Brain-computer interfaces in weightlifting: enhancing strength performance on the barbell back squat through neurofeedback

ABSTRACT Neurofeedback (NF), already proven efficient in neurorehabilitation, now also has become a promising tool for performance enhancement in the field of sports. Until to date, only little research has been done to enhancing movement kinetics such as force and muscle strength. This study aims to investigate how NF could enhance strength performance on the barbell back squat in weightlifting athletes. The primary motor cortex and the spinal circuitries both signal force-related information and should be addressed in NF. High gamma power and two brain potentials (i.e. MRCP and CNV) as recorded from the primary motor cortex correlate with muscle activity and the level of contractile force. On a more whole-body level, corticomuscular coherence (CMC) correlates with electromyograms (EMGs). Visualizing these brain measures in NF paradigms might help in enhancing strength performance. Combining physical training with motor imagery (MI) benefits strength enhancement, and NF by visualizing the levels of event-related desynchronization and synchronization (ERD and ERS respectively) increases the effectiveness of MI in strength enhancement. Taken together, this literature review provides relevant information on force encoding in the central nervous system (CNS) and offers possibilities for future research in both the fields of sport and neurorehabilitation.

Brain-computer interface: from neurorehabilitation to sports

A Brain Computer Interface (BCI) is a system that records neural signals from the central nervous system (CNS) and converts it into artificial output. This artificial output can be used to restore, enhance, supplement, or improve natural CNS output and thereby change the ongoing interactions between the CNS and its external or internal environment (Abdulkader et al., 2015; Brunner et al., 2015). BCIs are initially developed as biomedical applications. Currently there is a lot of research to their use in neurorehabilitation, for example in spinal cord injured patients. In these patients, neurofeedback (NF), a form of BCIs, is used to facilitate restoring movement ability, or even to replace lost motor functionality. NF is based on the observation that individuals are able to regulate their neural signals once they have a greater access to detailed information about these signals (Mirifar et al., 2017). Neural signals reflecting motor performance are transformed into external signals and then visually fed back to the individual, who can learn to change and influence them accordingly. Electroencephalographic (EEG) oscillations are widely used in NF, visualized for the individual on a monitor. Thus, NF relies on a closed loop that exploits brain activity in real-time (Perronnet et al., 2017). NF training appears not only to be a powerful tool for performance-restoring in neurorehabilitation, but also seems a promising tool for training performance-enhancing self-regulation of brain states. As such, NF has been deemed useful for improving sports performance. Until today however, not a lot of research assessing its effectiveness in sports has been done. Some studies are published about the use of NF in archery (Landers et al., 1991), gymnastics (Strizhkova et al., 2012), shooting (Cheng et al., 2017) and soccer (Jeunet et al., 2020), focusing mostly on visuo-spatial attention and movement kinematics. However, motor performance is not only determined by movement parameters such as direction, amplitude, speed, and path (i.e. kinematics), but also by force and muscle activity (i.e. kinetics). Therefore, this review will focus on movement kinetics, and in particular on the motor parameter force. Weightlifting seems a relevant topic, as force is of particular importance in this field of sports. Weightlifting has recently become part of my life and my personal goal is to improve strength performance on the barbell back squat. Therefore, this literature review focuses on the research question "how could NF enhance strength performance on the barbell back squat in weightlifting athletes?". To answer this question, we first have to understand how the brain codes for voluntary movement and force. After that, studies to force representation in brain measures and studies to NF will be addressed. Finally, proposals about the use of NF in sports and future research will be made.

The moving brain

Voluntary movements are produced by spatial and temporal patterns of muscular contractions, controlled by neural circuits in the brain and spinal cord. To perform a movement, a signal must begin in the primary motor cortex, which is located in the precentral gyrus. Here, the somas of the upper motor neuron are located. These neurons are responsible for integrating the excitatory and inhibitory input from the cortex and ultimately translate it into a signal that will either initiate or inhibit voluntary movement. Upper motor neurons have long axons, which travel through the brainstem all the way down the spinal cord as the corticospinal tract, on the contralateral side of the body. This tract directly synapses onto the lower motor neurons, which are located into the anterior horn of the spinal cord. The lower motor neuron transmits the signal from the upper motor neuron to the muscle to perform a movement. Thus, the upper and lower motor neurons form a two-neuron circuit. There are three broad types of lower motor neurons: somatic motor neurons, special, and general visceral motor neurons. Somatic motor neurons, and in particular its subtype α motor neurons, are of most interest here, because α motor neurons innervate extrafusal muscle fibers and are such the primary means of skeletal muscle contraction.

