# Chapter 5
# Feasibility of Electroencephalography for Direct Assessment of Concussion

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**Abstract** In this chapter, we will focus on sport-related concussions as studied through the use of electroencephalography. It should be noted that in this chapter the terms concussion and mild traumatic brain injury are used interchangeably.

**Keywords** Concussion • EEG • Power analysis • Coherence

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## Introduction

Worldwide, concussion is a critical public health problem that can lead to a variety of neurocognitive and psychological problems [1]. These problems can include loss of consciousness, cognitive deficits, depression, and, at a later period, the onset of dementia [2]. Concussion has been referred to as a "silent epidemic" and it is currently estimated that 1.6–3.8 million concussions occur each year in the United States, which may still be an underestimate [2]. Concussions can result from any event that causes the brain to make an impact with the skull. The most common examples are automobile accidents and contact sports.

Recent media presentations and scientific research have emphasized the role of concussion in athletics. The National Football League has supported studies of the long-term effects of concussion in professional athletes. Many universities have established centers for the study of concussion and several states have established laws related to concussion assessment and management in high school athletics as well as return to play guidelines. High school athletes are particularly at risk since surveys suggest that this group believes that there is not a problem playing sports with a concussion. Returning to sport before the concussion has been fully resolved can increase long-term injuries. Since adolescence is a time in which an individual's brain goes through a series of cortical reorganizations, brain insults at this time put the adolescent at greater risk for serious injury. For college and professional athletes, different pressures may cause players to ignore information concerning the effects of concussion. Overall, this can lead to a lack of candor when athletes at all levels describe their symptoms. Thus, it is critical to utilize measures that evaluate the effects of concussion beyond the traditional signs and symptoms seen with the disorder.

Acceleration/deceleration forces commonly lead to concussive injuries, which often produce diffuse microstructural injury. Due to the diffuse nature of these injuries, standard structural imaging, such as MRI and CT, may not be able to identify all abnormalities [3]. Instead of the gross structural damage or lesions found in penetrating head injury or severe traumatic brain injuries (TBIs), concussive episodes are characterized by their cognitive dysfunction, specifically in information processing and working memory [3].

## Need for Physiologic Measurement in Clinical Concussion Diagnosis/Management

Athletic participation is unique in its requirement of the able bodied participant. Physicians and allied health professionals making recommendations for athletes returning to sport from concussion or mild traumatic brain injury (mTBI) must ultimately be comfortable with the concept of repeated injury. In other words, clinicians must ensure that an athlete recovering from concussion to full athletic participation be as resilient to head trauma as a non-head-injured healthy athlete. Ultimately, clinicians must be assured that the athletes' risk of short-term or long-term effects from their concussive episode has been minimized as best as possible.

With these important clinical considerations in mind, management of sports-related concussion or mTBI must evolve beyond the limitations in the currently accepted definition of concussion describing *functional* recovery from concussion being representative of clinical healing. Considering the number of mTBI-linked short-term and long-term physical and mental health issues [4–7], clinicians and researchers alike must take important steps to ensure proper management of the athlete recovering from mTBI. Intense scrutiny of residual physiological and functional deficits as well as measuring and monitoring the athlete's rate of pathophysiological recovery from concussive injuries must become our primary focus. By increasing our collective efforts we can look to reduce significant short- and long-term health issues. Yet despite this need, clinical management of the mild head-injured athlete has not changed in decades.

One of the reasons that clinical management of concussion has remained largely unchanged is due partly to a disproportionate focus on functional cognitive testing. Neuropsychological testing remains the mainstay in determining the clinical recovery for the concussed athlete. As neuropsychological testing is limited to cognitive functional performance, it has seemingly maximized its clinical utility at present. Therefore, clinical researchers need to push the constructs of other applicable and relevant diagnostic tools to provide athletes recovering from sports-related concussion with better assessment and management tools. These tools must be able to distinguish residual functional *and* structural (physiological) recovery from mTBI. As both diffuse functional and structural injuries are present in mTBI [8, 9] clinicians and researchers must develop and research both functional and structural diagnostic tools when treating the athlete recovering from concussion. Due to the diffuse nature of the injury and the consequential cognitive dysfunction, electroencephalographies (EEGs), which are able to systematically evaluate the underlying neural process that contributes to functional networks, are a sensitive and appropriate tool to evaluate the effects of concussive episodes.

