed here, it would appear safe to conclude that future studies might establish that rs-EEG is a sensitive measure of neurophysiological changes and recovery after concussion. This systematic review highlights the need for further work to develop a consistent protocol for measuring rs-EEG in athletes so as to develop a normative database against which to examine the effects of concussion and post-concussion recovery trajectories.

Establishing these standards may become easier with the assistance of the biotechnology industry. For instance, in late 2016, the first handheld EEG device to assess TBI, the Brainscope Ahead 300 (Brainscope, Bethesda, MD), was approved by the Food and Drug Administration. Such flexible, portable, and affordable devices are likely to increase the use of EEG measures in randomized clinical trials and fast-track the specification of rs-EEG's sensitivity and specificity to identify early signs of concussion and evaluate recovery across athletes of different ages and abilities. This work is essential to develop a valid and replicable metric of abnormal EEG activity that has well-defined thresholds for characterizing normal versus abnormal activity and accounting for individual differences.

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