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Virtual reality training and EMG control of the MANUS hand prosthesis

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SUMMARY

The design of multifunctional upper limb prosthetics has been investigated in recent years. Several areas or research need to be developed for successful implementation of dextrous upper limb prosthesis, in particular better EMG interfaces for implementing command languages.

This article introduces a novel three-bit EMG command language concept as a user interface for the multifunctional MANUS prosthesis prototype. Following the global approach proposed by MANUS, a training process and the supporting Virtual Reality training software are also presented. The last section describes the evaluation process and the results.

KEYWORDS: MANUS; Virtual reality; EMG control; Prosthesis.

I. INTRODUCTION

In multifunctional prosthetic applications, the problem of the man-machine interface always appears, i.e. the more dextrous the prosthetic hand, the higher the number of command channels are required.

Commercial upper limb prosthesis can be classified into cosmetic, body powered and EMG controlled prosthesis. The latter two types of prostheses and their combination can be regarded as active rehabilitation devices. Amongst active prostheses, from the control point of view, just mechanical or body powered prostheses can provide the user with inherent bio-feedback on, for example, the force being exerted during grasping.[1,2]

In the simplest instance, EMG control provides unidirectional control with an inherent lack of feedback. Alternatively, EMG signals can be processed to render additional or extended control possibilities as compared to mechanical prosthesis. EMG control of prosthesis can be further classified into "ON-OFF" and proportional. Proportional EMG controlled prosthesis have recently been introduced.[3] Typically they comprise of one active grasping joint and, in some cases, an active wrist rotation. Provided no more active joints are included, one single EMG control channel, i.e. one muscle signal, can be used to control the hand. In most cases, an estimation of the force being exerted during grasping is obtained from the electrical motors' noise, as there is an inherent lack of other feedback channels. However, as reported by Pons *et al.*,[4] over 25% of electrical prosthesis users complain about excessive noise and would prefer noiseless operation. Based on these demands, we adopted the use of EMG control to obtain wider control possibilities and relied on a frequency modulated tactile device to partially overcome the lack of bio-feedback capabilities of EMG control.[4]

EMG pattern classification has been attempted for a variety of applications. Han *et al.*[5] present the application of EMG patterns to assist elderly in controlling a rehabilitation robotic arm. They use fuzzy logic and set theory tools to identify a set of essential EMG features which are independent of the particular user. A scheme based on fuzzy pattern classification is then employed to handle the selected set of features.[6] Also a scheme based on fuzzy classification is reported in Barreto *et al.*[7] It uses both EMG and EEG signals in order to develop an input device for subjects with severe motor disabilities. In the area of upper limb control, EMG management has been used in combination with tactile information to provide means for triggering state transition.[8]

Most of the current methods for the recognition of onset of EMG activity employ a simple algorithm that recognises the point where the mean of an large enough number of EMG samples exceeds the baseline activity level. These methods are acceptable when the difference between EMG signal intensities in the relaxed and the contracted state differ significantly. A method for low levels of EMG activity, where the residual muscle activity is poor is known as well, see Micera *et al.*[9] However, these methods are not appropriate enough for the comprehensive control of an advanced multifunctional artificial upper limb.

Single or multiple EMG electrodes have been attempted. An approach that uses amplitude analysis of four EMG channels is presented by *Beattie*.[10] In this approach, the combination of activation conditions of these four EMG channels determines the grip type of a multifunctional robotics hand. Once the grip is selected, the control system changes to a proportional control scheme. Again, EMG activation is based on signal thresholds. A time-frequency analysis is presented by Englehart.[11] The EMG signal is represented in the time-frequency plane. The classifier uses four EMG channels

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and four classes and was implemented to work both with steady-state and transient EMG signals. The former resulted in an accuracy greater that 99% while the latter was slightly reduced to 97%.

EMG pattern classification, or alternatively recognition of signal onset must be approached by using robust algorithms. In EMG, both the signal and the signal-to-noise ratio may be low. To be a practical solution for an artificial hand, the processing of the EMG signal and complex commands have to be completed in real time by a microprocessor with limited resources. Additionally, as the complexity of the EMG interface is increased a more dedicated training approach should be provided.