Several organizations include the presence of pathophysiology in their definitions of concussion. Thus, it seems appropriate to utilize a physiological measure to denote the presence of concussion. One such measure capable of this is EEG. The EEG was first demonstrated in humans by Hans Berger in 1924 and published 5 years later [10]. Since the neurons of the brain and their connections are constantly active, EEG can be measured in an individual both during conscious and unconscious states as seen in sleep and brain trauma. As such, EEG was the first brain assessment tool that was able to establish an alteration in brain function in a TBI population [11–13] and has continued to be useful in the brain injury field.

Early EEG research with 300 patients clearly demonstrated the slowing of major frequency bands and focal abnormalities within 48 h post-injury [14]. A study by McClelland et al. has shown that EEG recordings performed during the immediate post-concussion period demonstrated a large amount of "diffusely distributed slow-wave potentials," which were markedly reduced when recordings were performed 6 weeks after injury [15]. Additionally, Tebano et al. showed a shift in the mean frequency in the alpha (8–10 Hz) band toward lower power and an overall decrease of beta (14–18 Hz) power in patients suffering from mTBI [16]. The reduction of theta power [17] accompanying a transient increase of alpha–theta ratios [18, 19] was identified as residual symptoms in mTBI patients.

At the beginning of the twenty-first century, Gaetz and Bernstein [3] cited electrophysiological techniques as the most commonly used method to evaluate brain functioning, noting the relatively low cost, noninvasive nature of the test, and the long, well-documented history dating back to the 1930s. Leon-Carrion et al. [20] echo the benefits defined by Gaetz and Bernstein and also speak to the uncomplicated procedure, high test–retest reliability, and characteristic stability of EEG as additional features that contribute to its appropriateness as a diagnostic testing tool.

## The Nature of EEG

EEG reflects the electrical activity of the brain at the level of the synapse [21]. It is the product of changing excitatory and inhibitory currents. More specifically, graded postsynaptic potentials of the cell body and dendrites of vertically orientated pyramidal cells in cortical layers three to five give rise to the EEG recorded on the scalp. The ability to record the relatively small voltage at the scalp from these actions results from the fact that pyramidal cells tend to share a similar orientation and polarity and may be synchronously activated. Action potentials contribute very little to the EEG. However, since changes at the synapse do influence the production of action potentials, there is an association of EEG with spike trains [22]. The summation of these electrophysiological measures is precisely what makes EEGs better suited for the study of mTBI compared to several other types of brain imaging techniques.

Historically, the system of locating electrodes in EEG is referred to as the International 10–20 system [23]. The name 10–20 refers to the fact that electrodes in this system are placed at sites 10 and 20 % from four anatomical landmarks. One landmark is the front of the nasion (the bridge of the nose). In the rear of the head, the inion (the bump at the back of the head just above the neck) is used. The left and right landmarks are the preauricular points (depressions in front of the ears above the cheekbone). In this system, the letters refer to areas of the brain; O = occipital, P = parietal, C = central, F = frontal, and T = temporal. Numerical subscripts indicate laterality (odd numbers left, even right) and degree of displacement from the midline (subscripted z). Thus, C3 describes an electrode over the central region of the brain on the left side whereas Cz would refer to an electrode placed at the top of the scalp above the central area. With the development of dense array systems, the historical 10–20 system has been greatly expanded.

To record the EEG, electrical signals of only a few microvolts must be detected on the scalp. A signal can be found by amplifying the differential between two electrodes, at least one of which is placed on the scalp. Since the signal must be amplified almost one million times, care must be taken that the resulting signal is indeed actual EEG and not artifact. Where the electrodes are placed and how many are used depend on the purpose of the recording. Almost all EEG procedures currently use a variety of EEG caps with up to 256 electrodes built into the cap, although it is always possible to record EEG from only two electrodes.

**Table 5.1** Frequency ranges for each given bandwidth

| Bandwidth name | Frequency (Hz) |
|---|---|
| Delta | 0–4 |
| Theta | 4–8 |
| Alpha | 8–13 |
| Beta1 | 13–24 |
| Beta2 | 24–32 |
| Gamma | 32–60 |

Those recording caps that use 128–256 electrodes are generally referred to as dense array EEG recordings and are used in most research settings. However, research in clinical situations, such as the hospital emergency room, has shown that as few as five electrodes can be used for the screening of mTBIs [24]. In this study, EEG showed a 94.7 % accuracy rate when compared with computed tomography for detecting mTBIs. This underlines the potential of using even simple EEG montages for detecting concussions in a sports setting.

