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Neurorehabilitation of Persistent Sport-Related Post-Concussion Syndrome

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Abstract.
BACKGROUND: Persistent Sport-Related Post-Concussion Syndrome is often diagnosed with any type of prolonged PCS symptoms. However, there are not specific diagnostic criteria for PPCS such that misdiagnosis often occurs. Further, the signs and symptoms of PCS overlap with other common illnesses such as depression, anxiety, migraines, ADHD and others. Misdiagnosis may lead to less than efficacious treatment, resulting in prolonged symptoms.
OBJECTIVE: This article will review relevant evidence-based literature on PCS, pointing out the lack of a systemic diagnostic framework. It will also provide evidence that highlights the multiple conflicting findings in the literature. This article will posit the BioPsychoSocial framework as the best diagnostic framework for understanding the impact of concussions on the person and to generate individualized and personal interventions.
METHODS: A narrative review of sport concussion-related articles was conducted, after extensive searches of relevant and non-relevant literature by each author, as well as articles recommended by colleagues. Articles varied from American Academy of Neurology Class I to IV for evaluation and critique. Class IV articles were reviewed, as there is much public misconception regarding sport and other concussion treatment that needed identification and discussion.
RESULTS: Articles reviewed varied by quality of research design and methodology. Multiple symptoms, recovery patterns and rehabilitation treatment approaches are purported in the sport-related concussion literature. Current consensus data as well as the mixed and contradictory findings were explored.
CONCLUSIONS: Persistent Sport-Related Post-Concussion Syndrome is a topic of great interest to both professionals and the general public. There is much misunderstanding about the etiology, causation, diagnostic formulations, symptom presentation, prolonging factors and treatment involved in this syndrome. This article posits an individualized multi-system diagnostic formulation, examining all relevant factors, as generating the best interventions for neurorehabilitation of Persistent Sport-Related Post-Concussion Syndrome.

Keywords: Concussion, sport concussion, mild traumatic brain injury, Post-Concussion Syndrome, biofeedback

1. Introduction

Persistent sport-related concussion (SRC) is widely discussed both in the academic literature and popular press. Many academic review papers cite pre-existing medical and psychosocial factors for prolonging what should be a time-limited neurophysiological condition. Moreover, while traditional neuroimaging and clinical biomarkers typically do not show positive findings, experimental measures of brain functioning reveal abnormalities for weeks to months post-injury, even after clinical symptoms have resolved (Institute of Medicine, 2013). Over the past two decades, the field of concussion has progressed from a propensity to under-diagnose concussions and minimize their potential for persistent

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sequelae, to rapid and global expansions in concussion awareness, detection and formal protocols for response. In its latest dialectic iteration, there is now almost paranoia in popular press articles suggesting that even a minor impact head strike sustained in any sport, at any age, by any person could potentially lead to persistent SRC or dire progressive degenerative neurologic illness known under the moniker of Chronic Traumatic Encephalopathy (CTE). Former staunch advocates for collision sports and "playing hard" are now questioning the safety and value of youth participation in sports with concussion potential. Within this context, there is a need for frank, data-driven appraisal and interpretation of extant data to inform views on factors that influence concussion risk, management and recovery. The two-fold purpose of this article is to: (a) review the evidence-based literature that establishes the incidence and prevalence of sport concussion and examines its neuropathophysiology, sequelae, and factors influencing risk for protracted recovery; and (b) critically review established and emerging rehabilitation interventions for ameliorating persistent symptoms or deficits resulting from refractory SRC. Given the limited extent of Class 1 empirical data available, this article also will evaluate research regarding persistence of SRC and proposed rehabilitation treatment alternatives which may be promising but currently lack scientific rigor.