The motor parameter force

Synaptic input from various parts of the neuromuscular system ultimately converges to α motor neurons. The axon of an α motor neuron innervates many muscle fibers within a single muscle. There is a one-by-one association between the discharges of an α motor neuron and the action potentials in the innervated muscle fibers (Farina & Negro, 2012). For this reason, the α motor neuron and the muscle fibers it innervates are together considered a functional structure, called the motor unit. Motor units differ in size and power. Increasing the number of motor units can increase the amount of force produced by a muscle. A gradual increase in muscle tension results from the recruitment of motor units in a fixed order, according to their size. As synaptic input from higher motor pathways (i.e. the upper motor neurons) driving a lower motor neuron pool increases, the recruitment of motor units changes: with weak input the smallest units with the least power are activated, but with stronger input also the higher-threshold, bigger, and more forceful motor units are activated. This is known as the size principle. An important consequence of the size principle is that the brain cannot selectively activate specific motor units: the sequence of motor-neuron recruitment is determined by spinal mechanisms. Thus, the force that a muscle exerts depends on the amount of motor unit activity, changing with the number of motor units that are active, and the rates at which motor neurons discharge action potentials, i.e. the discharge rate. Strength training regimes can change the discharge rate and discharge characteristics of motor units, as well as increase the strength of muscle fibers. Duchateau et al. (2006) examined whether strength training also increased corticospinal excitability. This was not the case; thus, strength training does not change the output from the motor cortex, but only the functional properties of spinal cord circuitry. Taken together, this highlights that the spinal cord should be considered in NF to force.

However, the amount of force needed for a certain movement is primarily encoded in the primary motor cortex, which makes not only the spinal cord circuitry but also the primary motor cortex a relevant target for increasing strength performance. Evarts (1968) was the first to show that cells in the primary motor cortex are sensitive to the force needed for a given movement, which suggests that low-level movement control signals are present here. More recently, Morrow and Miller (2003) demonstrated that a small number of neurons recorded in the primary motor cortex contain sufficient information to reconstruct averaged muscle activity and its time course with considerable precision. This does not mean that primary motor cortex neurons encode individual muscles: whereas a minority of the primary motor cortex neurons encodes individual muscle force, a larger number seems to encode the amount of force needed for a particular movement. This is in line with the motor homunculus (see box 1).

Now we have a better understanding of which areas are involved in movement and how movement and force are represented in the brain and spinal cord, we can explore the possible targets for NF.

Box 1. The motor homunculus

The primary motor cortex is somatotopically organized according to body parts, also known as the motor homunculus. The lower body and core, both important in the barbell back squat, are represented more medial and are thus mediated by neurons located near the midline of the brain, whereas the upper body is represented more lateral. Within this somatotopical map, the size of the brain region associated with a body part reflects the complexity of the activities carried out with that particular body part rather than its actual size. Moreover, the somatotopical organization does not represent the movements of individual muscles, but more of individual body parts, which often require the coordinated activity of large groups of muscles throughout the body.

Neurofeedback to improve strength performance

NF to force: encoding force from brain signals and visualizing them

Previous research has shown a proportional relationship between the magnitude of brain-to-muscle signal and voluntary muscle force (Yao et al., 2013). This indicates that greater strength is, at least to some extent, a consequence of increased firing rate. This can be explained by the following: with training, a descending command from the brain could recruit motor units that were otherwise inactive and/or could recruit a higher discharge rate in the active units. Alternatively, a trained control network may be able to more effectively reduce inhibitory input to the motor neuron pool of muscles, resulting in a net increase in motor neuron output. This indicates that the brain is a relevant target for improving strength performance. Flint et al. (2014, 2020) observed that most information about force is recorded from the primary motor cortex. Therefore, visualizing these signals could be relevant for NF. In these studies, they demonstrated that motor cortical gamma frequency oscillations as recorded with an electrocorticography (ECoG) over the primary motor cortex can be used to decode electromyograms (EMGs) of multiple muscles. The high-gamma frequency band (70–115 Hz) contained the most information about muscle activity and has been the most informative frequency band for continuous force decoding. This finding matches well with the study of Nakanishi et al. (2017), who demonstrated a high gamma contribution to muscle activity and object weight, and a high delta contribution to movement. They also demonstrated that the weight at the channel recording from the primary motor cortex was much higher in muscle activity prediction, than in trajectory prediction. In line with this, Mizuguchi and collegues (2013) concluded that the discharge rate of primary motor cortex neurons is related to the level of contractile force, by examining corticospinal excitability through EMG. During voluntary contraction a graded modulation of this excitability, as assessed by motor evoked potentials (MEPs), was observed. Taken together, visualizing ECoG high-gamma power recorded from the primary motor cortex may be used in NF to force.

