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REVIEW

A review on the advancements in the field of upper limb prosthesis

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ABSTRACT

Amputation is one of the serious issue across the globe which is mainly caused by trauma, medical illness or congenital condition. Because of steep increase in amputation incidences, the need for progress in technicality of prosthesis is becoming imperative. In this article, the journey of advancements in upper arm prosthesis has been discussed step by step. Moreover, it has also been enunciated that how from a simple replacement for an arm it now has reached the mark of giving a patient a fully functional limb with the help of sensors and myoelectric transducers that are able to translate the remaining muscle signals into full movement of the prosthesis. However, researches are still going on to make the design of the prosthetic more impressive having better range of movement, to establish its interface with brain more efficiently and to make the control of prosthetic more user friendly. In this review, a special emphasis has also been given to myoelectric prosthesis as this prosthetic system possesses a decisive influence on rehabilitation results. Moreover, this prosthetic system is extremely elegant and cutting-edge in both design and technology and offers a great wearer comfort.

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1. Introduction

Amputation is defined as the elimination of a body extremity as a result of any blunt trauma, medical illness and prolonged constriction or surgery [1]. It has been found that limb amputation is one of the most ancient of all surgical procedures which is having a history of more than 2500 years dating back to the time of Hippocrates [2]. It can be caused by trauma, peripheral vascular disease, tumour, infection and congenital anomalies [3,4]. It has been reported that in the USA, about 1.7 million people live with amputations [5], and the number has increased in the recent years [6]. As per the report of 2008, world population of amputees was 10 million and incidence of amputation was 1.5 per 1000 [7]. Peripheral vascular disease is the major cause of amputation in developed countries; whereas, trauma, infections, uncontrolled diabetes mellitus and malignancies are the principal causes for amputation in developing countries [8,9].

As a surgical measure, it is used to control pain or a disease process in the affected limb. Similarly, congenital amputation is birth without a limb or part of a limb. It is caused either by blood clots forming in the foetus while *in utero* (vascular insult) or from amniotic band syndrome that is fibrous bands of the amnion which constrict foetal limbs to such an extent that they fail to form or actually fall off due to missing blood supply [10–12]. The other associated causes which might influence congenital amputation are ionising radiation, trauma, infections, metabolic imbalance and consumption of teratogenic drugs [10–12].

Both of the above-stated anomalies exist in every part of the world. People with these anomalies use prosthetics in order to replace the function of the particular limb in question. A prosthesis is an artificial device that replaces a missing body part, which may be lost due to trauma, medial illness or congenital condition [13–15]. Prosthetics today have come a long way from primitive cosmetic prosthetics to body powered and finally leading to the maximally advanced myoelectric prosthetics or even further advancement such as the brain–computer interfacing and neuroscience.

The scientists, the clinical associates and the patients themselves are all well aware of the need for a better and more intuitive way of controlling the artificial limb prostheses. With the great development of new techniques, new multifunction hands have been introduced during the last decade. The prosthetics have been developed to have greater degrees of freedom, have become more natural looking, have given

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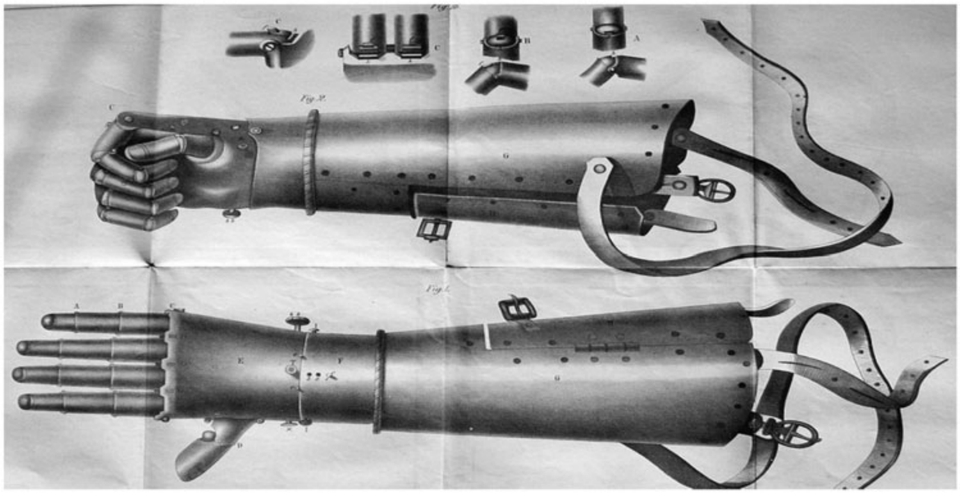

Figure 1. A painting of his Iron Hand from circa 1509. Image sources: Putti [15].

the user easier approach to do things and have been a better tool which has aided the patients more efficiently A new generation of prosthetics called the robotic prosthetics have also been in experimentation stages so a new era of artificial intelligence prosthetics might soon be seen. In this article, focus has been put forth to highlight the advancement in the field of upper arm prosthesis with a special emphasis on myoelectric prosthesis. Moreover, the new researches going on in the area has also been discussed.

2. Upper limb prosthesis

2.1. Body-powered upper limb prosthesis

The history of prosthesis is old and new revolution in this area taken place several times [13–15]. The first prosthetic hand was a mechanical replacement hand of iron. The most important property of this had was that it was more robust than healthy limb. Also described by Putti are the Petit Lorrain hand and the Stibbert hands and arms [15]. All these hands from fifteenth to sixteenth century were inspired by the body armour used in the battle at that time. They were designed with functionality and toughness as the main criteria rather than aesthetics [13]. Several of the designs had joints that could be locked by a spring ratchet mechanism through a metal lever which could be operated by the supporting hand [13–15].