The MANUS project was set up on June 1998 with the overall objective of developing a modular multifunctional hand prosthesis.[4] Since the MANUS project has attempted a global approach to upper limb amputee rehabilitation, it also proposed and developed a broad-band EMG user interface, the corresponding training protocol and the supporting training device.

The training device serves the purpose of starting functional rehabilitation immediately after upper limb amputation. It is based on Virtual Reality tools and enables muscle conditioning as well as command language learning. Just after the training process is finished, the MANUS prototype can be fitted and real manipulative operation can be started.

This paper introduces the MANUS training process, describes the EMG command language as well as the Virtual Reality training device.

II. THE MANUS TRAINING PROCESS

The MANUS multifunctional prototype, (see Figure 1), is an advanced prosthesis supporting up to four grasping modes, i.e. cylindrical, precision, lateral and hook grasps, in addition to wrist pronation-supination. Furthermore, the individual grasping modes can be conveniently combined to define complex manipulations. For instance the action of grasping a bottle with a cylindrical grasp and subsequent wrist rotation, for pouring water into a glass can be programmed as a single manipulation that is launched with a single command.

Fig. 1. One of the MANUS users performing a combined cylindrical grasp and wrist rotation.

In this approach, the possibility of assigning control commands to different levels of force or velocity for each grasping operation has been provided. As a result, a large number of different EMG commands are required for successful management of the prosthesis.

The training process as proposed within MANUS is a stepwise approach to control the enhanced functionality of our prosthesis prototype. It can be divided in four progressive steps as described below:

(i) The aim of the first step is to avoid the loss of limb activity during the training phase. It consist in the generation of simple EMG signals that can be associated to simple on-off devices, i.e. switching on and off a radio, light. The amputee experiences some control on the environment. This way, positive psychological factors are enhanced while negative ones are diminished. In addition re-education in a latter stage is avoided or at least decreased.

(ii) The goal of the second step in the training process is two-fold:

  a) To determine the character of the EMG activity of various muscles (the factors included are; amplitude, time of contraction, baseline activity, mean and standard deviation of EMG during rest and contraction.)

  b) To determine the appropriate method of prosthesis activation: analogue, three-bit language or combination of the two.

(iii) To learn the three-bit language, (see section 3), or the analogue language as a function of step (ii).

(iv) In this step, the three-bit commands are associated with grasping modes, or alternatively, a combination of basic hand operations in order to obtain complex manipulation schemes is created.

This stepwise approach is estimated to take from 4 to 5 weeks and for those who have suffered a loss of their hand it should be started, as soon after amputation as practical.

It is apparent that most of the training effort should focus on learning the MANUS EMG three-bit command language. As a consequence, the training platform is conceived both as a tool for professionals and for individual patient training. The tools provided for professionals use are mainly indicated to support the second training step in which muscle related aspects are determined and conditioned. The tools provided for patient use support the learning of the EMG command language and offer Virtual Reality simulation of the multifunctional prosthesis.

III. THE MANUS DIGITAL 3-BIT LANGUAGE

EMG signals from residual muscles are used as the human-machine interface. One of the main requirements of a multifunctional prosthesis is the availability of a user interface meeting the requirements of information transmission.

Analogue EMG control has been used for both proportional and on-off control of hand prosthesis. When the number of grasping modes supported by the prosthesis is low (typically 1 or 2) this offers no difficulties. However, when the number of grasping modes increases additional EMG channels (from different muscles) should be provided if analogue control is still desired.

The MANUS concept is instead based on digitally encoding the EMG signal. The users are asked to produce EMG bursts (by sudden contraction of the involved muscle). If proper EMG thresholds are defined each burst can be classified in three different levels. Each of these three levels is given the digital values "0", "1" or "2" respectively corresponding to a bit.