1.1. Definitions of sport concussion and post concussion syndrome

An updated consensus definition of sport concussion was developed at the 5th International Conference on Concussion in Sport held in Berlin, October 2016 (hereafter referred to as the "2016 Berlin Consensus Statement"). This document provides an international foundation that can help in establishing reliability of diagnosis across professional disciplines, sports, and geographic locations. This lengthy, empirically and clinically-driven consensus statement document should be consulted in its entirety (McCrory et al, 2017). This document delineates four core criteria for diagnosing a sport concussion: (a) a TBI injury induced by biomechanical forces including direct or indirect trauma to the head, face, neck or elsewhere on the body with an impulsive force transmitted to the head; (b) rapid onset of short-lived impairment of neurologic function that resolves spontaneously, although sometimes symptoms evolve over a time period; (c) negative standard neuroimaging reflecting a functional rather than structural injury and with or without a loss of consciousness; and (d) resolution of clinical and cognitive features typically following a sequential course, although in some cases symptoms may be prolonged. The accepted etiology of SRC is that postulated by Giza and Hovda (2001) of a neurometabolic cascade at a cellular level that essentially is based on a mismatch between glucose metabolism and hyper-glycolysis and reduced cerebral blood flow. In a majority of these animal studies, the metabolic cascade restores to homeostasis in about a seven-day period, with no irreversible damage at a cellular level in these animal models. This phenomenon has been extended to humans based on similar time courses for symptom presentation and resolution (McCrea, Prichep, Powell, & Chabot, 2010). The 2016 Berlin Consensus in Sport position paper is useful on a number of fronts, but has yet to be fully disseminated by medical practitioners and researchers, even those familiar with the consensus guidelines promulgated by the previous 2012 Zurich Consensus Statement (McCrory et al., 2013).

The lack of consistent and reliable diagnostic concussion criteria also has added to confusion and misdiagnosis of the condition termed Post Concussion Syndrome (PCS). Initially, a symptom course lasting three months after a diagnosed concussion was the standard required to meet diagnostic criteria for PCS. More recently, PCS has problematically been clinically diagnosed within a matter of days or weeks based primarily on mechanism of injury and resulting symptoms. This lack of diagnostic rigor is problematic with regard to tracking prevalence and recovery patterns, as well as researching PCS subtypes and response to treatment intervention. The American Medical Society for Sports Medicine (Harmon et al, 2013) as well as the recent 2016 Berlin Consensus in Sport Group and other professional organizations' position papers differ slightly, but shared features among all diagnostic formulae identify PCS as: (a) a physical hit or concussive force impact with generally immediate sequelae; (b) core resulting symptoms including headaches, balance problems, dizziness, fatigue, sleep disturbance (either sleeping too little or too much), noise/light sensitivity, visual changes, and dysregulated mood; (c) symptom course persisting beyond the *expected* recovery period of weeks to months post-injury, (d) with refractory symptoms not better explained by another etiology or maintained by secondary factors such as litigation or psychosocial gain. Despite general agreement on these criteria, there is a dire need for consensus in PCS diagnostic formulation.

1.2. Prevalence and demographics of sport concussion injuries

Overall, the CDC estimates 3 to 5 million concussions per year, a majority of which are due to accidents such as automobile accidents, falls in the elderly, and 17 percent due to sports (Centers for Disease Control and Prevention, 2011 & 2013). Of the estimated 45 million children and adolescents participating in organized or recreational sports (Ewing & Seefeldt, 2002), an estimated 5 to 10% receive a SRC with an emergency room presentation (Gilchrist, Thomas, Xu, McGuire, & Coronado, 2011). An additional 15 million adults participate in organized recreational sports. These figures are estimates based upon emergency room admissions which are acknowledged to underestimate prevalence, as many SRC do not receive medical care, especially at the level of emergency room presentation. At the college level of the 450,000 players participating in all sports, over 160,000 participate in sports identified as concussion generating (NCAA, 2012). At the professional level, there are fewer but more elite athletes participating, with an estimated 1600 players at some level in the National Football League, and about the same number in the National Hockey League. Concussion risk potential from such participation must be weighed against the well documented positive gains provided by sports participation on physical, social and intellectual development (Rieck, Jackson, Martin, Petrie & Greenleaf, 2013; Weiss, Kipp & Bolter, 2012) and mental health (Ahn & Fedewa, 2011).

Breakdown by sport and age indicates that a majority of youth concussions presenting to Emergency Departments and recorded as part of the surveillance studies in the United States are from playground and bicycle accidents. Once organized sports begin in the US public and private school settings, SRC prevalence data follow age and gender demographics for participation in contact/collision sports. Accordingly, American football and hockey in males and Soccer (European football), field hockey and volleyball injuries in females are primary SRC generators in the high school and collegiate population. At the professional level, males still dominate American football while soccer may be equally distributed, with SRC prevalence following these patterns.