## *EEG Frequency Bands*

One important parameter of EEG is a determination of frequency. Although there are some minor discrepancies in the literature in terms of the beginning and ending of specific frequency band, a general template is presented in Table 5.1. Frequency bands are generally determined through signal processing technique such as Fourier analysis and wavelet analysis.

Alpha activity can be seen in about three-fourths of all individuals when they are awake and relaxed. Asking these individuals to further relax and close their eyes will result in recurring periods of several seconds in which the EEG consists of relatively large, rhythmic waves of about 8–12 Hz. This is the *alpha rhythm*, the presence of which has been related to relaxation and the lack of active cognitive processes. If someone who displays alpha activity is asked to perform cognitive activity such as solving an arithmetic problem in his or her head, alpha activity will no longer be present in the EEG. This is referred to as alpha blocking. Typically, cognitive activity causes the alpha rhythm to be replaced by high frequency, low amplitude EEG activity referred to as beta activity. Since the discovery of the alpha rhythm, a variety of studies have focused on its relationship to psychological processes and broad developments of the cognitive and affective neurosciences amplified this interest (see [25, 26] for reviews).

High frequency activity occurs when one is alert. Traditionally, lower-voltage variations ranging from about 18 to 30 Hz have been referred to as beta and higher frequency lower-voltage variations ranging from about 30 to 70 Hz or higher are referred to as gamma. Initial work suggests that gamma activity is related to the brain's ability to integrate a variety of stimuli into a coherent whole.

For example, Catherine Tallon-Baudry and her colleagues [27] showed individuals pictures of a hidden Dalmatian dog that was difficult to see because of the black and white background. After training individuals to see the dog, differences in the gamma band suggested meaningful and non-meaningful stimuli produced differential responses.

Additional patterns of spontaneous EEG activity include delta activity (0.5–4 Hz), theta activity (5–7 Hz), and lambda and K-complex waves and sleep spindles, which are not defined solely in terms of frequency. Theta activity refers to EEG activity in the 4–8 Hz range. Grey Walter [28], who introduced the term theta rhythm, suggested that theta was seen at the cessation of a pleasurable activity. More recent research associated theta with such processes as hypnagogic imagery, REM (rapid eye movement) sleep, problem solving, attention, and hypnosis. Source analysis of midline theta suggests that the anterior cingulate is involved in its generation [29]. In an early review of theta activity, Schacter [30] suggested that there are actually two different types of theta activity: First, there is theta activity associated with low levels of alertness as would be seen as one falls asleep. Secondly, there is theta activity associated with attention and active and efficient processing of cognitive and perceptual tasks. This is consistent with the suggestion of Vogel et al. [31] that there are two types of behavioral inhibition, one associated with a gross inactivation of an entire excitatory process resulting in less active behavioral states and one associated with selective inactivity as seen in overlearned processes.

Delta activity is low frequency (0.5–4 Hz) and has been traditionally associated with sleep in healthy humans as well as pathological conditions including cerebral infarct, contusion, local infection, tumor, epileptic foci, and subdural hematoma. The idea is that these types of disorders influence the neural tissue that in turn creates abnormal neural activity in the delta range by cutting off these tissues from major input sources. Although these observations were first seen with intracranial electrodes, more recent work has found similar result using MEG and EEG techniques. Additionally, EEG delta activity is the predominant frequency of human infants during the first 2 years of life.

## *EEG and Concussion*

While conventional EEGs are not part of the current clinical "gold-standard" assessment battery, a number of studies show EEG differences in those individuals suffering from mTBI compared to healthy controls (see [32] for an overview). Of the differences observed on conventional EEGs, the most common abnormalities seen are generalized or focal slowing as well as weakened posterior alpha in mTBI patients [14, 33, 34]. These deficits were found in the immediate post-injury period (within a few hours of a concussive episode); however, similar findings have been reported even when there is a longer period between injury occurrence and injury evaluation.