The core of the training platform is the implementation of a new EMG command language. The selection of this new EMG command language was supported by the analysis of different approaches. Nineteen volunteers with various levels of hand loss were involved, together with twelve able bodied volunteers. The subjects were instructed to use three possible modes of controlling the MANUS prototype:

(i) A three-bit ternary EMG signal (high, low, no signal)
(ii) A sequence of binary EMG signals (high or low)
(iii) A sequence of analogue EMG signals. The increase of the signal intensity was fed back to the patient by changing the picture appearing on the PC display.

The muscle selected for the experiment was the flexor carpi radialis. EMG signals were recorded with the ALOR-2. This EMG processor is manufactured by Alorman Advanced Medical technologies Ltd. and is the same processor that was integrated in the MANUS VR training platform.

No significant specific difficulties were found in any of the proposed control concepts. As a consequence, the one providing additional control possibilities was selected for the MANUS approach, i.e. the three-bit ternary EMG signal.

III.1. Statistical analysis of the EMG signal

One of the problems of using EMG for prosthesis control is the determination of EMG signal onset. This approach is based on a statistical analysis of the EMG signal.

In the analysis it was assumed that the time series corresponding to the EMG observation can be classified according to two hypotheses:

- The null hypothesis, H_0. This hypothesis corresponds to the EMG in relaxed state and is characterised by the probability density function, PDF, p_0.
- The alternative hypothesis, H_1 with PDF p_1 and related to the relaxed state and to the contracted state together.

Initially, we assume that the hypothesis H_0 is true from time 0 to t-1. We suppose that p_0 is a Gaussian distribution with the mean equal to μ_0 and p_1 is not Gaussian with mean equal to 0.

The Kurtosis and Skewness coefficients of PDF p(x) characterise to what extent p(x) differs from a Gaussian distribution. The Kurtosis and Skewness coefficients of Gaussian distributions are equal to 0. If PDF of a given distribution is symmetric then the Skewness coefficient is also equal to 0.

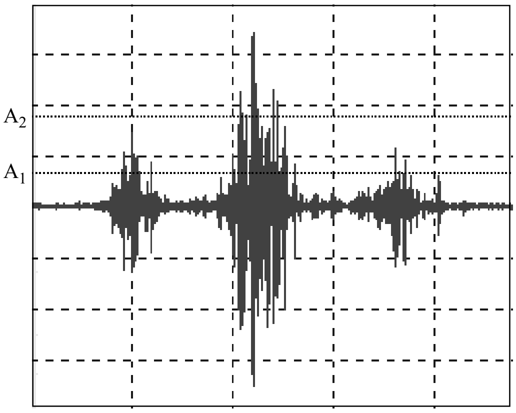

Fig. 2. A typical "121" EMG signal performed during calibration.

We will consider the Kurtosis coefficient as the decision function for determining the instant "t_{EMG}" so that

- For $0 < t < t_{EMG}$ the hypothesis H_0 is true
- For $0 < t < t_n$ ($t_n > t_{EMG}$) the hypothesis H_1 is true

With this definition t_{EMG} is considered the onset time of the EMG signal. When using K_c as the decision function for determining t_{EMG} (the onset of muscle contraction), the following rule can be applied: the hypothesis H_1 is accepted if $K_c > \gamma$, being γ the decision threshold defined by statistical data.

III.2. Calibration of EMG parameters

The aim of this process is to provide the hand controller or the training software, with the EMG characteristics of the user. The following definitions apply for the remaining paragraphs; see Figure 2 for a typical EMG signal produced during calibration:

- t_S: time during which EMG is actively generated
- t_{NS}: time between consecutive actively generated EMG bursts.
- C_s: Coefficient for occasional involuntary EMG signals with no relevance to the command. This value has to be defined individually for each user.

The calibration process has to be performed at the beginning of each time the artificial hand is worn or the VR training platform is being used. The calibration process comprises two stages:

(i) Noise characterisation. The noise characterization stage takes between 5 and 10 seconds. Noise is identified according to the average value, standard deviation (S_d), Skewness coefficient and Kurtosis coefficient (K_c).
(ii) Signal characterisation. For signal characterisation just the standard deviation and Kurtosis coefficient are identified.