1.3. Typical SRC recovery patterns

The 2016 Berlin Consensus statement cited most severe SRC symptoms in the first 24–72 hours post-injury, with a majority of balance, cognitive deficits and symptoms improving in the first two weeks post-injury. This typical SRC recovery course parallels the animal model research of Hovda and Giza cited above. However, further studies have shown prototypical but differing recovery courses based on prior SRC status, age and gender variables. In response to such, the Berlin Consensus acknowledged that "a sizable minority of youth, high school and collegiate athletes take much longer than 10 days to clinically recover and return to sport." The Consensus statement goes on to state: "At present it is reasonable to conclude that the large majority of injured athletes recover, from a clinical perspective, within the first month of injury." Development of subacute problems including depression and migraine headaches and pre-injury history of mental health problems or migraines were identified in this document as risk factors for symptom persistence of more than a month. Finally, teenage athletes, particularly of high school age, were identified as being most vulnerable for a persistent symptom course, with greater risk for female than male athletes. Consistent with these consensus statements, Neidecker, Gealt, Luksch & Weaver (2017) performed a retrospective medical record analysis of 11 to 18 year-old athletes who sustained first time SRC between 2011 and 2013 and found females remained symptomatic for longer time periods when compared with male athletes of similar age, regardless of sport played. Other studies have found that female concussed athletes generally report a higher number of symptoms than males, although there are confounding factors noted in these studies. Research has also examined how post-injury athlete symptom report varies depending on gender of the examiner, with data suggesting that a female examiner may elicit more symptoms than a male interviewer; whereas male athlete/male examiner dyads may yield the lowest symptom reports (Frommer, Gurka, Cross, Ingersoll, Comstock, & Saliba, 2011). These athlete-examiner gender dyads may present a confound when examining gender effects on concussion severity and recovery.

Nevertheless, the usual recovery course for a single, uncomplicated sport concussion in a collegiate or older athlete usually follows a consistent pattern of remission of symptoms in both frequency and severity over a time course extending from 7 to 10 days to a few weeks. Of course, this assumes that the athlete is following the current recommended treatment guidelines, which include immediate diagnosis and removal from sport.

1.4. Prolonged SRC recovery patterns

With regard to prolonged recovery, much research and clinical activity has focused on examining risk factors to explain why some athletes have prolonged sequelae and others do not. As with many aspects of science, the data is incomplete and sometimes contradictory, but currently is being guided by better studies on larger groups of concussed athletes (McCrea, McAllister, Hammeke, Powell, Barr & Kelly, 2009; Henry, Elbin, Collins, Marchetti & Kontos, 2016; Collins, Lovell, Leddy, Kozlowski, Fung, Pendergast & Willer, 2007). This article will examine prolonged recovery probability across three categories: premorbid, comorbid, and postmorbid risk factors.

1.4.1. Premorbid risk factors for prolonged recovery

Premorbid factors need to be investigated in any athlete with persistent PCS, as they may add to symptom burden or prolonged symptoms. Most frequently studied and cited in the Berlin Consensus is a personal or family history of migraine headaches, especially in female athletes (Kuczynski et al, 2013). Pre-existing personal and/or family history of migraines and/or headaches has been identified as a primary risk factor for posttraumatic migraines, which can be especially debilitating for a student-athlete Choe & Blume, 2016). Concern is noted that the diagnostic formulations of the International Classification of Headaches be followed and that the practitioner does not confuse chronic daily headache, tension or musculoskeletal headache, and migraine headache. Zasler (2015) and Arnold (2018) should be consulted as expert references for differential headache classification. More broadly, almost any pre-existing neurologic vulnerability should be recognized and examined as a premorbid risk factor, given that a concussion is a neurologic injury at its core. This would include any sort of early birth complications, seizure disorder, developmental delay or deviation, or history of sleep pathology. A history of depression or anxiety or other psychological disorder in the athlete or in first degree relatives may be a premorbid risk factor for prolonged concussion recovery (Broshek, DeMarco & Freeman, 2015; Hou, Moss-Morris, Peveler, Mogg, Bradley & Belli, 2012). Corollary to this, concussive injuries may exacerbate the expression and symptom burden of a pre-existing condition, such as ADHD, LD, migraines, depression, anxiety or visual dysfunction (Conder, 2018). More recent resiliency studies have identified pre-existing psychological coping resources of the athlete and his/her family as an important factor in mitigating the development or maintenance of symptoms. A person with flexible and adaptive psychological coping resources and a family system that is supportive but not symptom-reinforcing typically is better equipped to handle any injury, whether neurologic or orthopedic, than is the athlete without well-developed psychological coping resources.

