What evidence exists for new strategies or technologies in the diagnosis of sports concussion and assessment of recovery?

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ABSTRACT

Objective The purpose of this critical review is to summarise the evidence for the following technologies/strategies related to diagnosing or managing sports-related concussion: quantitative EEG, functional neuroimaging, head impact sensors, telemedicine and mobile devices.

Data sources MEDLINE, PubMed, Cochrane Controlled Trials Registers, SportDiscus, EMBASE, Web of Science and ProQuest databases. Primary search keywords were concussion, sports concussion and mild traumatic brain injury. The keywords used for secondary, topic specific searches were quantitative electroencephalography, qEEG, functionalMRI, magnetoencephalography, near-infrared spectroscopy, positron emission tomography, single photon emissionCT, accelerometer, impact sensor, telemetry, remote monitoring, robotic medicine, telemedicine, mobile device, mobile phone, smart phone and tablet computer.

Results The primary search produced 8567 publications. The secondary searches produced nine publications that presented original data, included a comparison group in the study design and involved sports-related concussion. Four studies spoke to the potential of qEEG as a diagnostic or management tool, while five studies addressed the potential of fMRI to be used in the same capacity.

Conclusions Emerging technologies and novel approaches that aid in sports concussion diagnosis and management are being introduced at a rapid rate. While some technologies show promise, their clinical utility remains to be established.

INTRODUCTION

Given the immense popularity of organised athletics throughout the world and a quickly evolving medical literature, sports-related concussion is now widely viewed as a developing public health crisis. The rising concern for both short-term and long-term potential complications from these injuries continues to press the need for accurate diagnosis and meaningful management strategies for patients of all ages and levels of competition. Central to this issue is the absence of objective tests that can confirm the presence of concussion or mild traumatic brain injury (mTBI).[1] Consequently, the diagnosis and management of these conditions continue to rely largely on the subjective clinical decision-making processes.

Unfortunately, the complexity of the brain creates significant variability in the type and severity of concussion presentations in the acute setting, making it difficult to rely solely on the clinical evaluation. Alternative or additional explanations for the cause of a concussion-like clinical presentation should always be considered. Likewise, signs and symptoms of brain dysfunction in the chronic postconcussion setting are often non-specific. The complexity of brain function, the non-specific nature of the clinical presentations, and the heterogeneity of injury resolution or progression, all underscore the need for meaningful diagnostic and management tools.

Current clinical practice does include several adjunct tools that may be directly helpful in decision-making, including, but not limited to, neurocognitive tests (computerised or pencil and paper), objective balance systems, clinical reaction time devices and objective measures of eye movements. These tests have, to a large degree, been employed with mixed clinical success.[2 3] Consequently, there has been increasing focus on newer diagnostic technologies, such as functional neuroimaging, and quantitative EEG (qEEG), with the hope of developing tools that possess greater clinical utility. At the same time, concussion injury surveillance is being augmented by the deployment of head impact sensors in the field of play and computerised media are being developed to improve sports concussion education, symptom tracking and access to care.

This systematic literature review presents the published evidence for several of these emerging technologies and strategies. This review is not designed to be inclusive of every technology or strategy, but rather we have elected to address the following emerging topics felt to be particularly relevant: qEEG, functional neuroimaging, head impact sensors, telemedicine and mobile devices. In some cases, the absence of a significant body of original data in the medical literature necessitated the use of supplemental background information to shed light on some of these potential tools.

METHODS

On-line literature researches were conducted using the following databases: MEDLINE, PubMed, Cochrane Controlled Trials Registers, Sport Discus, EMBASE, Web of Science and ProQuest. The key words ‘concussion’, ‘sports concussion’ and ‘mild traumatic brain injury’ were used inclusively in the primary search. The primary search results were then used to produce a series of topic-specific literature searches using the following terms or combination of terms:

- *Topic 1 (qEEG)*: 'quantitative electroencephalography' or 'qEEG'
- *Topic 2 (functional neuroimaging)*:
  - 'functionalMRI'
  - 'magnetoencephalography'
  - 'near-infrared spectroscopy'
  - 'positron emission tomography'
  - 'single photon emission CT'
- *Topic 3 (impact sensors)*: 'accelerometer' or 'impact sensor' or 'telemetry'
- *Topic 4 (telemedicine)*: 'remote monitoring' or 'robotic medicine' or 'telemedicine'
- *Topic 5 (mobile devices)*: 'mobile device' or 'mobile phone' or 'smart phone' or 'tablet computer'.

