BCI: Self-health monitoring and wearable technologies

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Abstract
Our society faces increasing health disparities, limited access to healthcare, and rising healthcare costs. Simultaneously, the technological sector has entered an era of neurotechnology producing wearable technologies that present viable solutions in healthcare by allowing individual management and continuous monitoring of a patient's physiological and neural activity (i.e. health status). With advancements in real-time processing algorithms, wearable neurotechnologies using wireless and innovative electrode technology enable real-world research settings within a broader spectrum of the population. These technologies may allow big-data analyses highlighting trends and mechanisms underlying neural activity and neurological disorders previously indiscernible due to studies with small sample sizes. With increasingly affordable consumer-grade devices, it is now possible for the public to monitor and modulate ones brain activity in the comfort of their own home. Biomedical BCI systems present mobility and communication solutions to patients, increasing their autonomy and sense of agency. In this chapter we review select wearable neurotechnologies, current applications and limitations, along with the future prospects and precautions underlying these technologies.

Key words (5-10):
Wearables, EEG, neurofeedback, BCI, mobility, real-world, big-data, home-use
Introduction

Our society faces increasing health disparities, limited access to healthcare, and rising healthcare costs. Simultaneously, the technological sector has entered an era of bio and neurotechnology producing wearable technologies providing real-time and longitudinal monitoring of physiological and neural activity that may present viable solutions to these issues in healthcare (Ghose 2012). Consumers can now access a wide array of wearable technologies which measure, monitor, and receive feedback from ongoing physiological and neural activity. The information provided by wearable technologies has numerous overlapping applications. For example, measuring patients’ vital signs at-home may result in higher quality, individualized treatment protocols that incorporate continuous, detailed information about the patients ongoing physiological status (Muse et al., 2017). A variety of prototypes and commercial products have been developed recently that provide real-time health data directly to the user or the medical center/professional physician, which can alert an individual or care provider in the event of a potentially threatening or imminent health emergency (Kumar, 2012). With an increasing capacity to acquire, share, process, store, retrieve, and apply big-data methods, wearable technologies may significantly improve our ability to tackle some of the major challenges of today’s society (Zheng, 2014). While the application of wearable technologies was previously limited to physiological measurements (e.g. heart rate, step-counter), recent advancements in wireless electroencephalography (EEG; the measurement of neural activity from electrodes placed on the scalp) is now leading to the development of new applications. Wearable EEG technologies allow for direct interfacing between an individual’s brain activity and a digital device, and allow us to train cognitive skills (Vernon 2003), reinforce specific brain rhythms (Brandmeyer 2013), play video games (Schoneveld 2016), or produce art and music
(Levicán, 2017; Grandchamp, 2016) based on measured neural activity. EEG measurement reflects the cumulative electrical activity associated with the depolarization of cortical neurons, can reflect rhythmic and transient activity (Buzsaki, 2006), and facilitates high temporal resolution neuroimaging analyses. Brain oscillations reflect the synchronized depolarization (i.e. action potential) of neuronal populations, either in response to a stimulus from the environment (i.e. evoked response potentials, ERPs), or associated with mental states (e.g. sleep, coma, cognitive activity etc.). EEG scalp electrodes measure the electrical waves as they spread across the scalp. The rhythmic activity is divided into frequency bands based on their spectral content, such as delta (1-3 Hz), theta (4-7 Hz), alpha (8-12 Hz), beta (14-30 Hz), and gamma (>30 Hz) rhythms. The high temporal accuracy of EEG gives precise temporal information about brain processing. EEG is also used clinically to diagnose and localize which steps in the brain’s information processing pathways are malfunctioning (e.g. visual, auditory, tactile processing).

The recent development of dry electrodes (Taheri 1994) and wireless technologies, have led to innovative wearable EEG systems, which are comfortable, offer quick and practical EEG data acquisition solutions (i.e. no gel, cleaning, or cables), usually include real-time data preprocessing, and correction for head movements. Some systems do not even require a computer, as recordings can be stored on the device (i.e. microSD) or transmitted wirelessly to a smartphone (e.g., Stopczynski 2014; Debener 2015). Because of these improvements, new possibilities in fundamental and clinical research fields have emerged. Not only can wearable technologies offer access to populations that were harder to include in studies before, such as children and the elderly populations (Neale, 2017; Ramirez, 2015), they also allow for longitudinal designs and larger sample-size studies (Hashemi, 2016; Kovacevic, 2015), and the ability to study the human brain in naturalistic settings (Debener, 2012). Modern wearable EEG headsets which are comfortable to wear and have elegant design, are becoming increasingly
attractive for general public use (Nijboer 2015), and may lead to innovative applications including practical, easy, and high-fidelity at-home recordings, neurofeedback (NF) and brain-computer interface (BCI) applications, group studies (i.e. simultaneous recording of different participants), big data analyses, and more.