Based on the values of S_d and K_c, the noise and signal calibration processes are checked out. The calibration process is performed according to the following algorithm:

a) Calibration of first threshold, A_1. This step is performed during relaxed muscle activity. A_1 is defined as the lower bound of amplitude of bit "1". The calibration is used to define Cs and A1.

Table I. The MANUS Three-bit command language.

Functional command	3-bit pattern	Remarks
Stop	100	Constant, pre-set, compulsory
Default position	200	Constant, pre-set, compulsory
Calibration	212	Constant, pre-set, compulsory
Rotate to right, until “Default”’ or until “Stop”	210	Individually adapted, recommended “preset”
Close, gripping mode “1”, Preset 0 to 250 gr. total pressure, or until “Stop”.	211	Individually adapted
Close, gripping mode “1”’ Preset 251 to 500 gr. total pressure, or until “Stop”	221	Individually adapted
Close, gripping mode “1”, Preset total pressure >500 gr., or until “Stop”	222	Individually adapted
Rotate to left, until “Default”’ or until “Stop”	101	Individually adapted, recommended “preset”
Close, gripping mode “2” Preset 0 to 250 gr total pressure, or until “Stop”.	120	Individually adapted
Close, griping mode “2”’ Preset 251 to 500 gr total pressure, or until “Stop”	121	Individually adapted
Close, gripping mode “2”, Preset total pressure >500 gr., or until “Stop”	122	Individually adapted
Close, griping mode “3” Preset 0 to 300 gr total pressure, or until “Stop”	201	Individually adapted
Close, gripping mode “4”, Preset: arch, or until “Stop”	202	Individually adapted
Available	111	
Available	112	

b) Calibration of A_2 and time of one bit, t_{BIT}. During this stage the user is asked to perform command “121”, see Figure 2. While performing this command the following parameters are defined

- Time of bit, t_{BIT}, as an average value of the bit duration and computed from t_S and t_{NS}.
- A_2 is computed as a function of bits’ amplitude.

Throughout the calibration process, the sampling frequency is set to 5 kHz since additional bandwidth is required for a good characterisation of noise.

III.3. Generation of EMG command language

Once the EMG parameters are calibrated for a given user, the generation of commands can start. The user is asked to perform consecutive muscle contraction according to the pattern defined by the desired command. The algorithm used to recognise valid commands check the following circumstances:

(i) Stand by and wait for command, i.e. ‘Sleep mode’. EMG signal is continuously sampled at 400 Hz.
(ii) A threshold approach is applied to detect voluntary signal onset. This approach is based on the analysis of the statistical data previously introduced.
(iii) After voluntary signal onset has been detected, interference and noise rejection is performed according to previously defined t_{BIT}.
(iv) Voluntary signal is check against A1 and A2 for identifying bits “1” and “2”, respectively.
(v) The process is repeated for each of the three bits in the command word.

According to this process a command language has been defined. In theory, 27 different commands could be defined with this three-bit ternary logic. However, the second step in the checking procedure during generation of the EMG command is rejecting all those commands starting by “0”, i.e. all “0XY” patterns. As a consequence 18 effective commands are available. Table I shows the default layout of the EMG command language.

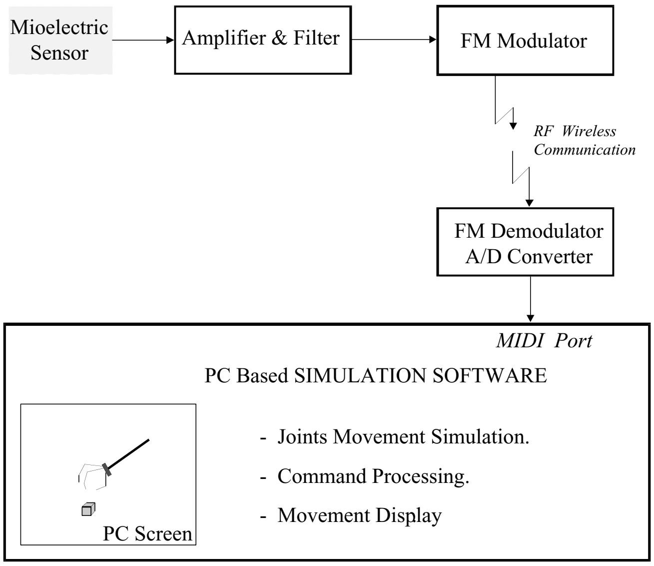

Fig. 3. Schematic representation of the VR training platform.