Results were then limited to the English language and hand-searched for relevance to sports concussion and for studies that included a comparison group. Papers focusing on moderate or severe traumatic brain injury were excluded. No restriction was made on year of publication. For the specific topic of 'mobile device applications', on-line commercial databases for iPhone, Android and Blackberry operating systems were also searched for relevant sports concussion tools.

RESULTS

The primary search of 'concussion', 'sports concussion' and 'mild traumatic brain injury' produced 8567 publications. The results of each topic-specific search are presented in table 1.

Quantitative EEG

qEEG is a technique that involves the computer-aided analysis of electroencephalographic data. In contrast to standard EEG, which employs visual inspection of EEG tracings, qEEG allows for identification of subtle changes or tendencies in the patterns of source EEG data.[4] In descriptive studies of patients with mTBI, qEEG has been reported to describe various electrophysiological trends.[4] Two of the more consistent findings are the reduction in mean α frequency and an increase in θ–α frequency ratios.[5–7] Similar to other tools used for concussion/mTBI diagnosis and management, these observed changes are non-specific as to cause, thus possibly limiting the clinical utility of the technology.

With that in mind, recent efforts have focused on the use of qEEG as diagnostic tool for sports-related concussion (table 2).

Baillargeon *et al* used a prospective cohort design to study competitive amateur athletes in three age groups: 9–12, 12–16 and adults. Using a visual three-stimulus odd ball paradigm to illicit event-related potentials (ERP), the authors found the P3b component of the ERP to have significantly lower amplitudes in the concussed study athletes.[8]

Barr *et al* compared symptoms, postural stability, cognitive function and a previously described qEEG index in 59 concussed athletes presented to an emergency department to the same measures in 31 controls. While the clinical measures were found to be significantly different between the two groups at the time of presentation, no difference was seen on day 8 or day 45. The qEEG index was found to be different between the two groups on the day of presentation and on day 8, with no difference seen on day 45.[9]

Cao and Slobounov evaluated a novel measure of EEG signal non-stationarity by testing 30 case and 30 control athletes prior to injury and 30 days postinjury with a technique labelled 'Shannon-entropy of the peak frequency shifting' (SEPFS). SEPFS values were significantly decreased in the occipital, temporal and central brain areas of case subjects.[10]

McCrea *et al* used a prospective case-control study to evaluate the clinical utility of a portable qEEG device. Twenty-eight concussed athletes and 28 matched controls underwent preseason qEEG and neurocognitive testing. Postinjury testing was repeated on the day of injury, days 8 and 45 postinjury. Concussed subjects performed poorly on neurocognitive tests on the day of injury but had no residual deficits on day 8 or day 45. Significant changes in qEEG results persisted on day 8 but were not present on day 45.[11]

Each of these studies provides intriguing preliminary data to suggest the possible clinical utility of qEEG technology. Although only four studies were identified, the data in them speak to the ability of this technology to document physiological dysfunction in the setting of concussion and, therefore, to possibly act as a useful measure of tracking recovery if evaluated in future prospective studies. As yet, however, there are no published data that speak directly to the ability of any qEEG platform to provide distinguishing features of the concussion diagnosis.

Table 1 Topic specific literature search results

Topic	Total publications	Primary data and comparison group
Quantitative EEG	30	4
Functional neuroimaging	533	5
Impact sensors	23	0
Telemedicine	5	0
Mobile devices	2	0

Table 2 Studies investigating the use of quantitativeEEG in concussed athletes

Authors	Year	Study type	Data collection	Total individuals (concussed)
Baillargeon	2012	Cohort	Prospective	96 (48)
Barr	2011	Case-control	Prospective	90 (59)
Cao	2011	Case-control	Retrospective	60 (30)
McCrea	2010	Case-control	Prospective	56 (28)

Functional neuroimaging

Routine neuroimaging (CT, standardMRI) has little clinical utility in the diagnosis of sports concussion.[12] CT does have an important role to play in screening for a potential bleeding event or identifying skull fracture, but has long been shown to be insensitive to mTBI. Like CT, standard MRI is not useful in the acute evaluation of concussion. MRI may be useful in monitoring for structural change over time; however, or for evaluating concurrent pathology that may complicate concussion management. These modalities have little or no clinical use in concussion based on the intrinsic limitations of their resolution as well as their nature as static tests that provide an estimation of structure. Given that concussion is widely held to be an injury of interrupted or diminished function rather than structure, their lack of clinical utility is not surprising.