The elbow joint can be given a motion by the release of a spring, whereas the top joint of the wrist is seen to allow a certain degree of rotation and motion in upward and downward direction. The fingers can also curl up and can be extended out as well [16]. It has similar mechanisms to the older hands, but it is more lightweight, has more degrees of freedom and has a leather socket. The next important step in the development of upper limb prostheses have been described by Kuniholm [17] and consists of the hook design, body-powered actuation by Selpho [18] and Reichenbach [19], and the split-hook design invented by Dorrance [20]. The split hook design was made to fix hooks and carry things but was unable to give a proper grip and lacked design sensibilities.

One reason for their popularity is that these devices are relatively cheap, simple and durable; another reason is that these prosthetics have sensory feedback, a concept which is often referred to as extended physiological proprioception [21]. This allows for precise handling of small or fragile objects but not able to grab and could not be of much use.

Body-powered prosthetic movement was restricted and could not achieve at a greater degree of freedom. The movements were basic and were more helpful for cosmetic purposes rather than actual movements (Figures 1–3).

2.2. Myoelectric prosthesis

In myoelectric prosthesis, biological signals are used to control movement of prosthetic [22]. The general idea of myoelectric prosthesis is to use electrodes to measure action potential. Normally obtaining signals from two different positions of opening and closing and the emissions measured on skin surface are of microvolt level by surface electrodes. Signal is amplified to use as controls for prosthetic motors. External source (6 V battery) is also needed to operate motor [22].

Myoelectric control is by definition the control of a prosthesis or other system through the use of muscle electricity. The term “myo” comes from the Greek

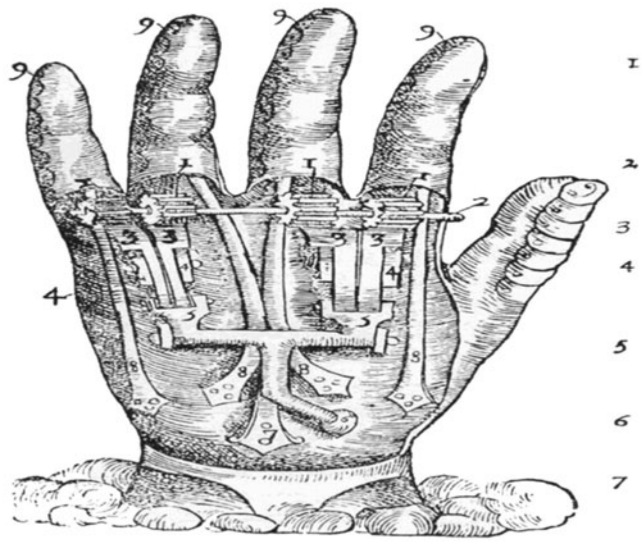

Figure 2. Demonstration of the mechanism in the "petit Lorrain" hand (16th century). Image source: Putti [15].

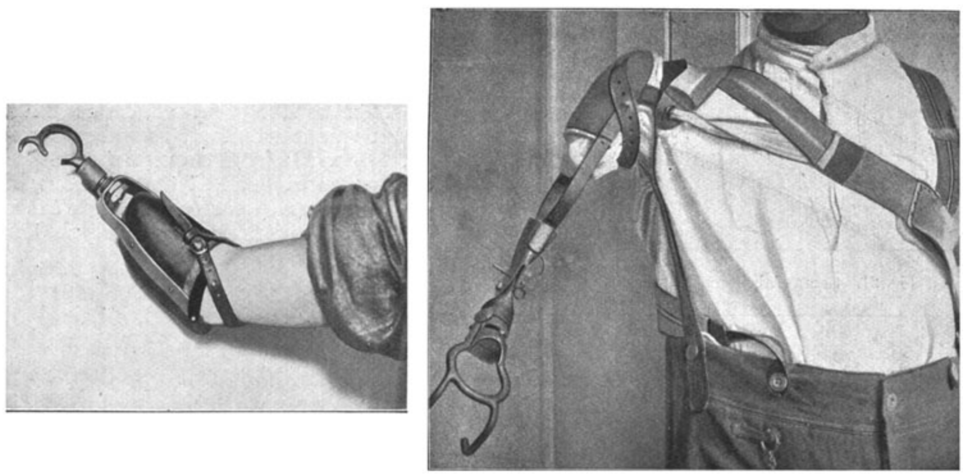

Figure 3. Passive hooks and shoulder harness by Weimar. Image source: Lange (1922) PD [18].

word "mys" (muscle) [23]. The myoelectric prosthesis is controlled by the contraction and co-contraction of muscles (motion mode and switching mode). The origin of the myoelectric signal is defined by the electrical activity produced by a contracting muscle and can be measured by the electromyogram (EMG) using pairs of internal wire- or needle electrodes, implanted electrodes or surface electrodes [22]. Several types of surface electrodes exist such as gel-type electrodes using an electrolyte interface to the skin in order to lower the electrical resistance, and the dry type made from metal for example stainless steel [23]. If they are supposed to be employed for an extended period of time, such as in prosthesis control, dry surface electrodes are the only practical solution available [23]. One may look at the EMG signal as a measurement of the prosthesis user's intent, since the muscles are the actuators performing the user's intended movements. Determining user intent from the electrical activity recorded from the brain is still in experimental stages with no exclusive success, as determined by the large effort being directed to the goal of brain–machine interfaces.