IV. THE MANUS VIRTUAL REALITY TRAINING PLATFORM

The training processes as well as the command calibration and generation steps as described above are implemented on the training platform. The general layout of the training platform is shown in Figure 3.

The hardware required for the training platform is:

(i) A standard ALOR-2[*] apparatus for acquiring EMG signals is used to record electrical signals generated by the muscles of the user. The sampling rate used is 400 Hz.
(ii) A Personal Computer with the following configuration is desirable:
  - Pentium CPU at least 133 MHz
  - 32 MB RAM
  - HD at least 20 MB

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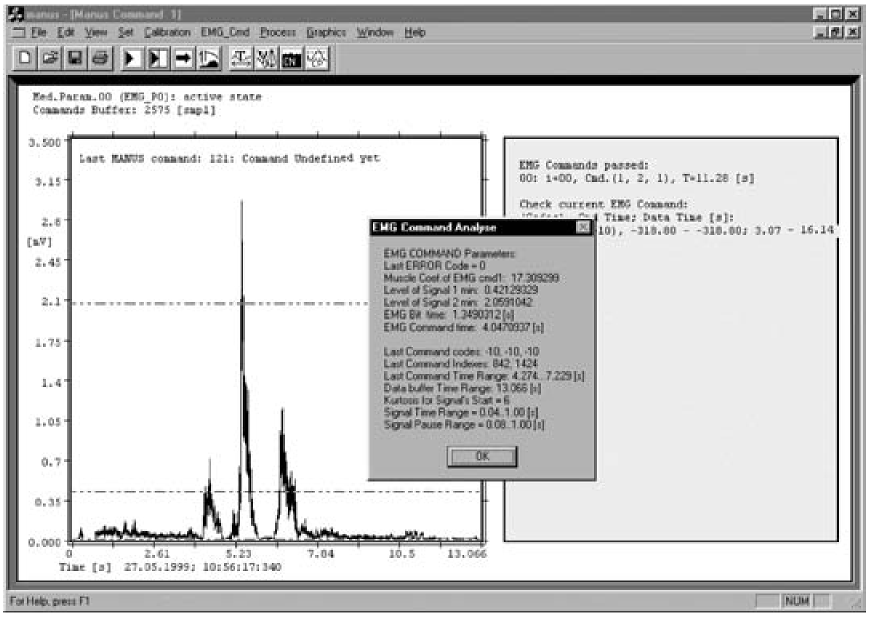
[*] ALOR-2© is a EMG processor manufactured by Alorman Advanced Medical Technologies Ltd.



```
Med.Param.00 (EMG_P0): active state
Commands Buffer: 2575 [smpl]
```

```
Last MANUS command: 121: Command Undefined yet
```

```
Time [s]  27.05.1999; 10:56:17:340
```

```
EMG Commands passed:
00: i=00, Cmd.(1, 2, 1), T=11.28 [s]

Check current EMG Command:
Time: Data Time [s]:
10), -318.80 - -318.80; 3.07 - 16.14
```

```
EMG COMMAND Parameters:
Last ERROR Code = 0
Muscle Coef.of EMG cmd1:  17.309299
Level of Signal 1 min:  0.42129329
Level of Signal 2 min:  2.0591042
EMG Bit time:  1.3490212 [s]
EMG Command time:  4.0470937 [s]

Last Command codes: -10, -10, -10
Last Command Indexes: 842; 1424
Last Command Time Range: 4.274...7.229 [s]
Data buffer Time Range: 13.066 [s]
Kurtosis for Signal's Start = 6
Signal Time Range = 0.04...1.00 [s]
Signal Pause Range = 0.08...1.00 [s]
```

Fig. 4. The MANUS VR training platform main window for calibration process.

