Guest Editorial

PROSTHETIC legs are vital devices to functional rehabilitation of people with lower limb loss. The use of lower limb prostheses is essential for restoring mobility, maintaining personal independence, and more effective inclusion in society. Over the past several decades, there have been many improvements in materials, control systems, and interfaces of artificial legs; e.g., running at near world record speeds has become possible with prosthetic legs. Unfortunately, our progress has not been as remarkable with upper-limb prostheses. Many people with upper limb loss choose not to wear a prosthesis [1] with a key reason being that upper limb prostheses do not provide enough function. Current commercial prostheses offer control of only one or two degrees-of-freedom at a time (e.g., hand open/close) with control methods that are highly unnatural for the users. For example, control of multiple joints often requires sequential control of individual joints with cumbersome switching techniques that can tire the user after a short while. However, in the past few years, exciting developments to improve the function of upper limb prostheses have been seen in laboratories around the world and are starting to be realized for patients. Biomedical instrumentation and signal processing methods are also evolving to improve the control of upper-limb prostheses [2]. Efforts in academia and industry have resulted in advanced robotic arms and much more highly dextrous robotic hands that combined with better and more intuitive control systems hold great promise for enhancing the ability of amputees. In addition, biologically-inspired feedback systems have enabled people with upper limb loss to actually *feel* appropriate sensations in their missing hands [3], [4]. However, to become fully integrated into a user's sensorimotor repertoire, the performance of upper-limb prostheses must still improve greatly.

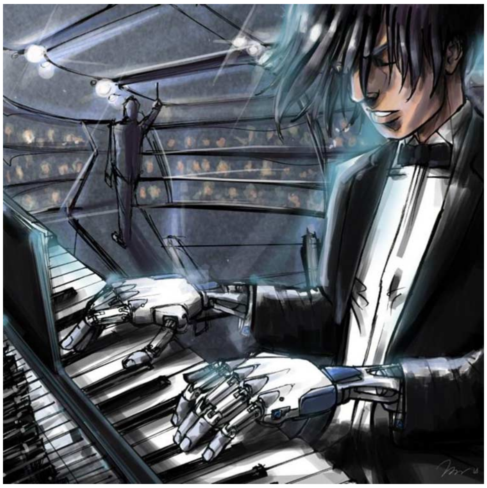

Fig. 1. Illustration of a musician playing the piano by means of multi-articulated upper limb prostheses. Will this become a reality? Artist: Alessio Tommasetti -D'ARC Studio—Rome, Italy.

This special section of IEEE TRANSACTIONS ON NEURAL SYSTEMS AND REHABILITATION ENGINEERING is focused on recent scientific and engineering developments in control of upper-limb prostheses, ranging from novel signal processing and machine learning strategies for enhancing and extracting movement intention-related features from the inter-muscular and surface electromyogram (EMG) signals to advanced surgical and experimental procedures for targeted muscle and sensory re-innervation. The illustration in Fig. 1 is the artistic view of a *bionic man*, as represented in the society's collective imagination. It presents an unaccomplished dream for this research community: restoring amputees' sensorimotor control of the natural arms and hands movement to enable them to perform complex bimanual tasks such as playing a piano. This illustration retells the gap between academic research and commercial adoption towards delivering real clinical benefit to the end users. The work described in this special section is still far from the illustrated situation. Nonetheless, it represents some of the necessary, albeit relatively small, scientific, and engineering steps.

We start this special issue with a review paper by Farina *et al.* [5] in which the authors first explain generative models of EMG and their application for prosthesis control. They will then offer a fresh look at current approaches for myoelectric control: 1) pattern recognition as well as 2) regression and 3) direct or abstract control. They suggest that simultaneous and proportional control over multiple degrees-of-freedom (e.g., concurrent grasp and wrist flexion), that is not yet possible in commercial prostheses, is more likely to be achieved via by adopting the latter two approaches. Farina *et al.* [5] conclude this review by discussing practical challenges that are yet to be overcome.

Five studies in this special issue examine the suitability and sensitivity of current pattern recognition algorithms for use in prosthesis control or develop novel machine learning algorithms. Ortiz–Catalan *et al.* [6] offers a complete account for pattern recognition algorithms and compare different classifiers and topologies. They show that neural network-based classifiers, such as the multi-layer perceptron (MLP) in contrast to the conventional linear discriminant analysis, can enable classification of simultaneous movements.

Despite advancements in pattern recognition-based control of myoelectric prosthesis in laboratory environment, there are a considerable number of challenges in translating research findings into a clinically viable implementation. One such challenge is that reliable and error-free EMG signal classification usually requires a large training time. To shorten training time, recent machine-learning research has proposed user-independent EMG classification [7] in which a pool of pre-trained EMG-

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movement pairs are stored in the memory of a prosthesis. When a new user wears the prosthesis, the prosthesis finds and updates the best matched model from a pool of stored datasets to fit a new subject. However, this exhaustive search process in a high-dimensional feature space consumes a lot of power, takes a long time, and usually requires a large amount of training data that may not be possible to collect easily in a clinical setting. Extending the bilinear decomposition approach [8], in this special issue, Khushaba [9] presents an efficient and model-free canonical correlation analysis (CCA)-based algorithm for multi-user EMG classification and tests it in two scenarios: 1) within-subject, in which the classifier is trained on data recorded from the able arm of the amputees and adapts to data recorded from the lost limb and 2) between-subject, in which the classifier is trained with the data from all but one users and evaluated on the remaining test dataset (the leave-one-out approach).