At present, wearable EEG technologies remain the most suitable for self-health monitoring, NF and BCI solutions. Recent innovations also include wearable headsets enabling transcranial electric stimulations (TES), functional near-infrared spectroscopy (fNIRS), and even the combination of these methods with EEG (See Table 1). In the following chapter we review several of the higher-fidelity wearable systems that are available today, mainly the wearable EEG systems (both consumer- and research- grade products), but also promising systems that combine EEG with fNIRS or TES. We then explore the different applications that already exist using wearable technologies, and address the limitations, prospects and precautions associated with such technologies.
I. Wearable neurotechnologies

In the following section we provide a list of popular and widely used (as of 2018) wearable neuroscientific systems that are available for fundamental and clinical research, NF, BCI and home-use applications. Excluded from this review were several devices which had either poor signal quality (Neurosky's Mindwave (Roesler, 2014; Maskeliunas, 2016), a lack of technical or scientific information available (Emotiv Insight, Foc.us EEG Dev Kit, FocusBand, Imec, and the two kickstarter products Melon and Melomind), or too much discomfort reported by users (Quasar’s DSI 10/20; Hairston 2014).

For information, the MOVE system from Brainvision (Bulea 2013) allows to convert any standard EEG system into a wearable one, but will not be developed further in this chapter.

Insert table 1a. and 1b. here (side by side)
Sensors: EEG activity is typically recorded from the scalp using gel-based electrodes in order to achieve a high signal-to-noise ratio (SNR) between the source (the brain activity) and the measurement device (the electrode). Active electrodes contain individual micro amplifiers which significantly improve the SNR and reduce application time. When passive electrodes are used, the skin must be properly prepared and abraded in order to achieve a high SNR. The main advantage of gel-based active electrodes is their high SNR. Disadvantages include high cost and relatively lengthy preparation and cleaning time. The recent development of dry electrodes (Taheri 199) along with wireless technologies have led to the development of innovative wearable EEG systems. While dry electrodes have an increased sensitivity to motion artifact, movement of cables, and electrostatic charges, they do not require extensive cap mounting time, skin abrasion, or hair washing. The

Sensor locations: The international 10–20 system is an internationally recognized method to describe and apply the location of scalp electrodes for EEG (Klem, 1999). The 10-20 system is necessary for the comparison of brain data collected from different laboratories, which entails the comparison across subjects and populations, variations in equipment, and variations in the electrode montage. In the 10-20 system, each electrode placement site is labeled according to the corresponding topographical location on the scalp prefrontal (Pf), frontal (F), temporal (T), parietal (P), occipital (O), and central (C).

Motion sensors: To prevent the loss in signal quality, a majority of high-end wearables using dry electrode technology generally include motion-sensors. The gyroscope indicates the orientation of an object in space (i.e. Along the 3 axis X, Y, Z), and the accelerometer measures the acceleration (along the 3 axis as well). Their sampling rates are similar to those of EEG. This information can be used to reject artifacts in the data. However, motion sensors - especially gyroscopes - generally present a significant drain on battery power and may decrease battery life.

Sampling rate: Sampling rates generally vary from 128 Hz to 2048 KHz kilohertz. Low cost EEG usually use multiplexing of a single analog to digital (AD) converter which scan each channels sequentially. So a 2048 KHz AD converter can convert 8 channels at 256 Hz sampling rate. Note that research systems usually have one AD converter per channel which not only allows for higher sampling rate but also ensures simultaneous acquisition of all channels (with the sequential solution, the acquisition time of each channel is slightly delayed for each channel which could potentially affect subsequent processing - although resampling techniques may be used to realign data collection time of each channel).

Connectivity: Bluetooth and Wifi use the same band at 2.4 Ghz (Wifi may also use the 5.0 GHz frequency). Wi-Fi direct promises device-to-device transfer speeds of up to 250 Mbps, while Bluetooth 4.0 promises speeds similar to Bluetooth 3.0 of up to 25 Mbps. Bluetooth technology cannot transmit as much data as Wifi.

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Data resolution (in bits): It is generally accepted that EEG signal resolution does not go beyond 24 bits (due to environment and electric noise). However, this means that all systems acquiring less than 24 bits may lose important data, unless a dynamical gain mechanism is implemented to increase the range of possible values. Most low-cost wearable EEG system use 16-bit A/D (Analog/Digital) conversion resulting in some loss of data.
Figure 1: Illustration of some wearable devices
Top row (from left to right): Muse (InterAxon); Epoc (Emotiv); Dreem (Rythm); Quick 30 (Cognionics); B-Alert X10 (ABM); Enobio (Neuroelectrics).
Bottom row (from left to right): Ultracortex Mark IV (OpenBCI); Octmon (Artinis); g.Nautilus (g.tec); g.Nautilus EEG-fNIRS(g.tec); Starstim 8, 16, 32 (Neuroelectrics).
II. Applications