Functional neuroimaging refers to a subset of neuroimaging technologies that provide an estimation of function, and thus have been receiving increasing interest from concussion researchers and clinicians. While each of the functional

Table 3 Functional neuroimaging subtopic-specific search results

Topic	Total publications	Primary data and comparison group
Functional MRI	533	5
Magnetoencephalography	7	0
Near-infrared spectroscopy	6	0
Positron emission tomography	36	0
Single photon emission CT	74	0

neuroimaging technologies reviewed here has its own unique physical property, they all provide an estimation of brain function based on measuring an aspect of neuronal metabolism. The results of the literature searches performed for each functional neuroimaging modality are presented in table 3.

Functional MRI (fMRI) is based on the relationship between blood flow and neuronal metabolism. fMRI takes advantage of the different magnetic states of oxygen-rich and oxygen-poor blood, primarily through the use of the blood-oxygen-level-dependent (BOLD) contrast technique.[13] Advantages to fMRI include the absence of contrast media and radiation exposure and its ability to be used concurrently with other measures of brain physiology. Five studies were identified that looked at fMRI changes in concussed athletes and employed the use of a comparison group (table 4).

Chen *et al* performed fMRI on 16 concussed athletes, one of whom was asymptomatic at the time of testing, as well as eight matched controls, describing differences in BOLD signal patterns between the control group and the symptomatic concussed subjects. The one asymptomatic concussed subject had a BOLD signal pattern indistinguishable from the control group.[14] In the same year, Jantzen *et al*[15] used BOLD activity at the baseline and postinjury to describe differences in neuronal function within 1 week of injury. In 2010, Slobounov *et al*[16] used fMRI to show that 15 concussed athletes showed larger cortical networks outside of the region of interest as well as significantly larger BOLD signal percent change at the right hippocampus, despite performing as well as 15 controls at a virtual reality task. In 2011, Slobounov *et al*[17] demonstrated significantly reduced connectivity in the primary visual cortex, hippocampal and dorsolateral prefrontal cortex networks of 17 concussed individuals as compared with control subjects at an average of 10 days postinjury. Talavage *et al*[18] published the results of a prospective case-control study showing that 11 high-school American football players had altered activation of the dorsolateral prefrontal cortex as demonstrated with fMRI performed preseason and postseason. Interestingly, only four of these individuals received a diagnosis of concussion during the study period.

Magnetoencephalography (MEG) is a brain mapping technique that records the magnetic fields produced by the brain's electrical activity.[19] As compared with fMRI, MEG has a higher degree of temporal resolution, providing data every 1 ms or less. MEG readings are also less distorted by the skull and scalp than EEG, which also provides an estimation of the brain's electrical activity. No studies were identified that investigated the use of MEG in sports-related concussion. MEG has been shown to be sensitive for mTBI in military and civilian populations suffering injuries from both blast and non-blast causes.[20 21] The use of MEG for the diagnosis and management of sports-related concussion has not been demonstrated, but these preliminary studies do support its' potential use.

Near-infrared spectroscopy (NIRS) detects changes in blood haemoglobin concentrations via measurement of the near-infrared (800–2500 nm) region of the electromagnetic spectrum.[22] NIRS is more portable than most functional neuroimaging techniques and can also be used on moving subjects.[23] Its utility is limited, however, being able to measure changes in cortical tissue only and not deeper brain structures. No studies were identified that reported on the use of NIRS in the evaluation of individuals with sports-related concussion. One study has reported the use of NIRS as a tool for measuring local haemodynamic changes in the setting of performing a cognitive task, perhaps hinting at the potential usefulness of this modality as a tool in sports-related concussion.[24]

Positron emission tomography (PET) uses a biologically active molecule, such as fludeoxyglucose, a glucose analogue, to introduce a positron emitting radionuclide.[25] High areas of radioactivity are assumed to indicate regions of high brain activity. Although PET has been shown to be useful in military patients with persistent postconcussion symptoms,[26] no studies were identified that reported on the use of PET in the evaluation of subjects with sports-related concussion. PET has also been shown to be sensitive to metabolic changes seen in the diagnosis of mild cognitive impairment, a possible predementia stage of Alzheimer's disease.[27] Thus, data do support PET as a tool for demonstrating metabolic changes associated with longer-term symptoms following a concussion, but there are no data to support its use in the acute setting.