These common abnormalities seen on conventional EEG recordings usually resolve within the first few months post-injury [35], similar to the resolution of functional and symptomatic deficits in typical concussive recovery. However, up to 10 % of individuals diagnosed with mTBI still show atypical electrophysiological readings in the late post-injury period [35, 36]. This small but significant portion of individuals who show electrophysiological abnormalities in the late post-injury period parallels those individuals who have atypical resolution of concussive symptoms and functioning.

Traditionally, in clinical settings, conventional EEGs were interpreted by the visual inspection of raw EEG signals. However, studies show that visual inspection of EEG lacks the sensitivity to detect changes following mTBI. With the advancement of computerized signal processing techniques, there is a growing body of literature that suggests more complex EEG paradigms may be used to assess changes in functional status after concussive injuries [3]. Compared to visually inspected EEGs, computerized EEG analyses are advantageous because they can detect subtle differences in signal patterns and shifts not visible to the naked eye [8]. Due to these benefits, Cannon et al. [37] indicated that the usefulness of EEG as an assessment tool for brain injury is due to its "direct signature of neural activity" and "ideal temporal resolution."

Several different types of variables can be isolated using quantitative EEG methods. Spectral analysis, relative amplitude and power in a particular frequency bandwidth, coherence, and phase are the most common types of analyses performed in EEGs. In terms of TBI, frequency and coherence analyses of particular cortical areas can offer important information [3, 8, 38]. By examining the pattern of activity between the cortical areas, it is also possible to delineate brain networks, see how they are involved in different types of tasks, and determine how they differ under certain conditions such as the presence of a concussion.

Coherence analysis describes how the EEG signal at each of two electrodes is related to one another. In simple terms, coherence reflects the manner in which two signals "covary" at a particular frequency. In specific, coherence measurements represent the correlation of signal phase stability between two different electrodes. Coherence measures within the same frequency band offer an estimate of the temporal relationships between adjacent neural systems. Like correlation, coherence is a measure between 0 and 1, where 1 represents a perfect phase correlation between two groups and 0 represents no correlation. Thus, in performing the coherence analysis, one can also obtain a measure of phase or synchrony.

The particular interest in EEG coherence is due to the biological nature of concussive injury. The brain structures involved in neural connectivity, such as the reticular system activation and thalamocortical tracts, are the structures most likely to be affected by mTBI. Considering the probability that these areas are altered following concussion, frequency and coherence analyses are likely to be the most sensitive electrophysiological measures to indicate deficits due to concussive injury.

According to Arciniegas [8], frequency measures can vary with the number of neurons (smaller number, smaller amplitude/power), the integrity of the thalamocortical circuits in which the neurons contribute (injury to the circuit causes slower frequencies), and the influence of activation from the reticular system (increases in reticular system activity cause higher frequencies, while decreases in reticular system activity cause lower frequencies).

Coherence, which by definition correlates the frequency measures between two different electrodes, may indicate the level of communication between different areas of the brain and signify neural network connectivity and dynamics [8]. Reduced coherence values can be attributed to damage in myelinated fibers and/or gray matter [38]. If lowered coherence values are seen in mTBI patients, it is still unknown which of these factors, or if a combination of all of them, produce these results.

Each concussive episode is individualized and may produce different changes in the brain. In turn, one might expect that the respective EEG measures would be different in each mTBI patient. While the electrophysiological deficits found for each concussive episode remain unique, several consistent EEG patterns have been identified. According to a review by Arciniegas [8], the most common EEG findings in mTBI include: (1) a decrease in mean alpha frequency [16, 19, 39–42], increase in theta activity [15, 17, 43, 44], or increased alpha–theta ratio [18, 19, 39, 42] and (2) lessened alpha and beta power between anterior and posterior regions, weakened alpha power (posterior region), and increased coherence between frontal and temporal regions [45–47].

Along with these findings, a literature review by Nuwer et al. [34] listed other common EEG findings after concussive episodes. These findings concluded that changes in EEG measures resolved along the same timeline as symptoms, with gradual changes mainly occurring over weeks to months. The researchers also found that left temporal slowing may correspond to lingering cognitive symptoms. In all the studies evaluated by Nuwer, coherence was not correlated to outcome or diffuse axonal injury. Due to how quickly EEG patterns can change in an mTBI population [8], it is critically important that research involving individuals being tested after a concussive injury are evaluated in as similar time points as possible.