Fundamental research

Over the past century EEG studies have served as a key methodological tool for the scientific study of human cognition, sleep, neurodegenerative diseases, and brain disorders (Luck, 2011; Regan, 1989). While traditional EEG laboratory recordings require lengthy application and recording procedures, several of these technical factors can be overcome by increasingly sophisticated light, comfortable, high-fidelity wireless EEG. Wearable EEG headsets have now been used to study a wide array of fundamental topics such as visual and auditory attention, perception {Krigolson, 2017; Krigolson, 2017; Debener, 2012; Barham, 2017; Boutani, 2013; Abujelala, 2016; Poythress 2008; Schmorrow, 2006 #157}, emotions {Bashivan, 2016; Jiang, 2016; Peter, 2005; Brown, 2011; Brouwer, 2017; Rodríguez 2013}, learning, and memory {Berka, 2007; Berka, 2005}. While critiques have been made regarding the viability of wearable EEG headsets for conducting EEG research in non-laboratory settings {Przegalinska, 2018; Cester 2008}, several studies have successfully compared and validated the signal quality of wearable EEG to research-grade EEG acquisition equipment {Barham, 2017; Jijun, 2015; Pinegger, 2017; Boutani, 2013}. Laboratory studies in psychology and cognition with artificial stimuli and fixed response options inevitably result in findings that are less ecologically valid in relation to real-world behavior. Wearable EEG may facilitate a more accurate understanding of the human brain and its highly complex mechanisms occurring in the natural settings. Thus, wearable EEGs have now been collected on participants walking outdoors on university campus {Debener, 2012} and walking in urban versus green space environments {Neale, 2017; Aspinall 2015}. Wearable EEG systems also facilitate an improved access to populations that were previously harder to include in studies because of lengthy,
uncomfortable experimental conditions, such as studies with children (Badcock 2016), even directly in classrooms {Bozkurt, 2014; Stevens, 2007}, and with elderly populations {Abbate, 2014; Dimitriadis, 2016; Neale, 2017; Ramirez, 2015}. In addition, the need for adapting creativity in the sciences and education might find solutions with these technologies by allowing not only to acquire more information about the developing brain, but also by demonstrating and explaining EEG and NF to the public or the classes in an interactive way. For instance, Grandchamp and Delorme developed the ‘Brainarium’ {Grandchamp, 2016}, a portable planetarium dome on which the EEG data - that is being recorded in real-time from a subject - is displayed as a multimedia content using NF methodology. This also demonstrates the growing importance of the arts contribution towards the sciences in various ways {Andujar, 2015}. BCI have been developed to play music using the Emotiv Epoc {Levicán, 2017} and the so-called ‘Encephalophone’ system {Deuel, 2016 and 2017}.

**Virtual reality**

A middle ground between real-world environments and laboratory settings has been brought about by the development of virtual reality (VR). VR represents an immersive and controlled environment simulating the ecological conditions which has supported neuroscience research and therapy (Bohil, 2011). The addition of wearable EEGs during VR experiences has improved the ability to evaluate alertness, vigilance, reaction time, fatigue, and drowsiness of automobile drivers in simulations {Armanfard, 2016; Johnson, 2011; Lin, 2014; Berka, 2007; Lin 2007; Brown, 2013; Wang, 2017}. Other studies have evaluated various aspects of effective driving including reaction time (Foong, 2017), feedback alarms {Berka, 2005}, emergency braking prediction based on a EEG signature {Haufe, 2011}, red and yellow stop lights distinction {Bayliss, 2000}, and controlling a car with EEG within VR environments {Zhao, 2009}. These findings are leading towards a prevention system linked to a wearable EEG
recording of the pilot/driver’s brain that would detect in real-time the loss of attention and drowsiness and could provide an auditory, tactile, and/or visual feedback to the driver in order to avoid an accident {Wei, 2018; Akbar, 2017; Healey, 2005}. Recently, Martínez (2018) developed the first EEG paradigm designed to study real-life driving situations which aimed to identify an EEG marker of an individual's intention to brake.

**Group studies and Big-data**

Wearable technologies enable the simultaneous recording of multiple individuals, opening up new applications of EEG research for the study of group dynamics, team cohesion, or social synchronicity {Stevens, 2010; 2012; 2013}. Big-data research studies have the potential to revolutionize the way we investigate individual differences and differentiate commonalities in brain activity across subjects. A majority of neuroimaging studies are conducted on small samples due to the time consuming nature of measuring EEG on large groups of participants. With larger samples come more robust statistical inferences about the general population, as well as a better representation of the sociodemographic differences. For instance, Hashemi and colleagues (2016) used the Muse to analyze the brain data of 6029 subjects ranging from 18-88 years in age and were able to identify subtle but robust sex differences in several EEG measures and age-related shifts in EEG activity on a year-by-year scale, as well as how these changes differ between males and females, in a representative population of individuals completing the tasks in uncontrolled, natural environments. In another study, Kovacevic and colleagues (2015) recorded 523 subjects with the Muse headband for 12 hours in a collective and immersive NF multimedia science-art installation. They found that the
participants’ EEG baseline activity predicted subsequent NF training, indicating the existence of a state-dependence effect in learning ability during NF.

The acquisition of brain data by the developers of NF Applications available on smartphones/tablets is currently participating in the acquisition of the biggest EEG databases in history. These big-data archives will allow for the development of new types of statistical analyses and may highlight patterns and trends in brain activity that were not possible with smaller data sets.