During the preparatory period preceding voluntary movement two electroencephalographic (EEG) measures (i.e. potentials) related to force can be recorded. These measures are the movement-related cortical potentials (MRCPs) and contingent negative variation (CNV). Both MCRPs and CNV can be observed from the central and frontal electrodes, above the primary motor cortex and the supplementary motor area (SMA). Several studies show that the recorded amplitudes of these brain potentials are linearly correlated with the level of contraction force (Siemionow et al., 1998). Also, resistance training influenced the MRCP: following a resistance training program for several weeks, MRCP over motor-related areas was attenuated and had an earlier onset. As the magnitude of contractile force can be predicted by the amplitude of MRCPs and CNV and MRCPs are influenced by resistance training, visualizing these potentials could be used in NF just preceding movement. However, it is not yet examined whether these potentials can be actively influenced by NF.

To fully understand how strength performance could be improved on a complex movement as the barbell back squat, it's not sufficient to only look at and give feedback to the brain, but also the spinal cord and the muscles should be considered. In a squat, an estimated 200 muscles are active (Kenville et al., 2020). In contrast to simple movements, voluntary control of each muscle during a squat seems unlikely, especially when considering the dynamic nature of the movement. Rather, a complex dynamic movement as a squat demands continuous, extensive central-nervous information integration. Frequency band related neural synchrony between brain regions and muscles enable the dynamic information processing on a whole-body level during the barbell back squat. This synchrony is detectable through corticomuscular coherence (CMC) measurements. Both an EEG-EMG and ECoG-EMG method can be used to analyze this functional coupling between brain cortex and muscle activities, i.e. CMC (Liu et al., 2019). Kenville et al. concluded that CMC in both beta and gamma ranges across multiple muscles were involved in a squat. Not surprisingly, several studies showed that CMC in these two frequency bands were also more involved in force than other frequency bands, with the CMC value of the betaband (13–30 Hz) being more related to the output of static force, and the coherence of the gamma band (31–45 Hz) being more related to the output of dynamic force (Liu et al., 2019). Moreover, it has been further shown that the level of CMC increases with an increase in EMG-signal, indicating that muscle output is dependent on CMC intensity. In the study of Kenville et al., CMC patterns were best modeled from the primary motor cortex, the SMA and the premotor cortex (PMC). CMC thus seems a relevant target for force-related feedback on a more whole-body level. Von Carlowitz-Ghori et al. (2015) investigated whether CMC could be voluntarily modified in a NF paradigm and this was the case. They demonstrated that CMC strength in the target frequency range was significantly larger when subject had to increase CMC as compared to decrease it. Thus, CMC could be effectively modified in the preferred direction. To conclude, visualizing CMC seems relevant in NF to force. CMC can be analyzed by both an EEG-EMG and an ECoG-EMG method, with the primary motor cortex, the SMA and the PMC being the most relevant targets for electrode placement. Noteworthy to mention, with recording EMG, activity of the lower α motor neurons and thus spinal activity can also be examined, seen the one-by-one association between the two (Farina & Negro, 2012).

NF to motor imagery: the relevance of complementing physical training with motor imagery

To increase the effectiveness of NF in increasing strength performance, physical training can be combined with motor imagery training (MI; see box 2). The combination of MI and physical practice has been extensively shown to be more efficient than physical practice alone. However, as MI usually does not outperform physical practice, it should only be used in combination with physical training, and not instead of it (Smith et al., 2003).

