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Towards Hybrid EEG-EMG-Based Control Approaches to be Used in Bio-robotics Applications: Current Status, Challenges and Future Directions

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Abstract

In the last few decades, bio-robotics applications such as exoskeletons, prosthetics and robotic wheelchairs have progressed from machines in science fiction to nearly commercialized products. Though there are still several challenges associated with electromyography (EMG) signals, the advances in use of EMG signals for controlling such bio-robotics applications have been enormous. Similarly, recent trends and attempts in developing electroencephalography-(EEG) based control methods have shown the potential of this area in the modern bio-robotics field. However, the EEG-based control methods are also yet to be perfected. A new approach of combining both these control methods, which take the advantages, and diminish the disadvantages, of each system might therefore be a promising approach. In this paper, we review hybrid fusion of EMG- and EEG-based control approaches in the bio-robotics field which have been attempted or developed to date. We provide a design overview of the method and consider the main features and merits/disadvantagages for the approaches that have been analyzed. We also discuss the current challenges regarding these hybrid EEG-EMG control approaches and propose some potential future directions.

Keywords

Hybrid EEG-EMG · Bio-Robotics Applications

1. Introduction

The recent advancement of the bio-robotics field has served in many ways to improve quality of life for a range of people. For individuals who are physically weak, disabled or injured, applications or devices such as prosthetics, exoskeletons, teleoperation robots, and intelligent wheelchairs have brought some hope to their lives. Controlling these devices, however, requires sophisticated technologies or methods, because they are usually interacting with human users. Main requirements such as accuracy, long-term reliability and safety are vital. As a result, many control methods have been proposed to satisfy these requirements, and different kinds of input signals are used in each method.

Electromyography (EMG) has been one of the frequently used biological signals in the control methods of bio-robotics applications, because EMG can directly reflect the human motion intention or muscle activity of the user. Even though there are challenges associated with using EMG signals, many encouraging control applications can be. Numerous examples such as wheelchairs [1, 2], prosthetics [3, 4], exoskeletons/orthoses [5, 6] show the effectiveness of EMG-based control methods. However, these EMG-based control approaches used alone have some disadvantages that depend on the user and on the application. In cases where the user cannot generate sufficient muscle signals, EMG-based methods are not useful as an input. For example, a person who has a totally paralyzed upper limb may not be able to use a device such as an exoskeleton due to the difficulty of getting control signals from the muscles of the paralyzed limb.
On the other hand, with recent advancements of technology, brain-computer interfaces (BCI) or brain-machine interfaces (BMI) have attracted a lot of interest in the bio-robotics area. Such interfaces may open new paths to directly decode the user's brain signals to control equipment such as prosthetics, exoskeletons or wheelchairs; for example, even though a user cannot make any sufficient movements of his limbs, he may still be capable of generating commanding brain signals, which can be used in such a brain control interface to drive an exoskeleton. Among the several methods of capturing brain signals, electroencephalography (EEG) is identified as a non-invasive and convenient method which may be suitable for practical systems. Various attempts to implement EEG-signal based interfaces can be found in applications such as wheelchairs [7, 8], prosthetics [9, 10], exoskeletons/ orthoses[11, 12]. However, BCI/BMIs which use the EEG signals alone as the primary input are not yet fully acceptable in bio-robotic applications due to difficulties such as low reliability, low accuracy, low user adaptability and low data transfer rates [16, 44, 45].

To overcome issues with both EEG- and EMG-based control methods, a combination of both systems, building on the advantages of each signal and diminish the limitations of each might be a promis-

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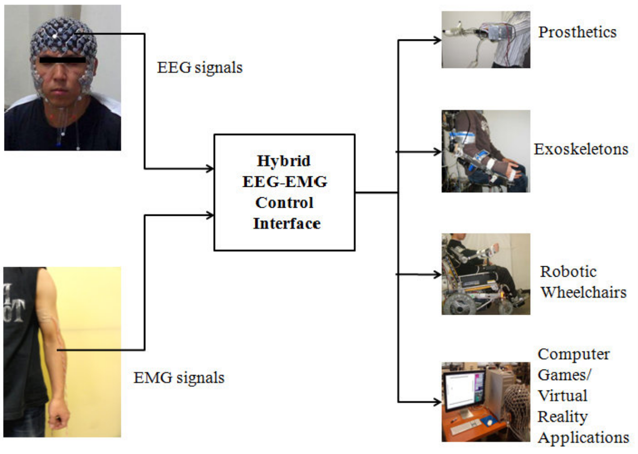