**Clinical Applications**

One of the more significant clinical applications of wearable EEG involves the use of event-related potentials (ERPs; also named evoked potentials), which reflect stereotypical changes in EEG activity evoked by sensory stimuli. They have played a pivotal role in our understanding of the relationships between physical stimuli and brain activity (Luck, 2011), and have been key in the study of cognitive disorders such as developmental dyslexia (Hämäläinen, 2013), specific language impairment (McArthur, 2004), psychiatric disorders (Park, 2010), and autism (Čeponienė, 2003), among others. As wearable EEGs were shown to accurately measure ERPs (Krigolson, 2017; Krigolson, 2017; Debener, 2012; Barham, 2017; Boutani, 2013; Abujelala, 2016; Berka, 2008; Pythress 2008; Schmorrow, 2006; Mayaud 2013; Badcock 2013), their widespread use in everyday lives has the potential to aid in the early diagnosis of brain disorders by detecting specific EEG components and markers associated with a given disorder (e.g. Nunes 2014). BCI integrate the real-time analysis of ERPs (Sullivan, Delorme and Luo 2012). The four main ERP components include the P300 (i.e. Positive brain oscillation occurring at 300 msec), used for bi-directional communication BCI, the mu (i.e. 8-12 Hz) and beta rhythms (i.e. 18-26 Hz), usually used for sensorimotor BCI, and the steady-state visual evoked potentials (SSVEP) which corresponds to active visual focus. The clinical application of
wearable EEG technologies have been used in traumatic brain injury {Hofmeijer, 2018}, Alzheimer's disease {Abbate, 2014}, Parkinson's disease {Nieuwhof, 2016}, epilepsy {Askamp, 2014}, autism {Billeci, 2016}, and to study stress and attention in surgeons while in operation {Maddox, 2015}.

Physical activity

While sedentarity is considered a high-risk factor for health, the benefits of physical activity have been extensively documented in the scientific literature {Tremblay, 2010; de Rezende, 2014}. Several studies have shown that regular sport-based activities produced neuro-angiogenesis (i.e. creation of new blood vessels) and neurogenesis (i.e. creation of new neurons) in the brain {Pereira, 2007; Fabel, 2003; Olson, 2006}. Exercise-induced cell genesis has a possible relevance to memory function and reversing neurodegeneration of the hippocampus {Praag, 2008; Pajonc 2010}, a structure associated with learning and memory, and victim of atrophy in aging and many neurodegenerative diseases {West 1994}. While most of the studies on exercise assess pre/post measures, a lack of research studying the neural mechanisms taking place during the practice of exercise is due to the reduced mobility imposed by cables and the signal artifacts produced by the movements of the subjects. However, with the development of wearable technologies, researchers have now been able to study the electrical activity of the brain during exercise, during performance on attentional tasks while walking outdoors {Debener, 2012; Tilley, 2017; Armanfard, 2016; Aspinall 2015}, walking on a treadmill {Lin, 2014}, or riding a stationary bike {Scanlon, 2017}. Some expert athletes train their whole life to develop relaxation techniques in order to keep a steady performance under stress and muscular fatigue. Some researchers were able to record EEG data from elite archers in order to study their relaxation capacities under stress and muscular activity {Lee, 2009}, while others have accelerated the training of archers, golf players, and rifle
marksman using NF strategies {Berka, 2010}. Studying the brain of individuals while their doing a physical activity will bring precious information on the effects and mechanisms of physical activity on the brain, which may have an important impact on both sport science (e.g. training strategies) and medical applications.

**Neurofeedback**

Stress has strong repercussions on both psychological and physical systems. As a consequence, chronic stress was shown to trigger unhealthy behaviors that contribute to morbidity and mortality {Jackson, 2010}, such as depression, obesity, sleep deprivation, attention deficit, mood disorders, grey matter atrophy in the brain, or substance abuse, to name a few {Miller, 2011; Sapolsky, 1996; Dallman, 2003; Duman, 2006}. However, meditation has been found to improve stress-related outcomes {Goyal, 2014}. Meditation techniques include focused breathing exercises that help to directly regulate the cardiovascular system {Steinhubl, 2015}, negative mood, stress, pain, anxiety and mind wandering {Bhasin, 2013; Prinsloo, 2013; Zeidan, 2010; Brandmeyer 2016}. Moreover, meditation practices were found to increase regional brain gray matter density {Hölzel, 2011}. Thus, by implementing meditation techniques (Brandmeyer 2013), NF can help users become aware of their emotions or negative mind wandering {Mooneyham, 2013} that are associated with stress, and develop strategies to overcome them {Brandmeyer, 2016}, as well as slowing down the neurodegenerative process of neuronal structures. Furthermore, by providing a direct feedback to the user, NF systems offer a faster learning progression by informing the users if they are using the right strategy and by providing a reward-based motivation (some NF systems use video-game types of reward systems). These benefits apply to cognition as well, as findings showed that NF increased memory, attention and cognitive performance {Nan, 2012; Zoefel, 2011; Wang,
Brainwave training provided by NF induces neuroplastic changes (Ros, 2010), suggesting important implications for therapies of brain disorders associated with abnormal cortical rhythms, and support the use of NF as a non-invasive tool for establishing a causal link between rhythmic cortical activities and their functions. NF has been well investigated in the treatment of attention-deficit/hyperactivity disorder (ADHD) and has shown clinical efficacy (Arns 2014; Gevensleben 2009).

The sharp rise of computer processing capacity have solved many of the difficulties faced by the NF and BCI pioneers of the 70's (Dewan, 1967) and 80's (Vidal, 1977). Some of the sophisticated software and hardware are now designed to process EEG data in real-time (Hu, 2015; Sullivan, 2007), facilitating reliable NF and BCI to consumers. An open access meditation NF protocol is currently accessible when purchasing the low cost Muse headband (see Table 1). Emotiv also offers with the purchase of the Epoc EEG headset (see Table 1) the Affectiv™ Suite that reports real-time changes in the subjective emotions experienced by the user, and the Cognitiv™ Suite that discern the user’s conscious intent to perform distinct physical actions on a real or virtual object (Fattouh 2013).