On the other hand, when it is measured on nerves or muscles, some of the interpretation has already been performed by the nervous system of the patient in question and thereby simplifying the task. The surface EMG signals are measured on the outside of the limb and will thus contain a mixture of signals from the nearby active muscles as well [23,24].

The interaction between muscles is called crosstalk and needs to be handled by the prosthesis control system. The myoelectric prosthetic is the most functional devices for a patient who has undergone amputation. The prosthetic systems require a combined application of electronic and mechanical engineering depending on the extent of functionality required for the device. Instead of using body power and a lot of force to generate motion, myoelectric prostheses give patient the feeling like he or she is regulating the same nerves to move [24].

2.2.1. Origin of myoelectric signals

With the development of modern electronic devices and equipment along with new techniques in signal processing and mathematical models, there is an intense study of EMG signal from the last two decades. The origin of EMG is closely related to the work of nervous system. It is a complicated signal, controlled by the nervous system and is dependent on the anatomical and physiological properties of muscles [25]. Electrochemical transmission between nerves starting from the brain produces action potential which propagates through nerve fibres and finally stimulates the skeletal muscle. This stimulation creates muscle contraction which results in the movement of human limbs. Action potential acts on a single nerve and there is vast number of skeletal muscle fibres. Thus, the electrical potential from muscle recorded for EMG is actually superposition of action potentials acting on skeletal fibre muscles [25].

Kinesiological EMG is the study of the voluntary neuromuscular activation of muscles within tasks, involving the stance of the body. It is proven to be a method of evaluation for applied research, physical therapy applications, sports training and human body interactions with industrial products [26]. Recording of EMG signal is done by means of electrodes. Three types of electrodes wire, needle and surface are commonly used where the latter being the most widely used being non-invasive [26].

2.2.2. Use of myoelectric signals in prosthetics

Prosthetic devices are often used to replace the missing parts of human body. Bioelectrical signals such as evoked potential, nerve conduction velocity, EEG, EMG, EOG fit well as an input for prosthetic device control [27]. The myoelectric control uses the electromyogram signals generated by muscular contractions as an input to controllers for powered prosthesis for many years. For the purpose of prosthetic control, surface electrodes are equally beneficial as intramuscular electrodes [27]. Numerous studies have been reported regarding studies in this area [28–30]. EMG controlled prosthetic device is developed by analysing signal for discrimination, classification, pattern recognition or feature extraction [28–30]. By employing pattern recognition lots of control information can be extracted from surface EMG (sEMG) signal. In terms of sEMG feature extraction method, various techniques have been reported [31,32]. In general, there are two categories of feature extraction techniques; one in time domain and another one in time–frequency domain. To that end, wavelet packet transform was used and for dimensionality reduction and nonlinear mapping of the features, linear, nonlinear feature projection method was proposed comprising of principal component analysis and self-organising feature map [31]. In another literature, various feature sets consisting of slope sign changes, number of zero crossings, waveform length, Hjorth time domain parameters, sample skewness, and autoregressive model from the EMG signals were extracted. These features were then reduced in dimensionality with the linear discriminate analysis feature projection [32]. It is proved that feature projection methods can consolidate such information more effectively than feature selection based methods in EMG classification problems [33]. For developing a prosthetic device, surface electromyogram data is usually taken from the subjects to analyse the sEMG signal characteristics. Data can be taken from muscles located at residual part of the limb where the prosthetic device is attached to. Remnant of the muscles in residual limb is likely linked with muscles of the lost limb. The type of prosthetic device ensures the location of surface electrode on muscles for sEMG acquisition. For instance, for prosthetic hand, extensor carpi ulnaris and flexor carpi ulnaris located on the forearm are the recommended place for placement of the electrode [34,35]. With the help of a much complex design, the different types of movements can be studied. An example of such a design is the prosthetic hand complete with digits. At the most 32 electrodes are used for decoding the individuated finger movements [36].

DSP-based controller for prosthetic hand has also been applied in the field of pattern recognition [37]. The parameters were grouped into four groups and combined with each other in the classification stage to choose the highest classification rate before the selected feature is implemented in the PC based discriminative system [37]. Different techniques have been implemented by researchers in their studies depending on the task to be performed. For example, in a work on developing fingers movement of prosthetic hand, time-domain features performed better in real-time decoding of hand and wrist movements [36,38,39].