Figure 1. A graphical interpretation of an example hybrid EMG-EEG control interface

ing approach. For example, some muscles required for EMG based methods in the case of prosthetic control could be unavailable. In this case, EEG signals can be used to compensate for the missing EMG signals. Moreover, in an example like exoskeletons, some muscles required for EMG signals might be disconnected or paralyzed, or some nerves to the required muscles might be disconnected. In this case also, EEG can be used to compensate for the missing EMG signals. Even if all required muscles for EMG are available, EEG can still be used to remove the effect of fatigue or undesired tremor.

The main focus of this paper is to review hybrid/fusion EEG-EMG interfaces that have been proposed for bio-robotics applications to date, and to identify important design features and merits and limitations of such systems. Even though there are many reviews of either EMG-based control approaches [13–15] or EEG-based control approaches (with BCIs) [16, 17] , it is difficult to find any current in-depth reviews of hybrid EEG-EMG approaches in bio-robotics applications. In fact, while a few reviews on hybrid BCIs [18, 19] have been published, none of them give details about hybrid EEG-EMG control approaches, especially for bio-robotics applications. A timely written review paper combining the approaches of EEG and EMG for controlling such bio-robotics applications may help, not only to identify the current status of the research field, but also to provide information to anyone who is interested in initiating/developing such systems. In addition to a review of the hybrid EEG-EMG-based approaches in bio-robotics applications, we discuss current challenges regarding hybrid EMG-EEG control methods which are employed in bio-robotics. Several potential future directions will also be proposed.

2. Review of Hybrid EEG-EMG Based Control Approaches

The basic idea behind a hybrid EEG-EMG based-control interface is the fusing of EEG and EMG signals in the control method. The fusion of the signals may be performed in many different ways, and may depend on factors such as the specific application, and the abilities of the users. Figure 1 shows a typical graphical interpretation of such a hybrid EEG-EMG based control interface. In this hybrid interface, a combination of EEG signals and EMG signals are used. Applications of the hybrid approaches may vary from a simple game control application for an able-bodied person through to a prosthetic arm control application for an amputee. However, as the main objective of this review is to study bio-robotics applications such as prosthetics and exoskeletons, the scope has been narrowed down to the study of hybrid EEG-EMG approaches in bio-robotics applications. As discussed earlier, there are many possible ways to combine the EMG and EEG signals, within a particular control approach, to improve the effectiveness.

Generally, the EEG or EMG signals can be used to operate individual parts of an application, such as parts in an assistive device. Alternatively all of them can be combined. The latter will allow users to smoothly switch from one control signal to the other, depending on their preference and performance. Several methods can be used to classify the hybrid EEG-EMG control approaches in bio-robotics applications, such as the particular applications/devices (e.g. prosthetics, exoskeleton, wheelchair) or the input-processing methods. As a two-input system, a hybrid EEG-EMG interface can either process the inputs simultaneously or sequentially. In this review paper, we will categorize each study of a hybrid control approach in a bio-robotics application into one of two categories, based on its input-processing method being simultaneous or sequential. (Similar classifications can be found in hybrid BCI [19] studies). A comparison of the EEG-EMG approaches and summary of the important features of the different hybrid methods discussed in this paper are shown in Table 1. It is important that, whatever the fusion approach of EEG-EMG signals, a higher effectiveness is gained from the hybridisation than from methods that use either EMG or EEG signals alone.

Few studies [24, 25, 28, 31] have reported compensation for problems associated with the EMG-based control methods in bio-robotics applications by using the hybrid approaches. The EMG signals are frequently used as a control input of devices such as prosthetics, exoskeletons or wheelchairs, because sometimes people who are disabled, physically weak, old or injured have residual activities of their muscles. There remain some challenges to be addressed in the EMG-based control approaches.