Video games have been shown to be powerful NF companions. Research suggests that the combination of NF methods and video game interfaces significantly improves symptoms associated with conditions such as ADHD and anxiety (Perales 2016; deBeus 2011; Muñoz 2015; Schoneveld 2016). Additionally, some studies are combining NF, video games and VR to obtain more immersive results (Lécuyer, 2008). These systems are now marketed to consumers as forms of cognitive enhancement and entertainment (Sandford 2007). Musical NF paradigms are being developed as well, presenting an interesting alternative to other treatments by offering to users the ability to manipulate expressive parameters in music performances using their emotional state (Ramirez, 2015).
NF may also be coupled with other technologies to enhance its efficacy. The Neuroscape center for Translational Neuroscience at the University of California, San Francisco has developed multiple games that implement NF, neuromodulation, and VR/AR such as the NeuroRacer, Meditrain, the Ace, or the Beep seeker to name a few. Neuroelectrics developed the Neurosurfer software for advanced NF applications, offering for the first time the possibility of combining NF with brain stimulation (if combined with the Starstim device; Aguilar Domingo 2015). They also provide NF games that are ready for use with a regular monitor or in a VR environment (3D) using the Oculus Rift (Desai 2014). Combined with VR, NF training may be used to enhance attention (Cho, 2002) and learning (Hubbard, 2017). In another experiment, a multimodal embodied interface was designed for 3D navigation as a modular wearable, with the user suspended in a harness that was directly controlled by the EEG activity of the user. This allows both physical and virtual displacement within an immersive virtual environment, allowing to simulate a flying experience (Perusquía-Hernández, 2016). A team is also developing a socially assistive robot that provides a personalized NF training session to maximize user engagement and performance (Tsiakas 2017).

**Combining physiological measures**

Heart rate variability (HRV) is the change in the time intervals between adjacent heartbeats that may be used to predict future health outcomes (Tsuji, 1994; Dekker, 1997; Shaffer, 2014). Reduced HRV has been shown to correlate with disease onset and mortality as it reflects reduced regulatory capacity of the body to adaptively respond to challenges like exercise or stressors (Dekker, 1997; BEAUCHAINE, 2001; Berntson, 2008). Self-regulation techniques (Alabdulgader, 2012) were found to improve the cognitive function, the parasympathetic system, as well as a wide range of clinical outcomes (Lehrer, 2003; McCraty and Zayas 2014). It can be enhanced by HRV feedback (McCraty, 2003), representing a therapeutic tool with a
considerably reduced health care cost (Bedell, 2010). Several wearable headsets offer features that allow for the simultaneous recording of the heart rate, the heart pressure, the respiration, and the EEG (see Table 1). By combining neural and physiological measures such as EEG and HRV [Steinhubl, 2015; Billeci, 2016; Riera, 2008] it is possible to develop NF paradigms aimed at improving measures related to anxiety, stress, emotions, cognition, and performance [Gruzelier, 2014; Shaw, 2012; Thompson, 2013]. Given that some NF protocols are already considered a first line of treatment for children with ADHD (Arns 2014; Gevensleben 2009), new NF protocols may soon be available as treatment options for stress management and the associated physical outcomes.

Sleep

Poor sleep quality concerns one third of the adult population [Roth, 2007], has been linked to many clinical and medical conditions such as depression and pain [Giron, 2002], and has proven costly (i.e. lost productivity, health etc.) for the societies and the individuals. The deleterious effects of chronic sleep deprivation and the associated outcomes have potentially dangerous and expensive consequences as a result of impaired neuropsychological functions for individuals at work, at home, and on the roads (Dongen 2003; Pilcher and Huffcutt, 1996). In addition, long-term health related concerns include increased risk for metabolic and cardiovascular diseases (Cappuccio 2011), as well as an overall decrease in immune (Bryant 2004). Research shows that 90% of the american population is using a technological device (e.g. tv, laptop or smartphone) in the hour preceding sleep [Gradisar, 2013]. Some wearable technologies developed in the last decades (e.g. wristbands, mobile apps, smart pillows) target sleep quality monitoring, but don’t focus on interventions supporting a healthier sleep or making use of sleep cognition [Ravichandran, 2017; Bianchi 2017]. However, EEG measurements can support and improve sleep transitions between sleep stages, and therefore
sleep quality [Aliakseyeu, 2011]. While only a limited number of sleep studies have been conducted using wearable EEG systems [Berka, 2007; Debellemaniere, 2017], recent advancements in neuroimaging research offer new ideas. These include the use of tDCS in the gamma frequency band during rapid eye movement (REM) sleep to increase self-reflective awareness in dreams [Voss, 2014], the use of TMS, and the use of pink noise to effectively manipulate sleep depth increasing sleep efficiency [Massimini, 2009; Suzuki, 1991]. Those findings could be implemented in BCI or NF applications with the help of wearable headsets such as the Starstim that allows simultaneous EEG and TES (see Table 1). The Dreem headband allows to record EEG during sleep and allows closed-loop auditory stimulation to modulate brain oscillations at the right moment by using a classification of sleep cycles (Chambon 2018; Debellemaniere 2018), enhancing sleep quality at night (Arnal 2017). Both the InteraXon’s Muse, the Rythm’s Dreem, and the Cognionics’ sleep headband offer the possibility to record EEG during sleep in the user's home environment (Debellemaniere et al. 2018; Onton 2016, respectively). To go further, a team from MIT media labs developed the first sleep BCI, an interactive interface named ‘Dormio’ [Haar Horowitz, 2018]. When the user enters the hypnagogic sleep stage (associated with high creativity), EEG and motor signals detect it and trigger an auditory feedback response provided by a robot located next to the sleeping user. The sound makes the user more aware of being in that state and extends the duration of the semi-lucid hypnagogic period, enhancing his/her creativity. Semantics were also used instead of a sound to influence the dreams of the users. Wearable EEG systems therefore present a promising future for sleep research, management, and monitoring.