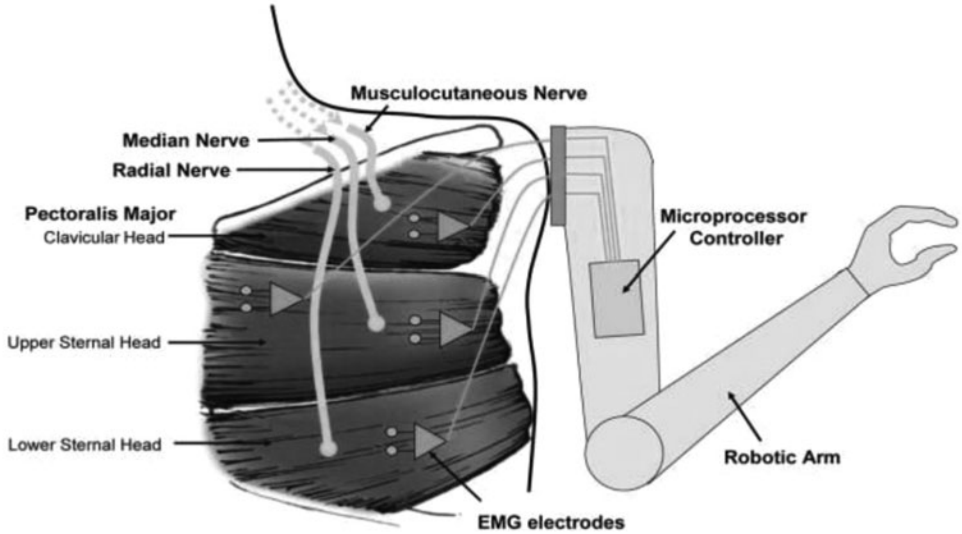

Figure 4. Neural-machine interface for control of artificial limbs [44].

Another work on prosthetic hand used both time and time-frequency domain for feature extraction and implemented the result on a neuro-fuzzy system for pattern recognition [40]. An evolvable hardware chip has been designed which works as a controller for myoelectric prosthetic hand that adapts to changes in task requirements with the help of its ability to reconfigure its own hardware structure dynamically and autonomously. The chip comprises a genetic algorithm hardware, reconfigurable hardware logic. Other parts include a chromosome memory, training data memory and a 16-bit CPU core [41]. A separate two-step incremental evolvable hardware is based on designing controllers for prosthetic hand providing six different motions in three different degrees of freedom; open and close hand, extension and flexion of wrist, pronation and supination of wrist [42].

The preprocessing layer, the intent interpretation layer, and the activation profile are the three important properties of the myoelectric control systems [43]. The preprocessing layer is the collection of information from the user, a function typically implemented using sensors and signal processing. The intent interpretation layer is the interpretation of user intent based on the available information from the above-stated layer. Finally, the activation profile is one property of the output layer of the system which easily tells the difference between proportional control and various on-off based schemes. In control of multifunction prostheses, sequential control is the most common strategy today [44]. Typical implementations allow the user to scroll through a sequence of available states by using co-contractions or a mechanical switch [43]. Sequential control allows the focus of the user on controlling only one motor function at that particular time (Figure 4).

2.2.3. Components of design of a myoelectric prosthetic

2.2.3.1. Human arm anatomy:. The human arm consists of two parts – the lower part and the upper part. In the upper arm, two groups of muscles have to function in opposing pairs (flexor groups and extensor groups) to move the elbow joint [45]. Working on the theory that the use of the three types of electrodes that are used for the EMG recording will allow all hand and wrist functions to be controlled simultaneously, the following muscles were chosen; muscle controlling supination and muscle controlling pronation to give wrist rotation, flexor carpi ulnaris to give wrist flexion and extension, flexor pollicis longus and extensor pollicis to control a thumb, and flexor diaitorum sublimas and diaitorum communicus for finger opening and closing [46].

In order to obtain meaningful EMG signals for eight kinds of prehensile posture [47], the placement of EMG surface electrodes is important. Recent advancements in the prosthetic hand show that the earlier ways of placing the surface electrodes did not provide data with greater accuracy. In addition, six surface electrodes are placed in an equally spaced array around the circumference of the forearm. It has been reported that with this modification in placement of electrodes generated some good results with minimum error and greater accuracies up to 92.8% [48].

2.2.3.2. EMG conditioning (hardware part). The main problem in the process of detecting an EMG signal is that this signal is easily affected by impure signals that come from different sources of noise such as 50/60 Hz electromagnetic induction from power lines. The next step is to remove the unwanted components of the EMG signal, which can be achieved by means of a band pass filter. As the power spectrum of EMG signals is concentrated in the 20–500 Hz range, the authors designed a hardware using a second order band pass Butterworth filter with cut-off frequencies of 20 Hz (low) and 5 kHz. Further filtering can be applied with digital filters implemented in the software [49]. It is worth noting that in a simple on-off device a notch filter at 50 or 60 Hz (depending on the frequency of the electric power supply) filter could also eliminate some important information present in the EMG signal and should not be used for multifunctional hand [50].

2.2.3.3. Feature extraction. Since late 1970s, the EMG signal was modelled as amplitude modulated Gaussian noise whose variance was related to the force developed by the muscle and as a consequence, most commercial microprocessors used in prosthetic control are now based only on one dimension of the EMG signal- the variance or mean absolute value [51]. The Otto Bock SUVA (Schweizerische Unfall Versicherungs Anstalt –Swiss Insurance Agency) Hand [52] is designed so that the grip force was controlled by the intensity of the muscle signal. In the 1990s, researchers found that there is useful information in the transient burst of myoelectric signal. Hudgins and colleague [53] showed that there is a considerable structure in the myoelectric signal during the onset of a contraction.

Feature evaluation. The three main parameters that evaluate the performance of a feature are maximum class separability, robustness, and complexity. EMG histogram feature performs best and is evaluated excellent among all the features on the basis of above three criterions [29]. The effectiveness of a variety of EMG features commonly used for movement control of cybernetic prostheses have been compared in several studies and it has been found that all the features extraction techniques that have already been mentioned are used but only some of them provide good results [54].