One problem which may be encountered when using EMG signals alone is muscle fatigue; this affects the EMG amplitude and frequency spectrum in addition to the normal levels of muscle contractions [20, 21]. Especially as the body gets older, the skeletal muscle fibers become smaller in size and lessen in power, which leads to a reduction of strength and a tendency to fatigue rapidly for older people [22]. The physical and mental condition of such older individuals change throughout the day, and muscular fatigue may occur in some situations due to physical exhaustion. In such cases, it is necessary to design the EMG-based control methods to deal with the effects of muscle fatigue conditions. Except for a few attempts [23], it is rare to find reports of studies conducted in order to develop EMG-based control methods, which are robust to muscle fatigue. On the other hand, instead of relying on the EMG signals alone, the EEG signals can be used as an additional input signal to deal with the muscle fatigue situation in the control approaches. Such an attempt of a fusion of muscle and brain signals for a hybrid-BCI were reported [24, 25]. In those papers, a parallel use of EMG and EEG depending on the user availability and reliability were introduced in a hand-control task. The EEG signals were measured through 16 EEG channels, and the EMG activities were recorded from four channels over the flexor and extensor of the right and left forearms. Two fusion techniques were tested to combine the

Table 1. A Comparison of sevaral different hybrid EMG-EEG approaches

Reference	EEG-EMG Fusion approach	Appilication(s)
[24, 25]	Simultaneous	Assistive devices
[28]	Sequential	FES-based rehabilitation device
[31]	Simultaneous	Upper-limb power-assist exoskeleton
[33]	Simultaneous	Upper-limb artifitial arm/prosthetic
[35]	Sequential	Exoskeleton robot
[36]	Simultaneous	Assistive technology software
[37]	Simultaneous	Assistive exoskeleton for walking rehabilitation
[38, 39]	Simultaneous	FES based rehabilitation/orthosis
[40, 41]	Simultaneous	to be used in assistive technology

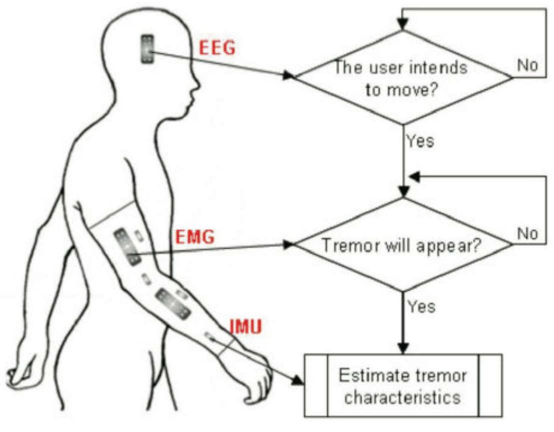

Figure 2. Integration of sensors to drive functional electrical stimulation (FES)-based tremor suppression. Adopted from [28]

EMG- and EEG-based classifier outputs. In the first approach, equally balanced fusion weights were used for combining the outputs of the individual EMG and EEG classifiers. In the second method, a Bayesian fusion approach was tested. The effectiveness of the EMG and EEG classifiers used alone was tested, and four conditions for fusion of EMG and EMG were considered according to different levels of muscle fatigue. Experiments were carried out with 12 healthy subjects (3 subjects had been removed) in [24]. The accuracy of the EMG activity alone was 87% , whereas for the EEG activity alone accuracy was 73% in this study. The accuracy of the first approach of hybrid EMG-EEG classifier fusion was achieved increment up to 91% and for the Bayesian fusion approach the accuracy was 92% with use of 50% EMG signal. The experimental results therefore suggested that the classification accuracy increased with the combined approaches as compared to cases when EEG and EMG inputs were used separately.