Single photon emission CT (SPECT) also uses the introduction of a radioactive tracer. In contrast to PET, SPECT has a lower resolution but is significantly cheaper.[28] Although no studies were identified that investigated the use of SPECT in sports-related concussion, several studies have shown the tool to be sensitive to non-sports-related mTBI.[29–33] SPECT has also been shown to demonstrate metabolic changes in chronic post-concussion syndrome.[34–36]

Table 4 Studies evaluating fMRI in sports-related concussion

Authors	Year	Study type	Data collection	Individuals (concussed)
Chen	2004	Case-control	Presentation	24 (16)
Jantzen	2004	Case-control	Prospective	8 (4)
Slobounov	2010	Case-control	Retrospective	30 (15)
Slobounov	2011	Case-control	Retrospective	34 (17)
Talavage	2010	Case-control	Prospective	11 (4)

Head impact sensors

Investigations into the biomechanics of concussion began in earnest with animal studies dating back to the mid-20th century. While animal studies continue as a cornerstone of pathophysiology and early-phase treatment investigations, biomechanics research has evolved to include computer modelling, video reconstruction and the in vivo use of accelerometers. Each of these more 'modern' technologies has provided important advances in the understanding of concussion biomechanics. The development of easily deployable sport equipment-based accelerometer systems, however, has also provided two unique, and potentially useful, clinical opportunities.

The first is the ability to monitor impacts during the course of an athletic event for the purpose of screening for potential injury. Although many researchers have analysed impact counts and characteristics across a variety of settings in the hope of establishing force 'thresholds' for injury, no such threshold has been discovered.[37–40] As efforts to improve impact-monitoring accuracy continue, however, so will the search for the 'concussion threshold'. At the same time, there may be a separate, but similar role for the real-time tracking of impact forces. Although an on-board accelerometer system may not be able to accurately predict injury, it may have utility as a screening device by alerting sideline personnel of an impact that has occurred above a predetermined magnitude that triggers either observation or clinical evaluation of an athlete. Although there are currently no published studies to support the use of impact sensor systems in this manner and a 'concussion threshold' is unknown, the potential clinical utility should be carefully considered.

The second potential clinical benefit of impact monitoring systems stems not from the idea of monitoring impacts for the presence of an acute injury-generating hit, but from the potential advantage of accurately cataloguing the number of hits and post-impact head acceleration being experienced by an athlete over time. Some have suggested the idea of a 'hit count' that is kept for athletes over the course of a game, practice, week, month, season or career.[41] This concept is fairly new and, as yet does not have published data to suggest that any particular level or number of hits has significant clinical meaning for any particular sport or position. Nonetheless, individual athletes may feel there is a benefit to having an estimate of forces their brain experiences over time.

Telemedicine

Around the globe, there is a clear mismatch between the number of athletes who experience a sports-related concussion and the number of available licensed healthcare providers who possess specific training in diagnosing and caring for the injury. In addition, the need for many patients to travel significant distances to access a sports concussion specialist for an acute concussion evaluation or return-to-play decision is another important barrier to care. As the subspecialty professions who care for concussed athletes continue the very large effort of training new sports concussion experts and improving the relevant clinical acumen of others to cope with demand, there is an obvious pressing need to improve access to care now. Telemedicine is one possible, albeit incomplete, solution.

Telemedicine has been employed with documented success in other neurological diagnoses, most notably stroke[42 43] and traumatic brain injury.[44] In the case of stroke, a well-studied, validated and reproducible physical examination tool, the National Institute of Health Stroke Scale, is used to help document deficits from cerebral ischaemia, thus aiding in clinical decision-making.[45] No similar scale exists for the evaluation of concussion. Given that concussion presentations are, on the whole, subtler than those of stroke, establishing techniques for the remote diagnosis and management of concussion may likely prove to be more difficult. At present, there are no published data that speak to the use of telemedicine in the diagnosis or management of sports concussion.