MI seems to trigger brain structures sharing similar neural networks with motor execution. MI even seems to induce LTP-like plasticity in the primary motor cortex in the same way as motor execution does (Jeunet et al., 2019). However, there is some controversy about the similarity between MI and motor execution (see box 2), being the reason that this paper will not focus on MI as the main method to enhance motor performance, but only as an additive to physical training. Here, the focus is on kinesthetic MI, as it seems to share more similar neural pathways to motor execution than visual MI (Guillot & Collet, 2008). Kinesthetic MI has proven effective in increasing strength performance. Yao et al. (2013) concluded that kinesthetic imagery training of forceful muscle contractions increases brain signal and muscle strength. This is supported by Ranganathan et al. (2004), who suggested that the mental repetitions of maximal muscle activation made the brain generating stronger signals (i.e. with higher firing rate) to the muscles. Closing the loop with NF enhances this effect of MI.

NF to MI is often based on EEG oscillations. According to Jeunet et al. (2019), the sensorimotor rhythm (SMR; i.e. mu rhythm) and the beta-band rhythm are a relevant and reliable neurophysiological measures that can be used in NF studies which aim at improving MI and/or motor execution and abilities. During MI, the amplitude of the mu rhythms (7-11 Hz) decreases, referred to as event-related desynchronization (ERD; Abdulkader et al., 2015). This occurs primarily over the scalp in sensorimotor cortical regions contralateral to the imagined part of the body (Brunner et al., 2015). After MI stops, there is an increase in the high-beta rhythm (12-30 Hz), referred to as an event-related synchronization (ERS; Abdulkader et al., 2015). The level of ERD can be used as an index of how a subject is engaged in a motor imagery task (Hanakawa, 2016). NF offers a visualization of the level of ERD/ERS reflecting performance, in order to make it possible for the subject to modulate their brain activity accordingly.

Thus, MI induces EEG oscillations primarily over the sensorimotor cortical (SMC) regions. Several functional magnetic resonance imaging (fMRI) studies have been done to MI as well. Because fMRI has a higher spatial resolution, these studies are better able to localize which exact areas within the SMC are most active during MI. Blefari and collegues (2015) provided evidence that the contralateral primary motor cortex BOLD activity during MI predicts improvements in motor performance, which seems to imply that the primary motor cortex is involved in MI. In contrast, another study showed a significant negative BOLD response in the primary motor cortex during kinesthetic MI, despite reinforcing feedback, and only showed a robust positive BOLD response in the SMA (Mehler et al., 2019). Also, NF provided some extra control of BOLD signals in SMA and therefor seems to target brain areas involved in imagery more than brain areas involved in movement. This is in line with research from Hanakawa (2016), who classified the primary motor cortex as ‘movement-predominant’, but the SMA as ‘imagery-predominant’. It should be mentioned however that MI is associated with both an increase in muscle tone and in excitability of the cortico-spinal pathway. This raises the question as to how such an increase might be produced during MI, in the absence of primary motor cortex activity. This can be explained by the fact that besides the primary motor cortex, several association areas have direct projections to the spinal cord through the internal capsule, of which among others the SMA (Solodkin et al., 2004). It could be argued that kinesthetic MI is part of a system for motor preparation more than for motor execution: during kinesthetic MI the SMA is exerting heavy influence on the primary motor cortex, hence being a way the system coordinates motor preparation with execution. Taken together, placing electrodes over SMA and visualizing the level of ERD/ERS as recorded from these electrodes probably is the most relevant for NF to MI. Also, MI training does not seem to robustly target the primary motor cortex and therefore might not be the best candidate for increasing strength performance on the level of motor execution. Nevertheless, it is still a relevant additive to physical training, as it seems to improve motor planning and has some effect on strength performance.

Box 2. Motor imagery

Motor imagery (MI), a cognitive ability, is commonly defined as the 'mental simulation' or 'mental rehearsal' of movement without actual movements and thus without muscle activation (Hanakawa, 2016). MI has been a promised neurorehabilitation technique. The rationale behind the application of MI in stroke rehabilitation is that mental practice with motor content engages areas of the brain that govern movement execution; thus, MI appears to share neural substrates with actual movement. Such reiterated engagement of motor areas is intended to influence brain plasticity both in patients and healthy individuals, improving its functional outcomes (Pichiorri et al., 2015). A widely adopted BCI paradigm uses the modulation of electroencephalographic (EEG) activity induced by MI. MI elicits event-related desynchronization (i.e., a reduction in spectral power; ERD) that occurs within certain EEG frequency oscillations and primarily over the scalp in sensorimotor cortical regions contralateral to the imagined part of the body.