2.2.4. Classification techniques

There are several possible classification techniques [55]. Among them, the most used are Bayesian pattern classifiers and artificial neural networks. Moreover, other techniques such as neuro-fuzzy classifier and support vector machines have also used in some studies [55].

2.2.4.1. Mechanical design. Mechanical design deals with (1) Grasping Capabilities and (2) Movement of fingers during grasping.

Commercial prostheses have been designed to be simple, robust and low cost; at the expense of their grasping ability [56]. Hands such as the all-electric prosthetic hand utilise a series of gears to transmit the motion of motors housed in the forearm to the relevant fingers. The initial design consisted of four fingers and a thumb attached to a palm. Actuation was to be provided using a servo motor driving a belt, through a series of pulleys to the joint requiring motions. This design was altered as it became overly complicated to create a relative motion between the joints in one finger when only one motor was being used to drive three degrees of freedom in the finger [57]. Another important issue is the selection of the most appropriate material, among the different commercial types of polymers, for matching the guidelines required for industrial production (taking a suitable shore, the CE93/42, concerning the fire proof requirement and the biocompatibility) [58]. During the last two decades, several robotics and anthropomorphic hands have been developed. All these hands have a high number of DOFs (up to 16) and dexterity comparable to that of the human hand.

2.2.4.2. Sensor performance. Intuitive myoelectric prosthesis control is difficult to achieve due to the absence of proprioceptive feedback, which forces the user to monitor grip pressure by visual information leading to fatigue and handling errors. Myoelectric sensors measure electric muscle activity and these sensors detect the level of muscle construction and therefore give amputees the possibility to control mechanical prostheses by muscle activity [59]. The motion of body-powered prostheses enables the wearer to sense device actuation through cable tension and harness position. The output of the current sensors is amplified and filtered in order to eliminate high transient effects that are particularly noticeable at motor start-up. The processed signals are then may input to the ADCs on board the microprocessor for controlling action [60].

2.2.5. Controls of myoelectric prosthesis

2.2.5.1. On-Off control. In the control mode called on-off control (also known as bang–bang control, crisp control or binary control), a function of the prosthesis is simply turned on or off (e.g. either constant speed in one direction, full stop, or constant speed in the other direction). The SVEN hand, first demonstrated at Chalmers University of Technology (Sweden) in the 1970s, allowed the users to have simultaneous control of six motion classes; Hand open/close, wrist flexion/extension and wrist pro-/supination [61–63]. It is one of the first known applications of pattern recognition in control of prostheses, along with the studies by Finley and Wirta [64] and Graupe et al. [65]. The SVEN system was based on a set of simple Bayesian perceptrons for myoelectric signals and controlled all motors simultaneously in an on-off fashion. The hand was not reliable nor portable enough for testing outside of the laboratories, but they experienced very promising results in clinical trials.

2.2.5.2. System training. System training is the training of a prosthesis control system to recognise input signals from the prosthesis user. This is often just referred to as training, supervision or supervised learning in pattern recognition. All pattern recognition methods need some kind of system training. The most recent method is prosthesis guided training (PGT); the prosthesis is moving while the user follows the motions with the phantom limb. The strength of this method is that it is simple, quick and does not require an external computer. Thus the user can re-train the prosthesis whenever needed, for example by pushing a button and thereby start a training procedure. Prosthesis guided training was first demonstrated with on-off control by Lock et al. (2011) [66].

2.2.5.3. Proportional control. Proportional control is exhibited by a prosthesis system if and only if the user can control at least one mechanical output quantity of the prosthesis (e.g. force, velocity, position or any function thereof) within a finite, useful, and essentially continuous interval by varying his/her control input within a corresponding continuous interval. Proportional control may be beneficial to the prosthesis user, for a number of reasons. Roesler [67] claimed that proportional control is required for quick grasping of objects, while at the same time having the possibility of slow and precise pre-hension. In a renowned work shortly after, Sörbye [68] demonstrated that skilled users can successfully use an on-off system to lift and manipulate delicate objects, even while being blind-folded and deprived of acoustic feedback from the prosthesis. Three decades later, Lovely [43] claimed that the need to control the finger speed originally arose because of the slow motions in early prosthetic hands. Since the current prosthesis motors are much faster, speed control is not a critical issue any longer. For elbows, however, the range of motion is larger and the need for rapid, coarse, positioning is higher, while retaining the possibility of slow and fine control for accurate positioning of the terminal device. Thus, it was concluded that proportional control is useful for elbows but not critical for prosthetic hands. Alley and Sears [69], on the other hand, claimed that proportional control systems allow the wearer to vary the pinch force in a terminal device much more precisely than is possible with on-off control. The controversy around the necessity and appropriateness of proportional control in upper limb prostheses thus is still very much alive.

In a multi-function prosthesis control system, it is hypothesised that proportional control will enhance the user's control ability significantly, because the continuous relationship between muscular contractions and prosthesis response will allow for more rapid and high-fidelity corrections of movements that deviate from the user's motor intent.

A simple example of proportional myoelectric control is a system in which the EMG from flexors and extensors of the user's forearm is measured, amplified, filtered and smoothed by two active electrodes. This provides estimates of EMG amplitudes that can be sent to a hand controller. After applying thresholds to remove uncertainty at low contraction levels, the controller sets a voltage applied to the motor that is proportional to the contraction intensity (Sears and Shaperman 1991) [70]. This functionality is essentially offered by several manufacturers of commercial prostheses. Simultaneous control, as opposed to sequential control, is hypothesised to be the most intuitive control system to handle for the prosthesis user. Sequential control is, on the other hand, deemed as slow and inconvenient by many users, but it is today the only method available in commercial multifunction prostheses. A real-time implementation of a control system with simultaneous proportional myoelectric control is associated with dual function prosthesis. The method includes prosthesis-guided training, and the assessment required development of a novel prosthesis socket equivalent for use by normally-limbed subjects.