**Biomedical BCI**
Modern BCI present a number of solutions for individuals with disabilities. Under certain circumstances, patients can regain partial if not all of the lost motor control if provided effective rehabilitation. Motor-imagery based BCI (Curran 2003) have been used as a means of providing patients real-time visual feedback of limb movement (corresponding to the injured limb) through a representative simulation on a computer screen. BCI protocols host the potential to accelerate rehabilitation through repeated reactivation of the underlying neural pathways (Pfurtscheller 2005; Kai Keng Ang 2010; Kai Keng Ang 2009). A difficult and frequently obstacle in patient rehabilitation involves maintaining the necessary levels of motivation to remain persistent during repetitive and demanding physical tasks. NF and BCI rehabilitation paradigms may improve patients’ sense of well-being and motivation by providing a more entertaining and engaging interfaces (e.g. video games) as opposed to more traditional clinical/medical settings.

When rehabilitation is not possible, prosthetic control can still provide improved mobility assistance, while promising research on BCI controlled wheelchair movements may soon be an option for patients with paralysis (Hassan and Roslinda 2015). The complex control commands required for robotic prosthetic limbs or exoskeletons have evaded BCI scientists for the last few decades, recent systems have overcome several key limitations (McFarland 2010). BCI patients are now capable of moving prostheses with increasing accuracy, flexibility (Clement 2011), and affordability (using 3D printing technology; Sullivan 2017). An exciting new BCI is currently being developed that enables the remote control of robots using EEG activity (Spataro 2017; Güneysu 2013). These technologies have tremendous potential for patients who are unable to engage with single-switch systems operated by movements such as eye-blinks, or the breath (e.g. late stage amyotrophic lateral sclerosis (ALS), high level spinal cord injury, stroke/aphasia, autism, severe cerebral palsy). BCI can also be used to facilitate linguistic communication, with
the most renowned BCI paradigm being the P300 speller designed by Farwell and Donchin in 1988 (Farwell and Donchin 1988; Mellinger, 2004; Cipresso, 2012). Other BCI allow the patients to navigate text, to control a cursor on a computer screen, browse forward and backward, or use bookmarks (Mugler 2010; Fruittet, 2010; Kübler, 2005; Krusienski, 2007). While only a limited number of studies have integrated fNIRS for BCI applications (Coyle, 2007; Aranyi, 2015), an increasing number of researchers are developing hybrid P300-based BCI interfaces via simultaneous fNIRS and EEG (Pfurtscheller 2010; Liu 2013; Fazli 2012; Khan 2014; Buccino 2016; Kaiser 2013; Blokland 2013; Tomita 2014; Yin 2015; Ge 2017). These studies show that simultaneous measurements of fNIRS and EEG can significantly improve classification accuracy of brain signals, improve user performance, and may serve to be a viable multimodal imaging technique suitable for future BCI applications.

Remote monitoring at home

BCI based applications have now been effectively delivered in home-based settings (Holz, 2015; Piccini 2005), and have shed light on the potential for future clinical-based interventions. The ‘home-based’ setting is key here as it can facilitate accessible and high-quality treatment options, reduce commute times, reduce the volume of consultations at clinics, increase the quality and quantity of patient information collected by healthcare professionals, and improve longitudinal measures of care quality. With increasing availability and integration of wearable EEG headsets, phone based BCI applications have been developed to enable practical and affordable everyday use.

Neurophones are brain-mobile phone interfaces which allow neural signals to drive mobile phone applications on the iPhone using wireless EEG headsets (Campbell et al., 2010; Wang 2011; Kumar 2017). Applications of NF devices in home-based settings could provide
significant aid to patients with traumatic brain injuries, ADHD, and more, by improving motivation for engaging in treatment, as well as directly improving secondary symptoms through access to applications that train mindfulness and stress-reduction techniques {Gray, 2017}. Wearable EEGs could help support the autonomy and independence of people with disabilities living at home, improve early detection of certain medical conditions, monitor sleep quality, and ultimately, provide large scale longitudinal data on the effects of aging in the brain and body (Light 2011). Bioserenity, a company specialized in developing mobile neurology diagnostic devices developed the Neuronaute, a diagnostic solution for epilepsy using mobile and continuous EEG recording, smart clothing, a smartphone application and a cloud platform {Valenza, 2015}. In the Netherlands, home-based EEG applications are currently used in ~30% of hospitals for the treatment and monitoring of epileptic patients (Askamp, 2014).