1.4.2. Comorbid risk factors for prolonged recovery

Comorbid factors also can influence PCS severity, course and recovery. These include active and current modifying factors such as concurrent psychosocial stressors within the athlete and/or his or her family system (Broshek, DeMarco & Freeman, 2015); presence or loss of support from the athlete's teammates and/or peer group; impact of athlete's injury on team performance; financial implications; and new-onset psychosocial responses of the athlete to changes in their sense of resiliency or control.

1.4.3. Post-morbid risk factors for prolonged recovery

Post-morbid factors include anything that may inadvertently prolong the frequency, severity or persistence of PCS symptoms or recovery. While historically not a factor in the treatment of athletes, now the specter of litigation has to be considered with prolonged symptoms if there is a context of gain (Millis, 2015). Ponsford and Kinsella (1992) followed Emergency Department admissions from concussion by etiology and found that over a course of three months, symptom presentation dropped significantly for the sports concussion athletes, while those in litigation continued to report a high symptom burden. To a lesser extent, stressors within a psychosocial group may prolong symptom burden. Even within the primary family group, family dynamics in terms of the meaning of symptoms and their function may be important to evaluate. For example, a young child evaluated by one of the authors and followed for a period of time continued to report a high symptom burden, although almost all objective measures indicated a return to premorbid baseline. Clinical investigation of psychosocial factors eventually led to the child's candid acknowledgement of worry that "If I get better, my parents will divorce." While dramatic, this emphasizes the need to look "between the ears" to the larger nexus of the athlete's existential situation (Conder & Conder, 2015a). The astute clinician should carefully elucidate the above premorbid, comorbid, and post-morbid factors which may be prolonging concussion symptom report or expression (Iverson, Gardner, Terry, Ponsford, Sills, Broshek & Solomon, 2017).

1.5. Post concussive syndrome

As discussed above, there is a poignant need for a clear and consensus-based diagnostic schema for delineating a syndrome which can be diagnosed reliably across sports and geographic locations (Legome, 2018). Based on the PCS definition offered in a prior section, its diagnosis de facto predicts the need for treatment interventions beyond the passive healing effects of time and physical or cognitive rest to address refractory PCS symptoms. Predominant among these symptoms are migraines/headaches; sleep disturbance (sleeping too much or too little); mood instability such as anxiety, sadness or irritability; balance/vestibular symptoms; oculomotor/vision symptoms; and neurocognitive problems such as declines in attention/concentration, memory and processing speed. Lumba-Brown et al (2019) reviewed the efficacy of various PCS rating scales in organizing symptoms and found a lack of consistency and comprehensiveness among the scales. Additionally, Iverson (2006) points out that none of these symptoms are unique to PCS, and many may be driven by psychological etiologies including depression.

Assessment of symptom meaning and maintenance is best done by an experienced clinician undertaking a diagnostic investigation from the Bio-Psycho-Social formulation elucidated by many authors (Conder & Conder, 2015b; Yeates, 2010; Engel, 1997). A BioPsychoSocial assessment is a holistic formulation which examines symptoms and signs at multiple levels, as well as interaction among multiple systems which may prolong symptoms. It posits that a concussion will begin with a physiologic event (the concussive injury) which may trigger secondary biological sequelae (headaches, vestibular-oculomotor dysfunction) especially in those with premorbid vulnerabilities, with concomitant psychological and psychosocial factors at any stage likely to impact or mediate symptom expression and maintenance.

Kontos, Sufrinko, Sandel, Emami & Collins (2019) have postulated six rationally derived categories for characterizing potential sub-types of post concussive experience. These include: cognitive/fatigue, oculomotor; vestibular; cervical; migraine; and anxiety/mood. The utility of these sub-types is that they help group symptoms into meaningful clusters and focus treatment interventions, depending on the primary area of symptom report. These categories are not orthogonal and many times symptom clusters may be overlapping. Nevertheless, this approach has utility for assisting the clinician in marshaling treatment resources. More research is needed to establish the empirical validity of these sub-types.

2. Neurorehabilitation and treatment of SRC

2.1. Guiding principles for rehabilitation: Regulation, resilience and mindfulness

While concussions are primarily assumed to be a central nervous system etiology, there are parallel Autonomic Nervous System (ANS) alterations associated with the concussive event (Goodman, Vargas, & Dodick, 2013, Hanna-Pladdy, Berry, Bennett & Phillips, 2001). These may be generated by brainstem injury but affect multiple levels of functioning. Other physiological concussion sequelae can also impact functioning. For example, research has identified EEG changes (Thatcher, 2006) and cardiac correlates including alteration in Heart Rate Variability (HRV) following concussion (Conder & Conder, 2014; Gall, Parkhouse & Goodman, 2004; Len, Nearly, Asmundson, Goodman, Bjornson & Bhambhani, 2011). All of these psychophysiological sequelae pinpoint Regulation as a primary function disrupted by concussion and amenable to targeted psychological, neuropsychological, or psychophysiological PCS treatment interventions and rehabilitation.