Tremor is a well-known problem for typical EMG-based control methods. The tremor is a commonly found disorder especially in older people, which causes rhythmic oscillation of a body part. People with upper limb tremor, in particular, usually show difficulties in performing activities of daily living. These unintentional movements generate EMG signals that do not represent the actual motion intentions of the users. Therefore, it is important to identify and cancel the tremor effects on control approaches of the bio-robotics applications such as exoskeletons. Studies such as those into the use of active wearable exoskeletons for tremor suppression [26] and attempts to avoid the unwanted vibrations or movements due to tremor when using power-assist robots have been reported [27]. Recently, however, a novel multimodal sensor fusion approach for tremor suppression was reported [28]. In this study, a multimodal BCI-mediated soft, wearable robot capable of compensating for upper limb tremor through functional electrical stimulation (FES) was proposed. In this study, the control signal to drive the FES-based wearable robot was supposed to be generated based on a combination of EEG, EMG and inertial sensor signals. A graphical interpretation of this sensor integration, as suggested in the original paper, is shown in Fig. 2. The hybrid fusion approach used in this case can be categorized as a sequential fusion method. In this approach, the first step was to recognize the intentional voluntary movements of the subjects using EEG signals recorded by means of surface Laplacian filtering of the C3, CZ and C4 electrodes (according to the 10-20 EEG electrode notation). Once it had been detected, the EMG signals were used to identify the tremor onset. Eventually, the onset tremor parameters were tracked by inertial measurement units (IMUs). The experiments were performed in 12 patients with a neurological tremor. Evaluation with data from the experimental session yielded an average tremor amplitude estimation error of 0.001 rad/s with a frequency estimation in the typical tremor frequency range as the final output. Apart from the final output, this study showed the importance of fusion and integration of different modalities in order to enhance the accuracy, and especially the robustness, of the detection and characterization of voluntary and tremorous components of movement.

Elderly or disabled persons sometime suffer from not only reduced motor ability, but also limited environment-perception ability. For such individuals, power-assist robots with the capability of perception-assist

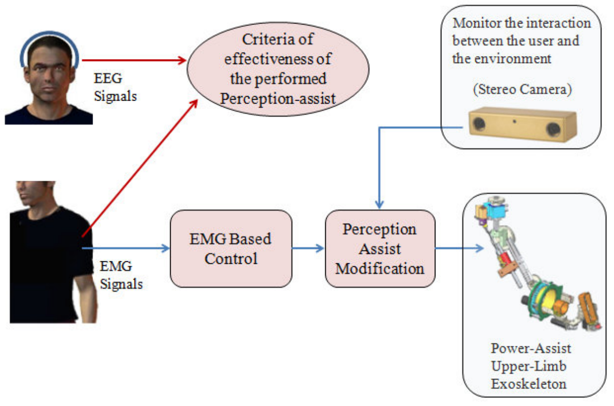

Figure 3. Use of EEG and EMG signals during perception-assist with an upper-limb power assist

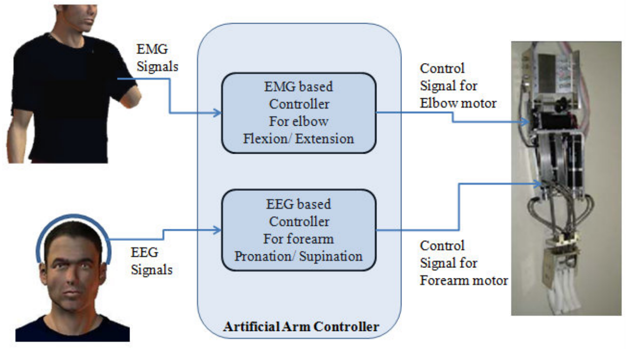

Figure 4. Combined use of EEG and EMG signals in controlling an artificial arm for an above-elbow amputee

were proposed and evaluated in the previous studies [29, 30]. Usually, to judge or verify the perception-assist and to teach the power-assist exoskeleton robot according to each task, EMG signals were used. However, there are some situations where there are not enough EMG signal variations to make such judgments. To overcome this problem, a combination of EEG and EMG signals in the upper-limb power-assist control was proposed [31]. The EEG signals were measured using a 256 high-density electrode system, and the EMG signals were recorded from the 16 muscles over the upper limb. The power-assist robot performs the perception-assist based on information from the surroundings (using stereo camera, ultrasonic sensors, etc.). The novelty of this study was the use of EEG signals, in addition to the EMG signals, in judging the effectiveness of the performed perception-assist. A graphical interpretation of the method used in this study can be seen in Fig. 3. Although the EMG and EEG signals were not fused directly with each other in this approach, the EMG and EEG signals were considered simultaneously in order to judge the performed perception-assist. The recognition rates of correctly or wrongly performed perception-assist were calculated for EMG alone and combined EEG-EMG approaches during the two experiments, which were carried out with four subjects. Average accuracy rates for the judgement of the perception-assist across all the subjects in the first experiment were 77.5% and 88.75% for EMG alone and combined EEG-EMG approach, respectively. The results for the same parameter, during the second experiment were 57.5% and 80% respectively for EMG alone and hybrid EEG-EMG approach. Using the combination of EEG and EMG signals led to the enhanced judgments of the effectiveness of the perception-assist.