In a study by Valenza et al. (2015), they used wearable textile technology to characterize depressive states in bipolar patients during their normal daily activity. The Starstim from Neuroelectrics could also be very valuable for home-based use as it enables simultaneous EEG recording and brain stimulation (e.g. tDCS, tACS, tRCS; Helfrich 2016; Dutta and Nitsche 2013), which was found to improve neurorehabilitation effects by training motor function and learning processes (Gandiga 2005), presenting valuable applications for epilepsy, depression, or Parkinson’s disease. The NUBE Cloud Service from Neuroelectrics provides a telemedicine platform, wherein clinicians and researchers can prepare general stimulation protocols, schedule the stimulation sessions for patients, confirm whether the sessions have been executed or not, and create pre-/pos-stimulation questionnaires. Clinicians can also remotely guide the stimulation sessions that patients can conduct by themselves from home. While Starstim is currently classified as an investigational device under US federal law, it is approved
in Canada for medical use, and complies with the European legislation for clinical research (e.g. depression, pain, addiction, stroke).

Another growing field is the development of Smart houses (Stefanov 2004; Chan 1995). Numerous intelligent devices, embedded into the home environment, can provide the resident with both movement assistance (e.g. intelligent bed, intelligent wheelchair, and robotic hoist for effortless transfer of the user between bed and wheelchair), and 24-h health monitoring. They are therefore particularly relevant for elderly and disabled populations, as it helps restore independence and autonomy. However, these devices lack methods for decoding the intentions of disabled residents, which in the future may be solved through the integration of BCI and wearable headsets (Miralles 2015; Miralles 2015; Vaughan, 2006; Lee 2013).

**Discussion**

**Limits and possible solutions**

While a majority of NF and BCI systems require a minimal level of experience and knowledge to effectively acquire quality data, misrepresentative findings and applications is always a potential factor to be taken into consideration when assessing the validity of scientific findings, respectively. Ensuring the proper application of wearable technologies is essential and is easily accessible through the manuals and tutorials that are available. Additionally, both structural (i.e. anatomical) and functional (i.e. brain activity) differences in brain activity have been observed across different categories of the population (e.g. children, elderly, mental disorders, etc.; Schlaggar 2002; Bjork 2004; Paus 2004; Reiss 1996). Moreover, no gold standard has been established regarding the choice of reference electrodes, with the regions of interest playing a key role when selecting the appropriate measures for obtaining good signal quality. Consequently, comparing different EEG systems remains a challenge. Future studies
should aim to identify reference systems that could be standardized across protocols and headsets. Additionally, the correct positioning of electrodes across the scalp is critical for applications involving neuromodulation wherein cortical regions are selectively targeted and and exert neuromodulatory effects {Villamar, 2013}. Variability in electrode types, location, software, file formats, or interfaces constitute a barrier in attempting to combine big databases across a range of sources. The newly developed Research Resource Identifiers (RRID), such as SciCrunch, may help resolve these issues, as they offer a platforms which enables straightforward searches of information pertaining to research studies implemented with specific types of technology and contain user information about the device, signal quality, and the literature. Unlike more general search engines, they provide deeper access to a more focused set of resources that are relevant to its communities and provides access to content that is traditionally “hidden” from web search engines. Users can also add their own data to the platform. Additionally, novel tools are needed to help facilitate the recording and streaming of EEG data from consumer headsets that can be interfaced with varying programming languages and software packages, and that allows for interchangeability across devices. The MuSAE lab is developing the MuSAE Lab EEG Server (MuLES), an EEG acquisition and streaming server that aims to create a standard interface for portable EEG headsets in order to accelerate the development of BCI and of general EEG applications in novel contexts. Successful, large studies could be conducted using these servers, with the open source data then available for future studies, limiting costs and time spent collecting new data.

Another limitation regarding wearable devices pertains to the identification of event-related signal onset. Whereas some companies provide features for markers and triggers which indicate the beginning and end of epochs in the data, several companies do not include such features, making the analyses of data time-consuming and challenging when attempting
to identify event related activity. For studies comparing conditions across trials, it is crucial that these features are implemented in all wearable EEG devices. One temporary solution (although not ideal) is the instruction for the subject to perform a small series of eye blinks at the beginning and end of each trials, as it is very easy to identify in the EEG signal.

The future of wearable technologies

A major limitation to the daily integration of wearables remains the feasibility of people feeling comfortable wearing such devices in public places. While great improvements in design, weight, and comfort are under active development, new technologies developed by companies such as Neuronate offer innovative solutions, such as the production of clothing that incorporates biometric sensors embedded into the material (see home-use section; Valenza, 2015).

Within the BCI domain, transparent EEG systems such as the “Ear-EEG” include both micro electrodes located in the ear canal and cEEGrids, a flex-printed C-shaped 10-channel grid that can be placed around the ear (Debener 2015; Bleichner 2017). The Ear-EEG is capable of extracting relevant focal temporal neural features such as the P300, presenting innovative solutions and applications for augmenting hearing technology (Fiedler, 2016) and epilepsy (Zibrandtsen 2017). Sensors are now being integrated into accessories such smart glasses (Jiang, 2017)(Vahabzadeh 2018), smart headbands (Ruminski 2015; Le 2013; Zang 2014), smart EEG-glasses (e.g. the Muse Lowdown focus or the Memento; Jiang, 2017), stick-on electronic tattoos (Zheng, 2014), and chemical wearable sensors (Matzeu, 2015). The development of “wetware” which combines technology with carbon based systems such as living cells now enables the collection of data using a single cell (Koniku REF). Koniku is currently building co-processors made of biological neurons that they can genetically program
to increase the desired attribute (e.g. firing faster in response to odors, for odor surveillance in an airport).