Resilience is defined as an enduring quality of proactive adaptation to adversity (Sisto, Vicinanza, Campanozzi, Ricci, Tartaglini, & Tambone, 2019). The concept of resilience has been widely studied in the field of Sport Psychology (Fletcher & Sarkar, 2012), focusing on factors that enhance performance and protect against or ameliorate negative outcomes in the face of adverse circumstances such as injury or poor performance. Just as risk factor analysis targets athletes with higher likelihood of prolonged PCS recovery, resilience data can identify protective factors to reduce symptom burden or promote coping post-injury. LeUnes (2008) posits a gradient in physiologic resilience as athletes progress from recreational to more elite levels, with professional or elite athletes more invulnerable to potentially career-ending injuries. Treatment techniques which foster resilience can be integrated with other rehabilitation interventions to maximize recovery.

Mindfulness is a new "buzz" word with a very old basis. Mindfulness as a meditative technique dates back to the 14th century, emerging from monastic and Buddhist traditions. Mindfulness meditation endorses observing phenomenon without judging or reacting. Its focus on accepting and allowing, rather than trying to actively control, undesirable experiences and symptoms fosters ANS regulation by activating the parasympathetic nervous system critical for rest and recovery functions (Criswell, 2017). In doing so, Mindfulness-based interventions can have desirable physiological and psychological effects which foster resilience in the face of adversity and enhance treatment response. Currently, mindfulness is being used not only for every day psychological enhancement but as part of treatment approaches for stress; chronic illnesses such as cardiac disease or cancer; and chronic and post-traumatic headaches or migraines. Inna Khazan at Harvard Medical School (Khazan, 2013) recommends combining mindfulness meditation techniques with biofeedback or with HRV in the treatment of PCS.

2.2. *Education as PCS treatment*

One of the most benign treatments offered has been education, provided primarily by means of hand-outs supplied by Emergency Departments and healthcare personnel with a background in mild traumatic brain injury. Used in isolation, this treatment approach traditionally has had limited efficacy, as many concussed athletes may not present to these facilities and not all primary care physicians were aware of new guidelines. This challenge has been admirably addressed over the past 15 years by efforts from the CDC to widely disseminate free downloadable, comprehensive educational resources including the CDC "Heads Up!" Concussion materials (www.cdc.gov/HeadsUp/) geared toward players, coaches, sports officials, and parents. The Heads Up materials are particularly suitable for K-12 sports participants and are made readily available to coaches, trainers, emergency rooms, urgent care clinics, sports medicine centers, physicians and youth sports organizations. With US state legislation mandates regarding concussion education and management in all 50 states and the District of Columbia, there is incentive by schools, trainers and concussion health care providers to document their own education and training and that they have taken steps to educate participants and parents. In the latest iteration, education efforts have extended to on-line training programs that document various stakeholders have received and understand concussion education and/or concussion management training.

Collegiate/NCAA and professional sports organizations have specific SRC training programs for their healthcare personnel based on the consensus data from the Zurich and Berlin conferences[1]. The National Football League, National Hockey League, and Major League Soccer also use a neuropsychological concussion evaluation model (Lovell, 2006). Similary, many professional organizations have developed specific concussion education and management guidelines for their disciplines, such as the American Medical Society for Sports Medicine, the American Academy of Neurology and the National Association of Athletic Trainers (NATA) (Echemendia, Giza, & Kutcher, 2015). Of the above, the NATA position statement is one of the most comprehensive and pragmatic documents available, readily implemented across medical and neuropsychological disciplines (Broglio et al., 2014). Overall, education plays a crucial first step in treatment, as evidence-based knowledge prompts players, parents and coaches to quickly recognize and appropriately manage a concussive injury.