Controversy about the role of MI in improving motor performance

There is currently a lot of controversy about the relationship between MI and motor execution. One of the main reasons is the involvement of different brain areas in both. As discussed in the text, the supplementary motor area (SMA) seems to be most involved in MI, whereas the primary motor cortex is most involved in motor execution. Some research indicates that it still remains possible that also the primary motor cortex is involved in MI. For example, Mehler et al. (2019) argued that participants can activate the primary motor cortex during imagery and gain volitional self-regulation with more training experience. However, even after a lot of research to MI, the controversy remains and its exact mechanism is still questioned. Because there are more robust findings on other relevant targets to increase strength performance, future research should not focus on MI alone, but should find other ways in which strength performance can be increased while focusing more on the level of motor execution.

The future of NF in sports

To conclude, there might be some relevant targets for NF in weightlifting. However, to answer the question how NF could enhance strength performance on the barbell squat in weightlifting athletes, more research needs to be done. I will propose how research could be done, as based on how movement is encoded in the CNS and which signals could be relevant to visualize during NF.

Strength enhancement of the barbell squat

To enhance strength of the barbell squat through NF, preferably motor execution is combined with MI, and NF is preferably available during both. Hanakawa (2016) argued that for boosting strength in large muscles, it is possible that motor execution at their best works most efficiently when in combination with a certain degree of adjunctive MI.

To start with, targeted feedback to force during motor execution could help in enhancing strength performance on a barbell squat. High-gamma frequency oscillations recorded over the primary motor cortex proved useful in decoding force (Flint et al., 2014, 2020; Mizuguchi et al., 2013; Nakanishi et al., 2017). To record these oscillations, ECoG could be used. In the studies of Flint et al., ECoG recordings have proved to be highly stable for a year in a closed-loop BCI. Chronically implanted multielectrode arrays, which are often used in BCIs as well, typically lose their ability to record spikes on most of their electrodes after several years. As ECoG recordings from the primary cortex also convey information about movement, and more importantly force, they could be a good and less invasive substitute for multielectrode arrays. Since neural oscillations could potentially offer greater recording longevity than spikes and represent the combined activity of thousands of neurons, loss of activity from a few neurons would not be likely to cause real change. However, an even less invasive technique would be scalp-recorded EEG. Recent studies have shown that EEG can also detect high gamma power changes. Darvas and collegues (2010) compared their high gamma EEG data with ECoG data and found EEG mapping and ECoG in good agreement. They also highlighted that EEG has an advantage over ECoG as EEG is able to localize activity, albeit with limited spatial resolution, anywhere on the cortical surface. However, ECoG activity does not suffer from EMG artifacts, whereas EEG can. Despite the latter limitation, I propose to study whether visualizing high gamma power as recorded with EEG could be used to provide NF to force and thus, could possibly help enhancing strength performance on the barbell squat. When high gamma power as recorded with EEG does not prove to be efficient, studying the use of ECoG in NF could still be considered. But as ECoG is a more invasive method, it is not the method of first choice in healthy individuals.

As mentioned before, it would be optimal to give force feedback on a whole-body level. The one-to-one relationship between the action potentials produced in α motor neurons and the ones generated in muscles, makes it possible to determine α motor neuron activity by means of EMG. Moreover, when EMG is combined with EEG, CMC can be determined. From previous research it can be concluded that coherence in the gamma band is most related to the output of dynamic force (Liu et al., 2019), that CMC modeled well from the primary motor cortex (Kenville et al., 2020) and it is possible to voluntary alter CMC in a NF paradigm (von Carlowitz-Ghori et al., 2015). Ushiyama and collegues (2010) did a study to the CMC in weightlifters and found training-related alterations. This suggests that the interaction between the brain and contracting muscles can be changed by long-term specialized use of the muscles and this eventually leads to finer control of muscle force during steady contraction. Their data indicates that it is important to reduce CMC in order to stabilize force fluctuations, as the weightlifters in their study appeared to suppress the oscillatory coupling between the brain and the spinal motor neurons. However, in novels the CMC was increased during forceful contraction. Thus, it might be that a strong corticomuscular coupling is beneficial in force production in novels, while a weaker corticomuscular coupling is more beneficial in advanced weightlifters. Taken together, I propose to study whether visualizing CMC in the gamma band, as recorded with EEG from the primary motor cortex and EMG from the lower limb muscles, is beneficial to improve strength performance on the barbell back squat in a NF paradigm. Also, I propose to study whether decreasing CMC in this NF paradigm is most beneficial in improving strength performance in advanced weightlifters.