**Ethical and safety questions**

The rapid advancements in the biomedical-tech sector present ethical questions such as consent, data protection, and identity (Trimper 2014). At present, there is no legislation regulating informed consent and protecting personal data extracted via BCI, either therapeutically or outside clinical and research contexts. Furthermore, the non-invasive nature of these technologies, the ease of engineering the relevant hardware, and the enthusiastic ‘Do It Yourself’ (DIY) culture interested in cognitive enhancement make exploring these ethical issues especially pressing. Having witnessed the public uproar and opposition to previous scientific and technological advancements, such as was seen with the cloning of Dolly the sheep, ethicists and scientists must work together to ensure that the technology is developed with the highest ethical standards, and that the public is informed accordingly (Wolpe, 2006).

While it is safe to say that a majority of wearable technologies are designed under the premise of improving the monitoring and betterment of one’s health and or cognitive abilities, these technologies also host tremendous power and potential to drastically influence the choices and actions of the users (i.e. how to breath, to eat, drink, exercise, work, sleep etc.). By offering consumers a way to simultaneously embrace and outsource the task of lifestyle management, one could imagine that such products exemplify and short-circuit cultural ideals for individual responsibility and self-regulation (Schüll, 2014). Ultimately, the companies depend on the engagement and participation of their customers, thus it is the role of consumers to educate themselves and to exert the ‘consumer influence’ over the quality and trajectory of future technologies.
As lifestyle, health, and technology become increasingly integrated and interfaced, it is crucial that these devices remain as tools to support and assist human needs. With an increasing rate of reliance on our technology, human beings are simultaneously increasingly vulnerable to the potential dangers and pitfalls of this reliance. Furthermore, when something is used to enhance or assist a function, this function no longer needs to be accomplished by the body anymore, which will then redirect the energy towards other systems (e.g. atrophied muscle after injury). This could potentially apply to the brain as well, if too many functions were to become supported or replaced by technologies. On the other hand, it is also possible that the technological support could participate in training natural abilities beyond their initial potential (e.g. a system detecting cues that are imperceptible to the awareness to warn from a danger, could train the brain to detect these stimuli). Additionally, one can argue that any lost abilities could be recruited for new abilities (e.g. the invention of writing offered many new possibilities for human cognition). If this is possible, future studies should focus on how to develop these technologies so as to produce long-term benefits. For example, NF systems can be used to help users train their own inner regulatory abilities (e.g. increased attention and emotion regulation).

With the development of new wearable technologies resurfaces the debate revolving around the effects of radio frequencies (RF) and cell phones (Mohan 2016; Croft 2010; Huber 2002; Hubert 2003 Vecchio 2009; Röschke 1997; Krause 2005; Laudisi 2012; Hung 2007; Pyrpasopoulou 2004; Bin 2014), as well as the effects of bluetooth and Wifi frequencies (Saili 2015; Banaceur 2012; Othman 2017; Mandalà 2013; Balachandran 2012). Biological effects are generally considered to be dependent on the distance and relative size of a given object, but also on the environmental parameters, and there may be additional interindividual differences in sensitivities to exposure. However, research suggests that regular and long-term use of RF emitting devices can have a negative impact on biological systems, most notably in the brain
(Kesari Kavindra Kumar 2013; Volkow 2011; Megha 2012; Megha 2015; Avendaño 2012; Atasoy 2013; Shahin 2013; Nurul Huda Ishak 2012). Wearable neurotechnologies concentrate RF energy from Bluetooth and Wifi in and around the area of the brain in larger amplitudes then has been studied previously. The potential for chronic exposure to RF frequencies resulting from daily BCI use demands that future studies explore solutions for RF protection or alternatives deliverance modalities.

Conclusion

Advancements in EEG wireless technology allow researchers and clinicians to study the brain easily, in natural environments, and with greater access to a wide range of the population (i.e. children, elderly). While several new wireless devices enable the collection of data with both high temporal and spatial resolution (i.e. combined EEG and fNIRS respectively), they also facilitate the simultaneous modulation of brain activity through the addition of stimulation sensors which administer transcranial electrical stimulation (TES). At home-use of wireless and wearable technologies has the potential to significantly reduce medical costs for both patients and medical centers in terms of both diagnosis and long-term treatment options. Online platforms now enable clinicians to arrange medical assessments and treatment interventions, such as EEG recordings or TES therapeutic sessions for patients (e.g. epileptic, disabled patients) without ever having to leave the comforts of their home. Based on our extensive review, the Muse, Epoc+ and Dreem systems offer the most reliable SNR for consumer grade NF and BCI applications. These applications are the best candidates for at home-use of BCI and NF therapies, providing user-friendly interfaces, tutorials, and software packages. With widely accessible wearable EEG technology comes an increased understanding of the brain and our abilities to interface with technology. By allowing patients to move, communicate, and create,
these technologies aid not only in rehabilitation, but in an individual's ability to regain a sense of well being, autonomy and independence. These technologies also present applications to the healthy population such as entertainment, art, education, and cognitive enhancement.

While the everyday use of wearable technologies may sound futuristic, major advancements in the technological sector and data processing are bound to lead to an exciting and unpredictable future for wearable technologies. While these technological advancements host the potential for significant improving the monitoring of one's health and in rehabilitation, mindful measures need to be taken to direct the evolution of wearable neurotechnologies towards positive applications serving the general interests of the public.