2.3. *Cognitive behavior therapy and psychotherapeutic interventions*

Cognitive Behavioral Therapy (CBT) has long recognized efficacy in the treatment of depression (Beck & Beck, 2011) and was one of the initial approaches to be is utilized as a first line treatment for anxiety and depressive reactions in athletes with refractory sports concussion (Hou, Moss-Morris, Peveler,

[1] www.ncaa.org/health-and-safetyconcussion-guidelines

Mogg, Bradley, & Belli, 2012). Using a modified CBT framework, the first stage in working with the injured athlete is to educate and alert them to identify maladaptive cognitions and distortions such as Overgeneralization and Catastrophizing that either result from the injury, or prolong recovery by maintaining symptoms. For example, athletes may see their concussion and need for supports as a sign of weakness, may stress that protracted recovery will transform into a career-ending event, or harbour a catastrophic fear that they will develop CTE, the latter not helped by distorted media attention. For elite athletes reluctant to consider pharmacotherapy, a modified CBT approach may have the added advantage of symptom control based on procedures that foster an internal locus of control over the recovery process and formulation of action plans congruent with an athlete's natural preference for self-efficacy (Feltz, 1984; Beauchamp, Jacksons & Morton, 2012). Another application of CBT in concussion rehabilitation addresses insomnia and parasomnias, as sleep disturbance is increasingly recognized as prominent in refractory SRC (Kostyun, Milewski, & Hafeez, 2014). CBT for Insomnia (CBT-I) protocols (Jacobs et al., 2004) are an alternative for those athletes who do not like or tolerate the sedating properties of sleep medication, or have poor sleep hygiene impacting recovery. CBT-I also could be paired with pharmacotherapy or relaxation training to potentiate normalization of sleep.

2.4. Behavioral medicine approaches in SRC rehabilitation

Behavioral Medicine approaches including training in relaxation and stress management are readily used by athletes to optimize sports performance and manage undesirable post-injury symptoms. In refractory concussion, athletes respond well to training in breathing exercises, progressive relaxation, positive imagery, autogenic phrases and mindfulness meditation (Brown & Gerbang, 2009; Jacobson, 1938; Norris, Fahrion & Oikawa, 2003) to reduce acute stress, headaches and autonomic arousal. Many elite and Olympic athletes know the value of breathing for enhancing performance and self-regulation and have worked with various breathing routines (Wilson & Cummings, 2011) so they respond well to yogic or diaphragmatic breathing training. Specific relaxation and/or hypnotic induction tapes or CDs are commercially available or can be individually made by a therapist for the athlete's specific circumstances (Schwartz, 2003). The latter tend to be more effective due to personalization of the athlete's situation and needs. These audio files can be made in the office with the athlete present, then an MP3 file can be given to the athlete for use outside of the office. Similarly, once trained in the relaxation response, injured athletes can implement breathing, imagery and/or meditation strategies in the naturalistic setting to reduce PCS symptoms.

2.5. Cognitive rehabilitation

Cognitive rehabilitation (CR) is the use of cognitive techniques to rehabilitate impaired information processing after a neurologic event such as a concussion, TBI, or CVA (Conder et al., 1988; Conder 1992). Kreutzer, Conder, Wehman and Morrison (1989) were early researchers examining the use of cognitive rehabilitation to enhance independent living and vocational outcome post mTBI. More recently, Cicerone and colleagues (Cicerone et al., 2011; Cicerone et al., 2005) have elucidated a cognitive rehabilitation schema in association with the American Congress of Rehabilitation Medicine. Most often PCS sequelae include problems with basic attention and concentration functions. Not only are these deficits problematic in their own right, but from an information processing view of cognition, attention/concentration are the gateways for information to flow to higher levels of cognitive processing including memory, problem-solving and executive functioning. An everyday example of this complex relationship is the injured student-athlete who experiences trouble attending to detail and maintaining focus upon returning to school or remembering specific plays on the field, which in turn creates cognitive fatigue and problems remembering reading assignments, studying effectively or executing plays. Without CR support, attempts to "gut it out" are likely to trigger headaches and stress, which in a cyclic manner further diminish strained attention resources. In the initial phases of recovery, direct teaching and practicing of strategies to remediate attention and working memory is advocated. After the athlete is symptom free, tolerating computer or screen-time activities, computerized cognitive rehabilitation programs targeting specific impaired/altered neurocognitive functions can also be efficacious both in an office setting and remotely for home use. Helmich (2010) presents a consensus conference review of cognitive rehabilitation for military personnel with refractory PCS and mTBI injuries.