- Display resolution: 1024 × 768 (desirable)
- Palette: 16 bit (65536 colours desirable)
- Operating system: Windows 95/98 (English based)

The signal as recorded from the user is amplified and high-pass filtered. A radio link at 433 MHz is used to transmit the signal to the Personal Computer. A standard PC can be used to record and analyse the signals generated. A radio receiver gets the EMG signal and then it is band-pass filtered. The MIDI port of the Sound Blaster card is used to acquire the EMG signal (see Figure 4).

The following functions are supported by the VR training platform software:

(i) **EMG calibration.** It is performed according to the previous section. This includes estimation of users' EMG parameters and visualisation of the EMG signal. In Figure 4, the main VR training platform window during calibration is shown. In addition to the graphical representation of the EMG signal and computed threshold, once the calibration in successfully performed an additional text window shows data relevant to the calibration process, in particular those parameters introduced in section 3.2.

(ii) **Virtual Reality simulation of EMG commands.** This function allows the user to define EMG commands. It is done by linking 3-bit patterns to functional commands, i.e. "get a key" for lateral grasp, "get a glass" for cylindrical grasp... The user can train in the generation of functional command. Once the command is successfully generated and the system decodes it, a graphical representation of the manipulative operation is shown. Figure 5 shows the main window for command training.

(iii) **Programming of complex commands.** The MANUS prosthesis prototype supports complex commands made up of combination of single grasping commands. The VR training platform supports the user programming of his own complex commands by linking them to available 3-bit patterns. Once defined the system can be used for training these complex manipulations as in the previous function.

In addition to these main functions the VR training platform supports a number of functions to help in the training process. For instance, a database with clinical data of users can be defined. It allows in maintaining an individual clinical history of the rehabilitation process.

Some "telediagnosis" facilities are also supported by the training platform. If home training is being conducted, relevant clinical parameters corresponding to the training sessions can be saved and automatically sent by e-mail to the therapist for follow up.

V. EVALUATION AND RESULTS

The objectives of the evaluation tests were to assess subject's ability to perform the following:

(i) To learn and master the principles and functions of the MANUS VR training platform and its 3-bit EMG language.

(ii) To perform desired commands by generating myoelectric signals from various muscles.

(iii) To receive subject's evaluation of the convenience and ease of practising the VR training platform system.

V.1. Methodology

The test was divided into two parts:

(i) During the first session (2 hours) each subject was introduced to the Prosthesis features, the VR training platform, the EMG signals, the 3-bit EMG language and the objectives of this test. A physical examination was conducted in order to identify the most appropriate muscles capable to perform the desired contractions.

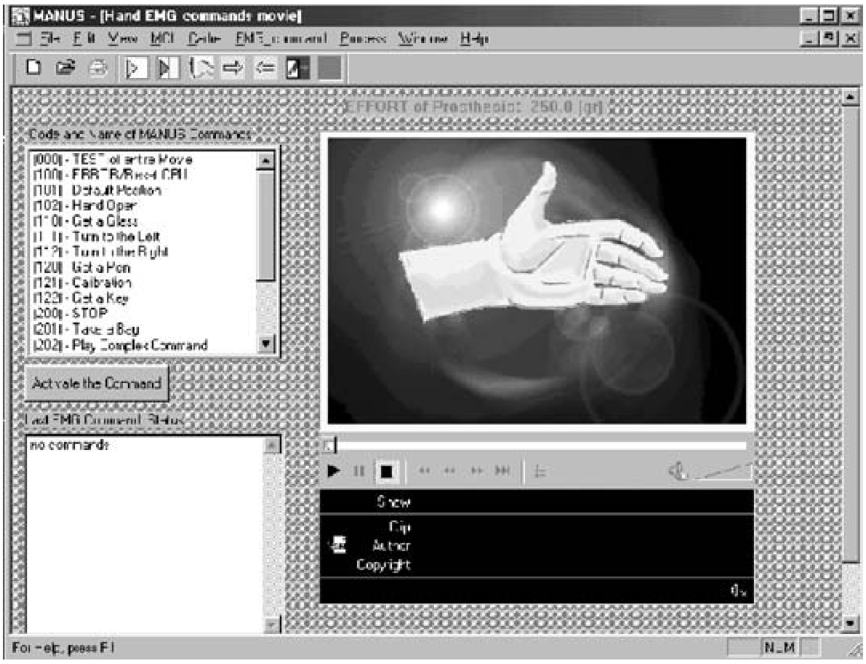


Fig. 5. The MANUS VR training platform main window for EMG training.