2.2.6. Other properties of myoelectric prosthesis

2.2.6.1. Robustness and artefact cancellation. External disturbances to EMG signals are often referred to as artefacts. Artifacts (in biomedical instrumentation) are those parts of a signal that originate from some source other than the one being studied. Another typical example is the unwanted interference of EMG from surrounding muscles when measuring ECG (electrocardiography). Artifact cancellation is the removal of such signal artefacts. Robustness in a prosthesis control scheme without feedback (other than visual) from the prosthesis to the prosthesis user is challenging to achieve. However, one common strategy for such a situation is to measure the conditions (e.g. a disturbance) affecting the system, and use this measurement to reduce the adverse effects (e.g. suppress the disturbance) [71,72]. In control engineering, it is referred to as feed forward control, and when describing an intent interpretation method, it may be expressed as gather as much relevant information as possible in order to make good decisions. Accelerometers were added to the forearm of the subjects in order to measure the limb position (by finding the direction of gravity) and thereby increase the system's robustness against changes in limb position [71,72]. The study was based on data from normally-limbed subjects, and the intent interpretation method used crisp classification (linear discriminate analysis).

As proposed by Scheme et al. [71,72], the multimodal approach is not the only way towards robustness of the prosthesis control system. Already when extending the system training protocol to include more variation (e.g. multiple limb positions, dynamic motions, external forces or fatigue), the system may become more robust towards those situations. This approach has also been studied by Hargrove et al. [73]. Actually, as long as the system training method and the optimisation criterion is well chosen, and the system is fast enough to handle the extra amount of data to process, the added measurement cannot degrade the reliability of the system. If a sensor (whether it is an EMG sensor or a different sensor modality) appears to be of no use during system training, the system itself will decide to ignore that measurement. The relative importance of each sensor is determined by the system training.

2.2.6.2. Motor coordination. The most recognised definition of the term motor coordination is the one by Bernstein. Coordination is overcoming excessive degrees of freedom of our movement organs, that is, turning the movement organ into controllable systems. In order to simplify tasks to the human mind, the body can coordinate the movement organs so that the person can relate to fewer degrees of freedom. This is similar to how the prosthesis manufacturers let the user choose a grip pattern (e.g. power grip, pinch grip or key grip) instead of controlling every finger joint one by one. To activate a specific grip pattern in a multifunction prosthesis system is not necessarily a simple task. Usually, the prosthesis user needs to scroll through a series of available grip patterns in a sequential manner, using co-contractions detected by EMG (or a mechanical trigger). Similarly, in a system with a powered wrist and a powered hand, one usually needs to switch between hand and wrist control, that is, another sequential control system. This method is commonly deemed as slow and inconvenient by prosthesis users. Although the finger movements may be coordinated internally in the prosthesis (as described above), the overall motion of the hand does not satisfy the above definition of dexterity (or dexterous). The feasibility of simultaneous control was demonstrated in the SVEN study in the 1970s [61–65]. Whether it is possible to offer a simultaneous control strategy that is robust enough for clinical use, has not yet been proved.

2.2.6.3. Simultaneous proportional myoelectric control. Use of this method has previously been reported only for crisp classification [66] so further adaptations were needed in order to be suitable for simultaneous proportional control.

The main reason was the subject's need to sense, or observe, the forces or the speed of the movements demonstrated by the prosthesis. While these variables can be controlled in an on-off manner in training of a crisp classification scheme, they need to contain continuous movements in training of proportional control. In order to follow those movements, the subject needs to perceive the motion. "Hand close" force was perceived by observing the prosthesis squeeze a soft rubber ball, and the subject tried to copy the force by using the finger flexors and/or wrist flexors. "Hand open" was trained in a similar way, by gripping around the prosthesis with the opposite hand in order to feel the applied force. Wrist rotations were trained by observing speed rather than force [66]. Without any feedback from the prosthesis, the system would not know whether the hand is moving or has stopped. In the end, a triangle-shaped voltage pulse was applied to the hand motors, and it was tuned so that the motors would stop approximately when the maximum voltage was applied. This is not optimal, but it works as a preliminary solution. For the wrist motors, similar triangle-shaped pulses were also tried as reference, but it was found difficult to know when the speed was at its maximum value.