Two other challenges of EMG classification that are often overlooked in clinical translation of the pattern recognition algorithms are: 1) how one could predict the real-time performance of a classifier by looking at its offline performance and 2) how to identify and deal with noise in real-time. The work of Gijsberts *et al.* [10] focuses on the former and, inspired by the automated speech recognition literature, introduces the notion of movement error rate as an alternative for performance measurement based on window-based classification accuracy. McCool *et al.* [11] offer a comprehensive account of EMG signal contaminant classification and discuss their effect on movement classification accuracy.

In 2009, Kuiken *et al.* [12] proposed the technique of targeted muscle innervation (TMR) in which nerves that would naturally innervate the distal muscles of the amputated limb are redirected surgically to more proximal and intact muscles that are biomechanically nonfunctional after the amputation. With TMR, the surface EMG signal recorded from proximal muscles can be used to infer user's movement intention. Three papers in this special issue report further progress in the application of TMR. First, Tkach *et al.* [13] bring experimental evidence that a generic electrode grid with wider inter-electrode spacing can yield comparable, or even better prosthesis controllability and EMG classification accuracy when compared to targeted (and optimal) electrode placement in both offline and real-time implementations. Farina *et al.* [14] uses the convolution kernel compensation (CKC) algorithm [15] to estimate the spiking activity of the motor units that generate the EMG signals recorded from re-innervated muscles using multi-channel (~ 450) electrode-grids. They show that with this approach it is possible to estimate the neural code underlying an attempted limb movement. In addition, one could envisage that the discharge patterns of these extracted motor units can be used not only for movement classification but also to estimate the intended force.

Control of current commercial upper-limb prostheses largely relies on visual as the main source of feedback about the state of the device. There have been several academic attempts to deliver sensory feedback noninvasively about the state of the prosthesis, such as grip force feedback via vibro-tactile or haptic stimulation [16]. An unexpected result of Kuiken's surgical TMR method [3] was partial restoration of cutaneous sensation due to re-innervation of afferents from the main nerve trunks into the denervated skin. Hebert *et al.* [17] report the result of a proof-of-principle targeted sensory re-innervation surgical technique in one amputee and subject's performance in different tasks, e.g., a single versus dual tactor and force discrimination.

Recent exploratory work with the EMG signals has resulted in the exciting notion of direct (AKA abstract) control of upper-limb prosthesis [18]–[22]. In fact, direct control has its conceptual roots in the bio-feedback experiments in early 1960s that demonstrated that the relationship between cell activity and behavior can be altered with operant conditioning [23]. In [23] and its more recent version [24], nonhuman primates were rewarded for producing arbitrary combinations of cell and/or muscle activity and rapidly learned to dissociate their normal neuromotor patterns. Their results suggested that there is considerable flexibility to neural encoding which may enable learning novel neuromotor associations [25].

Whether the biofeedback approach can be translated into clinically viable solutions for upper-limb prostheses is a topic of current research. Two of the studies in this special issue examine the possibility of direct control of a myoelectric interface. Cipriani *et al.* [26], building upon [27], shows for the first time that able-bodied subjects can control four independent degrees-of-freedom of a desktop hand prosthesis by using the intramuscular EMG signals that are recorded from their extrinsic hand muscles. An important consideration in designing such invasive myoelectric interfaces is to maximize independence of neural drives to muscle by setting system to work at relatively weak muscle contractions levels, e.g., $\sim 15\%$ of the maximum voluntary contractions. The immediate technical challenge that stems from this setting would be the degradation of the EMG signal-to-noise ratio (SNR). Although increasing the contraction level enhances the SNR, there is evidence that during maximal contractions of individual fingers, neighboring digits (and their controlling muscles) can become enslaved [28] and hence can impede independent control of prosthesis fingers. Another open question is whether myoelectric interfaces can be used to control abstract interfaces such as exoskeletons and robotic tele-operation in addition to prostheses. Earlier work [18]–[22] showed that subjects could learn to control a cursor in two dimensions on a computer screen through EMG activity recorded noninvasively during isometric contractions of multiple upper-limb muscles. In this special issue, Antuvan *et al.* [29] provide further evidence that once subjects learned the mapping between the muscle activity and the task requirements, they can retain and generalize it to a different motor task.

The final contribution in this special issue is by McMullen *et al.* [30] in which they report proof-of-principle results of a hybrid approach to control a prosthesis. In their method, to overcome the limitations of current prosthetic arms controllers, they combine eye tracking, computer vision, invasively recorded brain signals to control an intelligent robotic arm. The proposed hybrid system could allow patients to efficiently control (simultaneously) multiple degrees-of-freedom of a robot without extensive training. However, it would take many years of development and refinement before such sophisticated systems can be translated into any clinical benefit.

The papers collected in this special issue demonstrate important advances in myocontrol that have been achieved in recent years. In addition, they show new views and the identification of new research pathways in this field, after a relatively long period in which the focus was mainly limited to improving the classification accuracy in laboratory offline tests that are very different from real user scenarios. The recent efforts have the common denominator of identifying specific gaps between academic results and real clinical impact [31] and trying to fill these gaps either building on the classic pattern recognition scheme or starting from completely different approaches. We are confident, that some of these approaches will soon allow progress in the industrial (and thus clinical) state-of-the-art in myocontrol, after several decades of use of extremely simple, (but robust) control systems which are often rejected by the users, because the functional gain is overruled by the cognitive burden of a very unnatural control system.

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