The hybrid EEG-EMG control approaches are productive when a particular individual lacks the capacity to generate control signals to direct a bio-robotic device such as an active prosthetic arm. For an above elbow amputee, for example, the muscles which are used to generate forearm, wrist and hand motions are not present, even if he/she may have the muscles for performing elbow motions. To address this problem, a five-degree-of-freedom (DOF) myoelectric arm that uses shoulder and elbow motions as additional input signals was proposed [32, 34] . The forearm and the wrist motions were estimated by using an artificial neural network based on measured shoulder and elbow motions. It was not, however, easy to estimate various daily life motions with this method. A combination of upper-limb EMG signals and EEG signals from the brain was therefore proposed in order to control an artificial arm for an an above elbow amputee [33]. Control of the forearm pronation/supination motions of the artificial arm was performed using EEG signals measured from a high-density EEG sensor array (256 EEG electrodes), whereas the elbow flexion/extension motions were controlled by the EMG signals of the remaining bicep and triceps muscles.. The EEG-based controller used in the study was discussed in detail, and information about the EMG-based control methods were reported in previous studies [32, 34]. The simultaneous processing of the EEG and EMG signals to control the artificial arm for above-elbow amputee can be represented as shown in Fig. 4. In this approach, an artificial neural network was used for decoding forearm motions based on EEG signals and an EMG-based controller with a fuzzy-neuro modifier was employed for generating elbow motions of the artificial arm. The hybrid EEG-EMG-based control approach showed its potential advantages by introducing a control channel for the additional degree of freedom (forearm pronation/supination) with comparisons to the previous studies [32, 34].

It is interesting to discuss the possibility of integrating other sensors, such as motion or tactile sensors, to hybrid EEG-EMG approaches. Such an attempt to design an exoskeleton robot IntelliSense system based on multi-dimensional information fusion was reported [35]. In this study, a framework for the exoskeleton robot perception system was proposed to use information fusion between EEG, EMG, foot pressure sensors and an optical-fiber motion capture system. The basic framework of the design used the EEG signals for judging the direction of the human body movement intention, and EMG signals measured over the four major muscles in the human lower limb were used to recognize the human motion mode (i.e., running or walking). The human movement positions and attitudes were measured using the optical-fiber motion-capture system. Each measured signal was processed sequentially in the framework of the exoskeleton robot perception system. The EEG and EMG signals were not combined directly in the designed framework.

Several research groups have proposed the integration of EEG and EMG signals in control approaches for use in bio-robotic applications such as exoskeletons. In MIND WALKER project (Web address: https://mindwalker-project.eu/), the researchers proposed an integrated brain-computer approach mainly based on EMG and EEG signals related to human locomotion. In order to integrate the EEG and EMG signals, a design of a dynamic recurrent neural network (DRNN) that receives either the EMG signals from the shoulder muscles mim-

Table 2. Comparison of studies reporting quantitative performance results

Reference	Heathy Subjects	End Users	Performance Indicator	EMG	EEG	(EEG + EMG)	Remarks
[24]	12 (3 removed)	-	accuracy	87%	73%	increased to 91%	using simple fusion
			accuracy	87%	73%	92% (with 50% EMG)	using Bayesian fusion
[25]	6 (2 removed)	-	accuracy	83%	77%	increased to 91%	using simple fusion
			accuracy	83%	77%	88.8% (with 50% EMG)	using Bayesian fusion
[31]	4	-	accuracy	77.5%	-	88.75%	experiment 1
			accuracy	57.5%	-	80%	experiment 2
[33]	4	-	degrees of freedom	1	1	2	based on 5-DoF robot arm
[36]	6	-	time	-	high	low	Refer to plots
			error	-	high	low	for quantitative
			level of frustration	-	high	low	values
	-	1	time	-	34.8 [s]	19.13 [s]	
			error	-	33.9%	19.3%	
			level of frustration	-	4.6	3.3	