Evidence provided by Thornton [48] and Thatcher et al. [49] indicates that the EEG patterns seen in a concussed athlete do not quickly change over time and, therefore, should be present at the initial time of injury. While this is useful in describing EEG as a possible tool in diagnosing and evaluating concussed individuals, it also indicates that concussive episodes, even "mild" or "typical" episodes, cause long lasting alterations in brain electrophysiology. Work by Barr et al. [50] showed that despite improvement or normal levels of cognitive functioning, brain patterns remain altered in mTBI patients. This further suggests that the brain may not completely heal from concussive episodes; instead the individual learns to compensate for the deficit in order to achieve normal performance. The idea of compensation instead of recovery has been examined in a study by Thornton [51] and discussed in a book chapter [38].

Two prominent studies have examined the reproducibility of EEG absolute measures. First, a study by Corsi-Cabrera et al. [52] tested nine subjects 11 times over a 1-month period. When looking at absolute amplitude, the median correlation coefficient over the 11 sessions was 0.94. Alpha and beta bands showed greater variability than any of the other bands. Pollock et al. [53] evaluated test–retest reliability in each bandwidth over a 20-week period on 46 normal controls.

Absolute amplitude in theta, alpha, and beta1 had correlation coefficients that exceeded 0.60. Beta2 and delta correlation coefficients were found to be lower, with delta showing the poorest correlation. The authors also found that absolute amplitude has higher correlation coefficients than relative power and is, therefore, recommended for use in future studies. The high levels of correlation found in these studies, combined with the varying intervals between testing sessions (a common feature in concussion testing), imply that absolute amplitude is an appropriate measure for research purposes.

Although related to amplitude, several studies have separately analyzed the reproducibility of power. Salinsky et al. [54] tested absolute and relative power and found correlation coefficients of 0.84. Tests were run between 12 and 16 weeks apart on 25 normal controls. Cannon et al. [37] examined test–retest EEG power reliability by examining 19 normative controls over a 30-day testing period. Each participant was recorded for a 4-min interval under an eyes open and eyes closed condition. Intraclass correlation coefficients (ICCs) for absolute power were 0.90 for eyes closed data and 0.77 for eyes open data. The results of these studies closely mimic those found when evaluating amplitude, with power having sufficiently high levels of reliability over both short (days) and long (months) testing periods.

Mathematically distinct from amplitude and power, researchers have spent time considering the reproducibility of coherence values. Studies by Harmony et al. [55] and Nikulin and Brismar [56] evaluated the reproducibility of coherence during rest and cognitive tasks in individuals. Both studies found good correlations within a given task or under resting state conditions but Harmony et al. reported much lower correlation values between sessions, even within the same subject during the same condition.

While these early tests show low levels of reproducibility, even within testing sessions, more recent research has provided vastly different results. The Cannon et al. [37] study mentioned earlier also examined coherence over a 30-day testing period. For eyes closed coherence measures, ICCs for delta, theta, alpha, and beta bandwidths were all greater than 0.90. For the eyes open condition, coherence in all bandwidths had ICCs above 0.85. This indicates "good" to "very good" reproducibility for all EEG variables examined and deems coherence as a reliable enough measure to use in both a research and clinical setting.

In all of the studies presented, roughly half of the variance seen in all EEG variables was reproducible within the given subject. These measures have all been determined to have a sufficient level of reproducibility to use in future research. However, it should be noted that these results do not necessarily indicate that EEG can currently be considered a reliable diagnostic tool and differentiate between concussed and healthy individuals.

Although there are many benefits to using EEGs in concussion research and a wealth of knowledge has been gained, the use of EEG in this type of research is not without its criticisms and limitations. Nuwer et al. [34] have questioned the use of EEG in concussion research, citing the lack of clear EEG features that are specifically unique to mTBI patients, especially late after injury. While there is merit to a lack of unique abnormalities, several studies [57, 58] have found deficits in concussed participants up to 3 years post-injury.

Most EEG and concussion research focus on lower frequency bands, but several studies by Thornton [38, 48, 51, 58] demonstrated that extending the frequency to include gamma bands provides important additional information, particularly between correlating EEG variables and the participant's cognitive deficits. Additionally, most research and, consequently, normative databases provide information solely about eyes closed conditions. This severely limits the type of cognitive testing that can be simultaneously completed; restricting neuropsychological testing to auditory-based tests. While auditory-based cognitive research has provided valuable EEG patterns, such as those outlined in Thorton and Carmody [38], several cognitive domains cannot be adequately assessed via auditory tasks. The link between EEG patterns and cognitive domains, such as visual memory and attention, remains poorly established and under-researched.