Mobile devices

Given their widespread use by the public, portability and wireless connectivity, mobile devices are uniquely placed to address three significant gaps that exist in sports concussion diagnosis and management. First, is the need to educate all of the participants in sports concussion care, including but not limited to, athletes, coaches, parents, officials, support staff and medical personnel. Mobile devices provide the opportunity to download educational materials quickly and possess operating systems that support engaging and interactive solutions to learning. Second, mobile device applications can be used as a utility to organise information on injury demographics, symptom timing, recovery milestones and medical appointments. Third, diagnostic screening tools, such as the Sport Concussion Assessment Tool (SCAT 2) can easily be employed across any computing platform. It should be noted, however, that the suggestion of employing concussion assessment tools by individuals other than licensed health care providers might carry significant legal liability.

No studies investigating the use of mobile devices for sports concussion diagnosis or management were identified in the medical literature. A search of the applications for three popular

Table 5 Mobile device sport-related concussion applications

Application	Developer	Type	Intended audience	Cost
Concussion	SportSafety Labs, LLC	Diagnostic, Education	Public	Free
Concussion Recognition & Response: Coaches and Parents Version	Psychological Assessment Resources, Inc	Diagnostic	Public	US$3.99
Concussion Recognition & Response: Sport Version	Psychological Assessment Resources, Inc	Diagnostic	Health professional	US$9.99
Concussion 2	Andrew Poe	Diagnostic	Public	Free
Hockey Canada Concussion Awareness	Polar Mobile Group, Inc	Education	Public	Free
Hockey Canada Concussion Awareness for Kids	Polar Mobile Group, Inc	Education	Public (kids)	Free
ImCAT	ImPACT Applications, Inc	Education	Public	Free
ImPACT Mobile Costumer Center	ImPACT Applications, Inc	Diagnostic	Health professional using ImPACT	Free
KD Test Score	King-Devick, LLC	Diagnostic	Public	Free
PLAY IT SAFE Concussion Assessments	Concussion Health, LLC	Diagnostic	Public	Free
Pocket SCAT2	Inovapp Inc	Diagnostic	Public	Free
Return2Play	The University of Michigan	Education, Utility	Public	US$0.99
SCAT2	Wayne Hans	Diagnostic	Health professional	US$3.99
SCAT2—Sport Concussion Assessment Tool	Inovapp Inc	Diagnostic	Health professional	Free
Shockbox	Impakt Protective, Inc	Diagnostic	Public	Free
Traumatic Brain Injury (TBI)	6ps Media Group, LTDA	Education (TBI)	Health professional	US$4.99
USA Football Heads Up Football	Scott Hallenbeck	Education	Public	Free

mobile devices, iPhone, Android and Blackberry, found 17 applications created specifically for sports concussion diagnosis, management or education (table 5).

Six applications were found to provide educational materials for public consumption, one of which was created specifically for educating children (Hockey Canada Concussion Awareness for Kids). One application addresses concussion education for health care professionals as part of a larger educational programme of traumatic brain injury education (TBI). Eleven applications were identified that acted as concussion assessment tools, only four of which described the intended audience as health care professionals. One application acted as an injury management utility for patients (Return2Play).

It is likely that mobile devices will continue to be an important platform for sports concussion education, assessment and management.[46 47] Care should be taken to ensure that assessment tools are used exclusively by licensed healthcare providers.

SUMMARY

Existing gaps in concussion diagnosis, management and education are being targeted in some way by emerging technologies and strategies. Many technologies exist, undoubtedly, and this review should not be considered exhaustive. As well, the speed of advancing technology makes it possible that some of the information presented herein may be obsolete by the time of publication. The intense spotlight shining on the sports concussion issue will ensure that efforts to fuel technological progress will continue for the foreseeable future. The authors encourage all clinicians to keep up with advancing science and employ a comprehensive approach to concussion management.

Clinicians charged with caring for athletes with concussion find themselves in a rapidly evolving landscape of technologies and strategies designed to address gaps in clinical practice. As the clinical and basic science of sports concussion continue to unfold, some of these approaches may yet prove to have clinical utility. In the interim, the clinician should employ them with caution.

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What evidence exists for new strategies or technologies in the diagnosis of sports concussion and assessment of recovery?

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