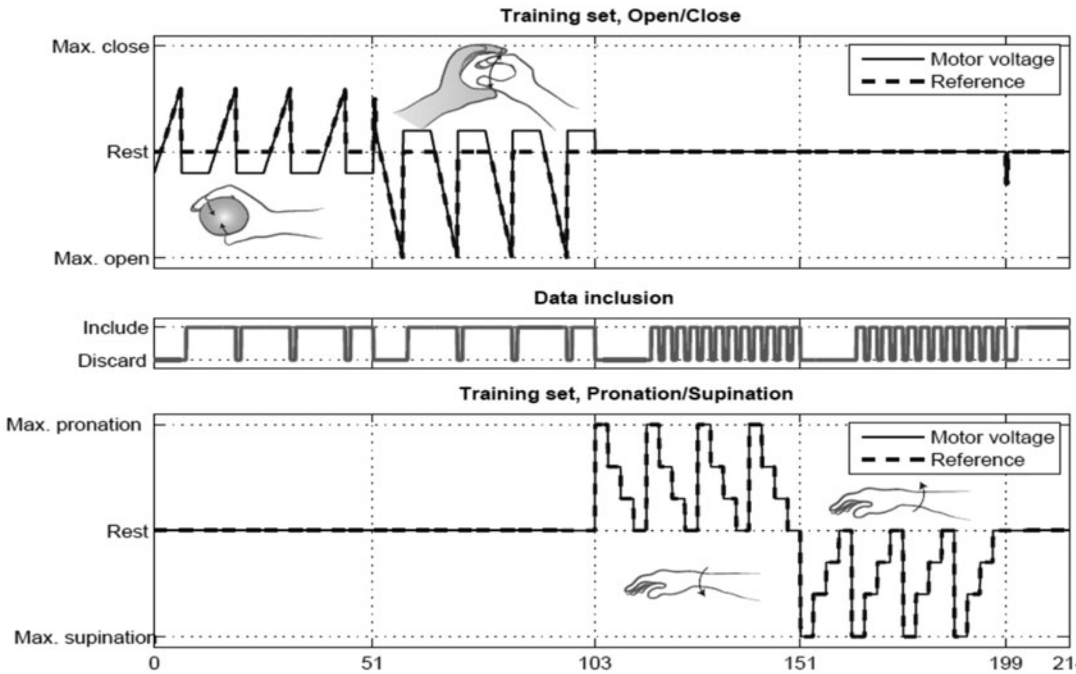

Figure 5. Prosthesis guided system training for simultaneous proportional control. The upper plot shows the voltage applied to the hand motor, and the lower plot shows the voltage applied to the wrist rotator. Some parts of the training procedure were discarded, as indicated by the boolean variable in the middle plot. The hand (colored) and prosthesis (white) sketches illustrate how each phase of the training was performed.

Thus, steps of three easily distinguishable levels (high, medium and low speed) were applied, the maximum value first. All motions were repeated four times. This allowed for the test subjects to "practice" during the first motion, which was not recorded, in order to be well prepared for the next three repetitions. The training method lasted for approximately five minutes, including short breaks between each type of motion. It was determined that a training set for simultaneous proportional control needs to contain simultaneous movements, unless some kind of interpolation is being used [66].

The need for better training methods, confirms the findings discussed previously [66]; the training methods need to be improved in order to exploit the modern multifunction prostheses, for proportional control as well as for crisp classification and other control strategies. The optimisation criterion used to train the linear mapping function was the minimisation of root-mean square.

The Clothespin Relocation task has previously been used by researchers in Chicago it was chosen as one of the assessment tools, so as to compare the control strategies' ability to handle a task where at least two motor functions (e.g. hand open/close and wrist pronation/supination) are needed. During the experiments, it was observed that compensatory movements were frequently used, especially when using the sequential proportional control strategy [66]. This indicates that compensatory movements may still be the fastest way to complete the Clothespin Relocation task for this control system – even though the test is designed to encourage the use of two motor functions. Thus, there might be a need for other assessment tools with a stronger dependence on using multiple motor functions, or ones with an explicit restriction of compensatory movements. However, one cannot deduce from the results that all training effects (specifically the user's adaptation to the system) had died out by the completion of the fifth session. More extensive user training would increase the perceived functional performance to the point where the subject would instinctively prefer to utilise another prosthesis motor function rather than compensating with other body movements. Both subjects in this study needed longer time (more than five sessions) to achieve scores in SHAP, while the results were relatively stable already after two sessions of the Clothespin Relocation task. For a continuation of this study, one should consider extending the number of recordings with SHAP. By increasing from 5 to 10 sessions, one may achieve more consistent scores [66] (Figure 5).

2.2.6.4. Need for up-gradation of prosthesis design. *In the field of technology of grasping.* The human hand is a very powerful tool for sensing and operating in the environment. Moreover, it is an imperative sophisticated means for physical and social interaction. It allows the human beings to accomplish complicated movements, from power to precision tasks, thanks to the large number of degrees of freedom (21 DoFs for the hand and 6 for the wrist) and the supreme role played by thumb opposition [74]. To that end, hand loss can be perceived as a devastating damage which forces people to change their life style because it affects the level of autonomy and limits the capability of performing not only critical works but also routine social and daily living activities. The levels of upper limb loss can be classified as transcarpal, wrist disarticulation, transradial, elbow disarticulation, transhumeral, shoulder disarticulation and forequarter. The available prosthetic solutions are not capable of fulfilling the complete needs due to limitations in the interfaces adopted for controlling the prosthesis and to the lack of force or tactile feedback, thus limiting hand grasp competencies [74]. Though technologically advanced assistive devices are nowadays available to restore grasping, but effective and effortless control integrating both feed-forward (commands) and feedback (sensory information) is yet to achieve its full potential. Thus, there is still a need to develop a user-friendly interface for the semi-automatic and closed-loop control of grasping and to test its feasibility [75]. Though, research in the field of control of upper limb prostheses is still coarse, progress in the field of mechanics [76] is notable, as confirmed by the advanced poli-articulated myoelectric prosthetic hands available on the market, that is, the i-Limb [77], the Bebionic [78], and the Michelangelo hands [79] which enable several grasping tasks thanks to the number of DoFs [80].