2.6. Academic and work modifications

In conjunction with the cognitive rehabilitation interventions reviewed above, academic and work modifications can be critical in addressing persistent post-concussive functional declines in vocational and educational settings. Most common yet complex are the problems experienced by injured student-athletes in the classroom, especially those enrolled in more demanding academic pursuits such as college students or high school students taking Advanced Placement or International Baccalaureate courses. At the other end of the spectrum, student-athletes with pre-existing ADHD or learning disabilities often experience magnified impairments that severely compromise post-SRC academic re-entry. Given that concussions at a neurophysiological level affect the information-processing capacities of the brain, any activity dependent upon the integrity of the brain may be attenuated. Academic settings not only primarily focus on brain-based processes for new learning consolidation (which are generally harder than post-injury resumption of routine vocational skills), but have the added age burden of a population where brain development is not yet complete at the time of injury.

Within this context, recent efforts have focused on Return-to-Learn (RTL) needs of concussed student-athletes (Halstead, McAvoy, Devorc, Carl, Lee, & Logan, 2013). Cognitive re-entry is more successful with tailored supports to address cognitive-academic functions still recovering at the time of school re-entry (Conder, 2011). Typical academic modifications to reduce the compromising impact of PCS-related declines in attention, memory, processing speed, visual tracking/accommodation, or cognitive stamina include: provision of class notes and Power-Points; reduced screen time and reading activities, modified assignments and extended assignment deadlines, more frequent breaks and repetition, and test modifications (Conder, 2013; Conder, 2018). A tailored, practical problem-solving approach is indicated in these situations rather than uniform or global recommendations that may actually hinder recovery or add to academic stress. For example, exemption from all assignments or prolonged medical leave may be detrimental in a majority of cases, whereas successful school re-entry benefits from analysis of which activities for what duration trigger symptoms or require impaired resources in a particular student. A recent study by Reiger, Lewandowski, Potts, and Shea (2019) highlighted the need for interventions to target anxiety and stress about academic concerns as an integral part of PCS recovery.

2.7. Biofeedback interventions in SRC rehabilitation

Biofeedback (BFB) interventions, also known as psychophysiological intervention, have a long and efficacious history in the behavioral medicine literature (Norris et al., 2003; Schwartz & Andrasik, 2016) and in the sports psychology literature (Wilson & Cummings, 2011; Blumenstein & Orbach, 2012; Conder & Conder, 2014; Wilson & Somers, 2011). They provide an adjunct treatment for somatic complaints that have a psychophysiological component or provide information that can improve optimal performance in elite athletes (Beauchamp, Harvey & Beauchamp, 2012). Traditionally, BFB methods such as temperature biofeedback in the peripheries, galvanic skin response/electrodermal response, and electromyography have been used successfully with medical conditions such as chronic headaches or vestibular problems, and psychological conditions including depression or anxiety. It is unsurprising, therefore, that these techniques have applicability to these same complaints presenting in the context of a refractory PCS process.

A primary advantage of psychophysiological BFB protocols in post-concussion treatment is their provision of sensitive, objective physiologic measures of interest, which can provide data independent of subjective symptom report. There are no true biomarkers for concussion that are generally accepted. However, the Institute of Medicine report notes alteration on numerous neurophysiologic parameters post-concussion, such as fMRI, DTI, MEG, and Evoked Potentials. BFB data can be instrumental in objectifying athlete symptom report, identifying dysregulated systems, and identifying targets for BFB and psychotherapeutic treatment intervention, with the ultimate goal of teaching self-regulation. After a concussion, post-traumatic headaches and cardiovascular changes may cause vasoconstriction leading to significant alterations in temperature regulation in the extremities, which can be assessed and intervened with traditional thermal biofeedback. Muscle contraction headaches can be treated effectively with electromyography BFB measuring tension at the frontalis and masseter muscle sites. Finally, electrodermal response (GSR) is very sensitive to negative thinking, making it possible to objectively measure changes in GSR within seconds of a maladaptive thought or awareness of a stressor (Mann & Janelle, 2012).