In summary, reviews by Arciniegas [8] and Nuwer et al. [34] have cited numerous studies that have proven EEG as a useful tool for identifying and managing concussive injuries. While EEGs are one of the least expensive and easiest to use neuroimaging tools, the expertise needed to administer and evaluate EEG results, as well as the lack of research between EEG and concussion, has kept EEG evaluations from becoming part of the current clinical gold standard. The most comprehensive EEG study using a database of 608 mTBI subjects that were followed up to 8 years post-injury revealed a number of findings. These include: (a) increased coherence in frontal–temporal regions; (b) decreased power differences between anterior and posterior cortical regions; and (c) reduced alpha power in the posterior cortical region, which was attributed to mechanical head injury [47]. A study by Thornton [58] has shown a similar data trend in addition to demonstrating the attenuation of EEG within the high frequency gamma cluster (32–64 Hz) in mTBI patients. Overall, resting EEG has demonstrated alterations in power dynamics across electrical spectra [8], increased short distance coherences [59], and decrease in connectivity across long-distance connections [59]. These consistent findings in resting EEG and mTBI research point to the sensitivity and validity of using EEG in the assessment and management of concussion. However, it should be noted that one controversial report concluded that no clear EEG features are unique to mTBI, especially late after injury [34].

## Current Work from Our Lab

In our work, significant reduction of the cortical potentials amplitude and concomitant alteration of gamma activity (40 Hz) were observed in mTBI subjects performing force production tasks 3 years post-injury [57]. More recently, we showed a significant reduction of EEG power within theta and delta frequency bands during standing postures in subjects with single and multiple concussions up to 3 years post-injury [58] and reduced amplitude of cortical potentials (MRCP) up to 30 days post-injury [60]. Unfortunately, there is no systematic EEG research available in the literature on subjects suffering and recovering from multiple concussions.

We applied advanced *EEG-wavelet entropy* measures to detect brain functional deficits in mTBI subjects. These EEG measures were significantly reduced after the first and more significantly after the second mTBI far beyond 7 days post-injury. Most importantly, the rate of recovery of EEG entropy measures was significantly slower after second mTBI compared to the first concussion [61]. Recently, we reported the alteration of EEG signals in mTBI subjects detected by a novel measure of nonstationarity, named Shannon entropy of the peak frequency shifting [62]. These findings are complementary to our previously published concussion report indicating the presence of residual deficits in mTBI subjects detected by multichannel EEG signals classifier using support vector machine [63]. We also conducted an EEG resting state study and reported the alteration of cortical functional connectivity in mTBI subjects revealed by graph theory, ICA, and LORETA analyses. Overall, a clear departure from *small world-like network* was observed in mTBI subjects [59].

The presence of a residual disturbance of the neuronal network is involved in execution of postural movement in mTBI subjects incorporating EEG- and VR-induced measures [64]. There was a significant increase of *theta* power during the progression of a balance task. Specifically, this *theta* increment was obvious initially at central areas with further diffusion to frontal electrode sites bilaterally. Interestingly, no significant *theta* power was present in concussed subjects at either phase of postural task progression. Most recently we reported that 85 % of mTBI subjects who showed significant alteration of alpha power in acute phase of injury did not return to pre-injury status up to 12 months [65].

## Compensatory Approach During Concussion Assessment Batteries

Several studies have found electrophysiological deficits in asymptomatic concussed participants [66–68]. In these studies, concussed participants displayed normal levels of cognitive functioning, yet continue to show physiological dysfunction on EEG measures. The authors cite an unknown compensatory mechanism as an explanation for the findings. As part of our research, we sought to investigate this compensatory mechanism in more detail. In order to assess this, we chose to record EEG signals while participants were completing clinical concussion assessment measures, specifically the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) neuropsychological and VR balance and spatial navigation modules, as well as EEG resting state evaluations in order to highlight the differences between clinical cognitive and balance performance and neuroelectric measures.