icking the walking movements or the spontaneous EEG signals during walking simultaneously was proposed [37]. This integrated approach of assistive exoskeletons for walking rehabilitation was suggested for use in helping handicapped people who are suffering from locomotion disabilities. A similar proposal for an FES-controlled method, based on a hybrid BCI system, for rehabilitation of the upper-limb in post stroke patients has also been reported [38]. As proposed in this study, in the hybrid approach, the motion intention of a given patient is recognized using EEG patterns, and the muscle contraction is produced through FES only if specific EMG features of the patient's voluntary attempts are detected. The authors concluded that preliminary experiments in the laboratory with healthy volunteers showed the feasibility of the approach, and more tests will be conducted with the participation of stroke patients and rehabilitation experts. In the meantime, the same research group has proposed a hybrid BCI-based device with multimodal feedback to support post-stroke motor rehabilitation of the upper limb [39]. In this approach, EEG signals were measured using three 16-channel biosignal amplifiers, and EMG signals of upper-limb muscles (flexor and extensors of the fingers, biceps and triceps of the arm) were recorded. Both signals were simultaneously fed into parallel processing pipes, which deal with EEG and EMG signals. Only when both EEG and EMG conditions occurred simultaneously (involvement of motor cortex, and physiological muscular pattern) at the right time, did the fusion module allow activation of the FES. In these experiments, the patients can observe their own hand move with the help of FES-orthosis controlled by the proposed hybrid BCI.

Apart from the mentioned approaches, few papers [40, 41] have proposed conceptual designs of hybrid sensor fusion in BCIs. In those designs not only EEG and EMG signals, but also other inputs such as signals from simple switches and motion sensors are combined in order to improve the information transfer rates, usability, reliability, etc. In these proposed methods, depending on the user preference and/or availability, the hybrid BCI are supposed to decide which input channels, or combinations of fused channels, offer the most reliable signals in the assistive technology system.

Though not a straightforward bio-robotic application, it is interesting to discuss a study that reports an attempt to develop a hybrid control of a P300-based BCI for communication in severely disabled end users. The main intention of this study was to evaluate the hybrid BCI interface that uses EMG, together with the P300 features from the EEG signals, to control assistive-technology software [36]. EEG and EMG signals were measured using 8 EEG channels (according to the 10-20 system) and 2 EMG electrodes respectively. Experiments were carried out with six healthy subjects and one severely motor-impaired end user. In the experimental session, participants were asked to spell online three predefined words (21 characters) using the system, under two conditions: no-hybrid task and hybrid task. In the no-hybrid task, the method used only BCI control, whereas the EMG control signal was used in the hybrid task to cancel any errors in the spell task. Eventually, the efficiency of the hybrid BCI approach was evaluated using three measures: time, the percentage of errors, and the levels of user frustration. As in the indicated results, efficiency of the hybrid BCI-system was higher than for the no-hybrid version. As for the healthy subjects, the three measures all showed a significantly lower score with the hybrid approach relative to the no-hybrid approach. Furthermore, the severely motor-impaired end user was able to achieve lower mean values for time (19.13s) and percentage error (19.3%) in the hybrid approach as compared to the no-hybrid approach (time 34.8s and error 33.9%). The measure of frustration was also lower when using the hybrid method (3.3) compared to the no-hybrid method (4.6).

Table 2 compares those studies, which presented quantitative performance results. Other studies which did not present quantitative performance results consisted either of studies currently under testing [38, 39] or those such as conceptual designs [40, 41]. From Table 2, it can be seen that different performance indicators have been used for evaluating studies. Also, in most of the studies, experiments with real patients or the expected end user have not been conducted. However, it is important to verify these studies with at least few expected end users, as these bio-robotics applications should really provide clinical benefits for the patients.

3. Challenges

One of the main issues with hybrid approaches is the difficulty in achieveing flawless integrations of EMG- and EEG-based methods. Although different techniques can be used to combine EMG- and EEG- based methods, it should be noted that not all the combinations are feasible. Sometime the effectiveness of the combined approach may be less than that of EEG or EMG alone. It is therefore important to critically consider how to combine both signals within the control approaches for a particular application in order to gain optimal results.

On the other hand, all the challenges involved in dealing with EEG- or EMG-based control methods alone, will still be issues for the hybrid EEG-EMG approaches as well. Technology is one of the limiting factors for hybrid EEG-EMG-based control approaches. High density EEG systems can provide a lot of details, but it is sometimes not practical to use such systems when they cover the whole head of the user, as the user may feel uncomfortable. Compact and low-weight designs for EEG- and EMG-data measuring systems need to be introduced, in order to allow use when users need to move around. In the case of bio-robotic applications such as exoskeletons or prosthetics, in particular, there is a high possibility of EEG signals being contaminated by movement artifacts. It is, therefore, essential to incorporate movement-artifact-removal methods in the controller approaches.