One of the major limitations of current devices is the lack of an intuitive and reliable interface able to map the user motion volition to real movement of the prosthesis [81] and finally, the necessity of a rigorous training required to properly manage the artificial hand, the lack of sensory feedback and the noise produced by the actuators during movements make the prosthetic hands still far from fully addressing the users' needs [82]. Thus, more prolific research is essential in this field which can help and satisfy the hand control in order to assure tasks of daily living and to integrate the sensory feedback so as to restore the amputee sensations related to the interaction with the environment.

Robotic prostheses. Robotic prostheses are also gaining immense popularity in recent times. Significant improvement has been found in upper limb motor function after stroke using robotics for upper limb rehabilitation [83]. The basic principle relies on integrating several components of robotic limb into the body's function while biosensors detect signals from the user's nervous or muscular systems and sends this information to a controller located inside the device, and processes feedback from the limb and actuator such as position or force, and sends it to the controller. Controller also monitors and controls the movements of the device [83]. Such biosensors are also now employed in myoelectric prostheses.

Through targeted muscle reinnervation technique motor nerves which previously controlled muscles of an amputated limb, are surgically rerouted such that they reinnervate a small region of an intact muscle, such as pectoralis major resulting contraction of a small area of muscle on patient's chest when patient thinks about moving the thumb of missing hand. By insertion of sensors at an appropriate position over the reinnervated muscle, these contractions can be made to control the movement of an appropriate part of the robotic prosthesis [84].

Targeted sensory reinnervation is a similar technique where sensory nerves are surgically rerouted to skin on the chest instead of motor nerves rerouted to muscle. In addition, recent robotic limbs are now capable of taking signals from the human brain and translating those signals into motion in the artificial limb. Studies are also going to tag artificial limb into the nervous system [85]. Progressions in technology of processors used in myoelectric arms helped scientists to gain more fine-tuned control of prosthetics such as Boston digital arm which allows movement in five axes and allows the arm to be programmed for a more customised feel. The i-Limb hand, invented recently in Edinburgh, Scotland has become the first commercially available hand prosthesis having five individually powered digits and manually rotatable thumb operated passively by the user and allows to grip in precision, power, and key grip modes. The ultimate aim of a robotic prosthesis is to deliver active actuation during gait to improve the biomechanics of gait including stability, symmetry and energy expenditure for amputees (Figure 6).

Bionic prostheses. The term bionics was first used in the 1960s which evolves as a combination of bio meaning life with the nics of electronics. Bionics is the study of mechanical systems that function like living organisms or parts of living organisms. In spite of immense popularity of bionic hand in the field of engineering excellence [82] it remains an inferior replacement to the real organ and consequently its acceptability is still

Figure 6. iLimb Pulse, from Touch Bionics, Inc. Examples of commercially available multi-articulating prosthetic hands (CC BY-NCSA).

questionable amongst the upper limb amputee population. Because of complex nature of human hand, replicating its functions using a bionic device is a significant challenge. Moreover, controlling a bionic limb must be quick, easy and reliable for it to have any advantage over a non-functioning alternative. Myoelectric control is the most widely used method of control in commercially available bionic limbs which relies on complex algorithms to make sense of the massive amount of electrical activity in the stump [82,86].

Among the bionic limbs, BiOM Ankle System from iWalk (designed to increase mobility with revolutionary propulsion technology, while reducing energy demands and stress on the body) [87,88], Power Knee from Ossur (a motor-powered prosthetic knee that benefits the user with symmetry, strength, and endurance) [89], Proprio Foot from Ossur (gives heightened stability and mobility to amputees through lifelike powered-ankle motion) [90], The iLimb from Touch Bionics (appears and functions like a biological hand, featuring natural joints as well as automated grip patterns and gestures) [76,77], The Michelangelo prosthetic hand from Otto Bock (able to grasp and hold objects with greater control and less effort) [79,91] etc. gained huge popularity among the amputees. Despite this even the best bionic limbs still do not come close to replicating the complex intrinsic functions of the innate hand.

The next advancement in bionic limb technology is the emergence of mind-controlled bionic limbs to utmost level of perfection especially, improvement of designing of prostheses which can be integrated with body tissues, including the nervous system more precisely, these highly advanced prosthetics will be able to respond to commands from the central nervous system and therefore to more closely replicate normal movement and functionality, while also instantly trigger the desired movement with less lag time. There are several different procedures and technologies currently in the research and development phase considering all these aspects.

3. Conclusion

Through a complete review of the already reported studies on proportional myoelectric control, the work of this article has united the historical contributions and offered a comprehensive overview of the area for present and future researchers in the field. It revealed that methods for system training, both the choice of method and the composition of the training data set, need further research in order to achieve acceptable results with proportional myoelectric control. The need for incorporating a multi-modal unit (e.g. EMG-electrodes with accelerometers and force sensors) has also been discussed in order to increase the robustness of the system. If this requires an extension of the system training protocol, for example by applying various amounts of external forces, an effort should be made to otherwise simplify the procedure. It has been mentioned that the training method should contain simultaneous movements when used in a simultaneous control scheme. During the initial trials of the study reported, it was found too difficult for the test subjects to follow simultaneous motions when they are being demonstrated by the prosthesis. However, these were preliminary studies. The training protocol needs further development, and one should not reject the possibility of having simultaneous movements in parts of the system training.

Disclosure statement

There is no conflict of interest among the authors.

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