In a sample of 13 normal volunteers and seven concussed participants, no differences were found between groups on ImPACT and VR composite outcome scores. When looking at sub-scores, the only significant difference was poorer stationary balance in the concussed group. However, several significant group differences were found when looking at the EEG variables. For EEG resting state and ImPACT conditions, the concussed group had significantly lower power in the theta and beta bandwidths. Additionally, the concussed group had significantly lower alpha power during the ImPACT conditions and significantly lower delta power in the VR conditions. Conversely, the concussed group displayed significantly higher levels of coherence during EEG resting state and ImPACT evaluations, but lower levels of coherence during VR balance and spatial navigation testing.

Overall, for EEG resting state and ImPACT, these results indicate that concussed participants could not establish enough local effort (seen via lower power), so they recruited additional long-distance network connections (seen via the increased coherence). By recruiting additional networks, the concussed participants were able to successfully compensate for their neuroelectric deficits and produce normal clinical results. For the VR modules, concussed participants were not able to compensate as successfully. This was seen via the inability to recruit additional long-distance networks and clinically in the overall poorer balance in the concussed group, specifically the significantly worse static balance. This research indicates a disconnect between cognitive and neuroelectric resolution. Future research projects aim at determining whether cognitive functions resolve before physiological function or if current clinical concussion assessments are not sensitive enough to detect the residual affects of concussion.

## Return to Play and EEG Concussion Research

One specific area that is still lacking in research and is noted in second international consensus statement [69] and in the statement from the World Health Organization's (WHO) task force on mTBI [70] is the area of return to work or play. The WHO task force found no studies that demonstrate acceptable evidence to suggest when a person or athlete may safely return to work or the athletic field. As it has demonstrated its ability to identify physiological differences in the recovery from TBI, EEG should be considered as a feasible diagnostic tool for use within the "Return to Play" protocol and recommendations given to athletes returning to activity and sport.

As previously mentioned throughout this chapter, EEG has been used to study concussion or mTBI throughout all stages of recovery from acute, subacute to chronic or long term. One such clinical stage EEG has not been used is within the "Return to Play" stepwise progression back into athletic participation. The "Return to Play" protocol is the internationally accepted method for the safe return to activity of an athlete recovering from concussion [71]. This formalized "Return to Play" protocol has been in place since the original 2001 Concussion in Sport Group (CISG) Consensus Statement and remains unstudied and based on little to no scientific evidence, yet is still used as the "gold standard" for returning athletes to competition.

Under this procedure, "Return to Play" after a concussion follows a stepwise progression of increasing efforts and risk as outlined in Table 5.2. First the athlete must be completely asymptomatic at rest for a period of at least 24 h. Once asymptomatic and cleared by a supervising physician, the athlete may progress to a light

**Table 5.2** Graduated "Return to Play" protocol

| Rehabilitation stage | Functional exercise | Objective |
|---|---|---|
| No activity | Complete physical and cognitive rest | Recovery |
| Light aerobic exercise | Walking, swimming, or stationary cycling keeping intensity <70 % age-adjusted MHR. "No resistance training" | Increase heart rate |
| Sports-specific exercise | Skating drills in ice hockey, running drills in soccer. No head impact activities | Add movement |
| Non-contact training drills | Progression to more complex training drills (e.g., passing drills) | Exercise coordination |
| | "May start resistance training" | Cognitive load |
| Full contact practice | Following medical clearance participate in normal training activities | Restore confidence and assess functional skills by coaching staff |
| Return to play | Normal game play | |

aerobic exercise such as walking or stationary cycling. This light aerobic challenge is limited by restricting athletes to <70 % of their calculated maximum heart rate.

With this activity progression, each stage of increasing efforts should be separated by 24 h with health professionals monitoring the athletes and their symptom status. If any of the athlete's post-concussion symptoms should manifest before, during, or after a stage within the protocol, the athlete is instructed to drop back to the previous asymptomatic stage and try to progress again after a further 24-h period of rest.

In our lab we investigated the use of EEG as a supplementary tool in the clinical assessment of concussion during the "Return to Play" phase of recovery. Specifically, we looked at the differential effect of exercise (modified YMCA bike protocol) on the quantitative EEG measures of spectral absolute power and coherence in normal volunteers vs. mTBI subjects. We hypothesized that the YMCA bike protocol would induce differential EEG measurement between each group. We also hypothesized that the YMCA bike protocol would induce similar physiologic measurements (heart rate, self-reported post-concussion symptoms) between groups performing the exercise protocol and that both groups would demonstrate clinically asymptomatic performances.