Due to the complexity of hybrid EEG-EMG-based control approaches, sometimes those systems may be difficult to train or adapt by users. Special consideration has to be given to the training procedures used in the hybrid EEG-EMG-based control approaches. Moreover, most of experiments have been conducted with able or healthy subjects in the reviewed studies. It remains an open question whether the EEG signals of real users (who usually physically weak, disabled or injured) may behave similarly to those of healthy subjects. Another great challenge will be the testing processes of these control approaches with real patients or disabled individuals.

4. Conclusion and Future Directions

In order to take advantage of EMG/EEG-based techniques and diminish the disadvantages of each, the EMG- and the EEG-based control methods can be combined to form a hybrid EEG-EMG-based control approach. In this paper, we have reviewed existing approaches that use combinations of EEG and EMG signals in their control methods. We have discussed the design overview and main features of each control approach. Success rates or quantitative values with EEG or EMG alone, and with the combination of the EEG-EMG signals, were provided for comparison of effectiveness.

We classified each approach as sequential or simultaneous, based on the combination of each EMG and EEG signal. In most of the reviewed studies, EMG and EEG signals were processed simultaneously. The main benefit of the simultaneous approach is that the accuracy of the overall system can be enhanced if the fusion is done appropriately. It was observed that in some of the approaches, sensors such as motion sensors have been employed in the design. Integration of sensor signals other than EEG and EMG could be important, as they not only provide additional information but also may improve the reliability and accuracy of the systems. Few studies reviewed here used a sequential combination of EMG- and EEG-based control methods in the hybrid control approach. In this approach, either EMG signals were used as a switching mechanism to the EEG-based control method or vice versa. The main advantage of this approach is that the complicated control requirements can be distributed among EEG and EMG channels.

A number of advantages of the hybrid EEG-EMG-based control approaches can be highlighted. The hybrid approaches can provide positive improvements in several performance criteria such accuracy, reliability or robustness in comparison to individual use of EEG- or EMG-based control methods. Combining EEG-EMG control approaches can improve the potential of applications such as prosthetics and exoskeletons by introducing an additional degree of freedom, and also enhances the robustness of the control approaches. Even if all required muscles for EMG-based methods are available, EEG signals can be used to compensate for some common problems in the EMG-based control, such as the effects of fatigue or undesired tremor. Moreover, unlike fully EEG-based control approaches, where users may have to have high concentration on his/her activity, these hybrid approaches may help to reduce the mental effort of the users while they using bio-robotic devices.

Nevertheless, as discussed in the challenges section, there are many issues yet to be sorted out in order to improve the effectiveness of the hybrid EEG-EMG methods for use in bio-robotic applications. Also, it is important for future studies to present quantitative performance measures for such hybrid EEG-EMG approaches, in order to demonstrate their effectiveness in comparison to other control methods. To draw general conclusions, it is necessary to present the efficiency results in terms of signal processing based on the actual data of the EEG and EMG. As far as the reviewed studies in this paper are concerned, it is obvious that most of them lack clinical studies or test results with actual patients. Even though the bio-robotics field is a growing area of interest, advances should really benefit patients on a clinical basis. In this context, it is important for future studies to conduct more clinical experiments in order to validate proposed methods with the real end user. From a methodological point of view, new methods for combining individual control methods, such as adaptive fusion methods of EEG and EMG signals, can be studied. For example, a patient with movement disorder may not be able to move a rehabilitation exoskeleton using EMG signals at the beginning, hence a higher priority can be given to EEG-based control methods to control such a device initially. When the user becomes accustomed to this rehabilitation process, more weight can be given to EMG-based control methods. Also, research findings such as correlations between EEG and EMG signals [42, 43] can be considered in design processes for hybrid EEG-EMG-based control approaches. In conclusion, with the current trend, we can see the potential for hybrid EEG-EMG-based control approaches to be used in bio-robotics application, however, more studies should be carried out in order to improve effectiveness, and to eventually bring these technologies out of the laboratory.

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