Furthermore, as discussed before, the two EEG potentials MRCP and CNV are related to force as well and can be recorded during the preparatory period preceding voluntary movement (Siemionow et al., 1998). When NF to high gamma power seems insufficient in enhancing strength performance, it is possible to study whether MRCP and CNV are good alternatives.

Lastly, for optimal enhancement of strength performance, it seems relevant to combine physical training with MI, and also provide NF to MI. Visualizing ERD/ERS levels as measured with EEG from electrodes over the SMA has proven most efficient in MI NF paradigms (Abdulkader et al., 2015; Hanakawa, 2016; Mehler et al., 2019). However, as the results of ERD/ERS NF paradigms are quite variable between studies and users and their accuracy is not very high, more research is needed (Hanakawa, 2016). To make MI most effective, first-person perspective kinesthetic-dominant imagery is recommended. This imagery appears to work best in re-organizing motor-somatosensory networks and thereby probably in enhancing strength as well. Moreover, kinesthetic imagery but not visual imagery seems to activate motor-associated structures and modulate corticomotor excitability during motor imagery tasks. Therefore, I propose to study whether first-person perspective kinesthetic-dominant MI can be helpful in improving strength on the barbell squat, and whether the effectiveness can be increased by visualizing ERD/ERS levels in a NF paradigm. A future challenge of MI NF through EEG is to link this with sports in ecological settings, that is performing the barbell back squat during a competition. Even though EEG may be used to monitor the effect of MI, and possibly the increase in strength through MI, it is even more relevant when EEG could be used in real time performance. Thus, it should be examined whether, and how, portable EEG systems can record athletes' brain signals during performance. Then, advanced techniques to decode these signals in real time that help the athlete alter their signals accordingly should be developed.

Finally, the primary motor cortex is somatotopically organized (see box 1). This somatotopic organization indicates that recoding neurons located near the midline of the brain (mediating lower body and core) will be most efficient to give targeted feedback to the barbell back squat. This somatotopic organization proves a stable functional topography for both single limb movements, as well as for moving several body parts as during a barbell squat (Ma et al., 2017; Mattia et al., 2006). Therefore, I propose to study whether it is most efficient to spatially locate the electrodes at the medial part of the primary motor cortex.

Downside of NF

A general problem with NF is that the competence to voluntarily change brain patterns needs to be transferred from a training environment to actual competitions (Mirifar et al., 2017). Actual performance situations should therefore be included, and NF should not only be targeted to MI. Research needs to be done whether findings in the laboratory are external or ecological valid. Thus, the effectiveness of NF for enhancing strength performance needs to be tested by assessing outcomes directly related to performance in a competition. Furthermore, it should be addressed how athletes may be aided in transferring the skills acquired through NF to the real world of competition. An even more ideal option would be real-time NF during performance, but these techniques applicable in sports environments are still to be developed.

Creating the ultimate athlete over helping patients?

When NF proves to be effective in enhancing strength performance, it remains the question whether it is ethical to enhance motor performance using NF. As enhancing performance through steroids is considered doping, it is questionable whether enhancing performance through NF can be considered legal. With both, performance is enhanced in another way than through mere physical training, exceeding the goals of sports competition. However, the ethics of enhancing performance through NF is beyond the scope of this review and, thus, will not be elaborated on further.

Moreover, also the use of NF in neurorehabilitation is still in its development. Therefore, it is of more importance to focus future research on restoring and/or improving motor performance in patients first, instead of enhancing motor performance in healthy athletes. This literature review offers some relevant information about force encoding in the CNS. This information could be used in future research to the kinetics of prosthetic limbs and exoskeletons, possibly improving neurorehabilitative treatment of patients.

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