There were several major findings from this study. Of particular clinical significance was the clinical symptomatology surrounding the mTBI group. All mTBI subjects had all returned to clinical asymptomatic status at rest as determined by self-reported symptom scores (SRSS), clinical cognitive measures (SCAT-2), clinical balance measures (BESS), and computer-based neuropsychological test scores (CNS Vital Signs, ImPACT). These athletes had also been cleared by a sports medicine physician for the initiation of the "Return to Play" protocol as outlined above. All subjects met the clinical criteria for asymptomatic at rest [72] for a period of at least 24 h prior to exercise testing.

In addition, the modified YMCA bike protocol was capable of producing similar physiologic changes between groups in terms of heart rate dynamic changes during the bike with both exercise and post-exercise recovery; meaning there were no group differences in dynamic measures of heart rate throughout the bike protocol or post-bike recovery phase. In addition, both groups demonstrated no differences in the presentation of symptoms related to concussion and all subject participants were able to finish the exercise protocol without stopping due to excessive fatigue or the onset of exercise-induced post-concussion symptoms. These clinical findings are significant as they comply with a typical clinical progression back into activity without adverse clinical consequence. The absence of clinically significant symptoms allows the athlete to progress in stages of the "Return to Play" protocol as outlined by the CISG International Guidelines [69, 71]. As a result of the absence of clinical symptoms within each stage of the "Return to Play" protocol, the athletes within the mTBI group returned to normal sports participation within 4 days. They demonstrated no clinical abnormalities requiring a delay in their progression and were subsequently fully released based on current clinical standards. However, some differences were evident when reviewing the physiological data from the EEG evaluation.

Both groups (normal volunteers, mTBI) demonstrated no regional power differences at rest and at 24 h follow-up. In addition, both groups demonstrated no significant differences in mean or regional coherence values at rest or at 24 h follow-up. Historically within the literature, abnormal attenuation of alpha power and an increase in focal slow-wave distribution are short lasting and typically return to normal within the subacute phase of experimental concussion [73–75]. Further, in a recent quantitative EEG examination by McCrea et al., no resting state differences in athletes recovering from mTBI at days 8 and 45 post-injury were found when compared to age-matched controls [76]. Within the neural imaging research, resting-state fMRI findings of mTBI cohorts at rest do not vary significantly from normal volunteers [77]. This is an important finding as researchers look to develop the clinical significance of EEG as a diagnostic tool for mTBI. Resting state EEG measurement remains largely normal as reported throughout the literature.

With the introduction of exercise, physiologic differences were observed between groups. The modified YMCA bike protocol increased alpha, beta, theta, and delta absolute power amplitudes across all regions (frontal, central, and posterior) in the mTBI group vs. normal volunteers. Specifically, exercise significantly increased the power of theta and delta frequency ranges that are considered broadly to represent a pathological state that has been established in the literature. Theta power increases stem from injury and pathophysiologic changes in the cerebral cortex [17]. As is known, mTBI results in altered cerebral blood flow [78, 79], decreased energy metabolism [80], release of excitatory amino acids (EAA), and decreased postsynaptic function among other effects already mentioned. In work by Nagata, his group demonstrated that cortical blood flow (CBF) and oxygen ($O_2$) metabolism correlated negatively with delta and theta power [81]. Meaning, as CBF and $O_2$ metabolism decreased there was a subsequent increase in delta and theta power. In addition, increases in theta power have long been established in the mTBI literature [15, 44] and are indicative of pathology. Delta activity has been known to increase in many pathological states. This increase of delta power in resting EEG has been documented in different pathological conditions [82–84]. The lack of specificity of this effect linked with any range of pathological conditions suggests that increase of slow waves (delta/theta frequencies) represents a typical response to any brain injury, pathology, and disruption of neural homeostasis.

The specific findings of this investigation would suggest that the use of EEG within the "Return to Play" protocol for athletes recovering from concussion is feasible. Moreover, current clinical guidelines used to evaluate the athlete may not bring residual abnormalities to the forefront and lead to premature "Return to Play." The inclusion of EEG as a physiologic tool proves to have some worth in examining the recovering athlete and may provide clinicians with valuable data when making "Return to Activity" decisions. Furthermore as demonstrated by this investigation, exercise may be an effective mechanism for uncovering residual abnormalities in recovering athletes.

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