2.8. Heart rate variability biofeedback (HRV-B)

An evidence-based form of psychophysiological biofeedback for sports performance and SRC rehabilitation is heart rate variability (HRV) training, discussed in detail by Conder and Conder, 2014; Tan, Fink, Dao, Hebert, Farmer, Sanders, A., . . . Gevirtz, 2009. As noted above, there are cardiac consequences of a concussion. These most often include reduced cerebral perfusion with exertion post-concussion (needed by athletes attempting to perform at their normal strenuous competitive level). Essentially, the healthy heart has variability in heart rate, measured by the R-wave intervals, which may reflect an alteration between input from the sympathetic and parasympathetic branches of the ANS (Strack & Gevertz, 2011). In cardiopathology, there is reduced variability between R-waves which reflects illness and which can predict serious cardiac events. Multiple studies have shown that an athlete's heart rate variability is reduced post-concussion (Gall, Parkhouse & Goodman, 2004), reflecting ANS changes driven by the vagus nerve, both at rest and more importantly at exertion. Post-concussive changes in cardiac inter-beat variability can be measured with the traditional biofeedback protocol in the laboratory, such as using the protocol of Leddy with the Buffalo Treadmill Test (Leddy, Haider, & Willer, 2018). This reduction in heart rate variability post-concussion may have implications for changes in cardiac demand while performing sports, as well as reduced cerebrovascular perfusion. Lagos, Thompson, and Vaschillo (2013) modified Lehrer's heart rate variability training successfully with concussed adolescents. In HRV-B training, an athlete learns to increase variability through respiratory sinus arrhythmia resonant frequency breathing. While the resonant frequency varies by individual physiology, gender and age, it is usually between four to seven breaths per minute (BPM), with six BPM as the modal rate. Cognitive correlates of heart rate variability training, especially in the low frequency band, have shown improvement in complex neurocognitive performance including executive functioning. There are portable instruments to assess and treat not only heart rate variability but also temperature and EDR that the athletes can use in everyday life, including during athletic practice. HRV-B treatment provides an objective measure of heart-brain connectivity impacting persistent SRC, and preliminary studies by the military and clinical researchers suggest promising efficacy in promoting a quicker return to pre-injury status.

3. Conclusions

As noted above, there is a need for reliable and valid diagnostic schema for identifying concussions and diagnosing Persisting Post Concussive Syndrome that can be adopted by all practitioners for all sports in all geographic regions. This reliable diagnostic formulation would help with understanding and studying the phenomenon of PCS, perhaps leading to more effective and focussed treatment. As also noted and discussed, PCS is not an entity unto itself and its symptoms are shared with other disorders, particularly depression and anxiety. Consequently, a comprehensive differential diagnostic approach from the Bio-Psycho-Social formulation is needed to understand not only the degree of biological injury, but the syndrome's manifestation based on premorbid and comorbid psychological factors occurring within a psychosocial context. These phenomena should be examined for their role in prolonging presentation of symptom degree and frequency. Not only is analysis of secondary gain needed, but also analysis of primary gain to better understand intrapsychic, social and family systems factors impacting the PCS presentation. Unfortunately, the specter of litigation also must be factored in as a component that can prolong symptom presentation. Further, a fundamental misunderstanding of PCS and concussions, in general, is promulgated by the popular media and/or by persons who may have an interest in prolonging the symptoms, and are not cognizant of relevant, rapidly evolving neuroscience literature. Appreciation and attention to all of these factors can improve concussion management and protect the health and safety of student-athletes.

Future directions should include further investigation of objective biomarkers. Evoked Potentials have been shown to be altered for up to a year in concussed collegiate athletes and may serve as a viable biomarker (Broglio, 2009). However, not all practitioners may have the availability of equipment to measure this. A discussion of computerized testing is out of the scope of this paper but other studies should be consulted which elucidate the problems with reliability and validity of such forms of administration (Schatz & Maelender, 2013; Maelender et al, 2013; Malerlender et al, 2010). The authors would generally advocate that computerized testing results in and of themselves be interpreted cautiously, due to general problems with reliability. From a philosophy of science perspective, they provide one level of data to be considered within an overall clinical formulation undertaken and synthesized by a qualified practitioner in their diagnostic decision-making. Ultimately, the diagnosis of Persistent Sports Related Concussion is the burden of a skilled diagnostician, as inappropriate diagnosis of this syndrome can lead to symptom burden and morbidity, when not necessary. Going forward and guided by better research studies, it is hoped that clinicians will be more inclined to rely on a variety of assessment modalities, including objective physiological and psychophysiological data in addition to the clinical examination and neurocognitive assessment, assist in diagnostic formulation and treatment intervention development for concussed athletes. While concussive injury is a physiologic and neurophysiologic entity, persistent sport related concussion should be recognized as a psychophysiological entity best elucidated using a BioPsychoSocial diagnostic formulation to guide diagnostic accuracy and formulate treatment and neurorehabilitation interventions to maximize symptom remission.

Conflict of interest

All of the authors declare they have no conflict of interest. No sources of funding nor outside support was received for this project.

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