Only then, the subject could start practising the generation of EMG command.

(ii) The second session (1 hour) took place 2–3 days after the first one, during which he repeated the exercises, so we could examine the improvement in learning and in the assimilation of the EMG Command Language.

The muscles used in the test were the carpal flexors, carpal extensors, biceps, brachialis, pectoralis major, all on the amputation side, biceps brachialis on the contralateral side, gastrocnemius and tibialis anterior on the amputation side. The device used the already described VR training platform and standard children ECG electrodes.

V.2. *Subjects*

This test examined 15 limb absent individuals in accordance with the protocol described in section 5.3. The age range of the group was 21–54 years, all were occupationally active at work, and at home they also participated in sport and leisure pursuits. There were no other medical conditions. Only one of the subjects had a congenital absence. The rest were of traumatic origin (war veterans, work accidents). All of the subjects were a minimum 10–20 years after their amputation and all experienced phantom sensations. The remnant stump in good condition. Without any discernible articular problems. All of the subjects, (except in the one case of shoulder disarticulation), had a trans-radial absence, including one wrist disarticulation. There was only one case of a bilateral trans-radial loss.

All the subjects were independent and were thus able to perform the conventional Activities of Daily Living. All of the users had experience of the available types of prosthesis: cosmetic, body powered mechanical and myoelectric, but only 3 were currently using myoelectric prostheses. All individuals gave informed consent to the experimental procedures.

V.3. *Procedure*

The procedures for clinical trials were carried out according to the five-step protocol:

(i) A visual demonstration of the myoelectric signals was displayed.
(ii) Calibration process of noise (sensor and device), and that of subject's EMG signal parameters (calibration command 121).
(iii) Subject exercised the generation of soft signals (level 1), rapid signals (level 2) and rest (bit 0), until the stage he was able to generate for 10 consecutive times each contraction.
(iv) The basic commands of the Protocol are exercises: hand open (102), close grip mode 1(110), mode 2(120), mode 3(221), mode 4(201), pronation (111) and supination (112).
(v) Generation of random commands after learning 5 EMG control commands.

V.4. *Results*

Upon examination of the limb for inclusion into the study it was noted that there was muscular atrophy of the proximal limb muscles. The basic results of the clinical trials are summarised. In general, the results were satisfactory. The time involved in the generation of a three-bit command varied widely according to the subject. Command generation time as short as 0.5 s was experienced, but also generation periods up to 2.5 s were found. However, it was observed that the generation time reduced with training:

(i) All of the Subjects were able to successfully perform the basic commands after about 45 minutes, and except for two, who were able to memorise the 5 commands as well.

(ii) After 30 minutes of training, some of the subjects complained of pain, fatigue and swelling of the stump muscle used for signal generation.
(iii) After lowering the threshold of level "1" and/or level "2", it was much easier for those subjects who felt muscle fatigue and thus enabling them to extend exercise period.
(iv) Gastrocnemius muscle may be a useful generator of signals, only if the subject was sitting (i.e. at worktable). However, not enough data was available to make a similar statement about the tibialis anterior.
(v) The use of muscles from the opposite arm or forearm are not practical, since it may confuse the subject and may interfere with the normal function of the good arm.
(vi) Calibration procedure was quite easy to perform and no particular problems were observed.
(vii) While giving a command, it was slightly more difficult to produce a soft signal (level "1") right after performing a rapid signal (level "2"), i.e. 221, than the *vice versa*.

The results of the test were found to be satisfactory. It was quite easy for the subjects to learn the command language and perform the generation of signals after a very short period. All the subjects were enthusiastic about the novelty of the prosthesis, with the extended range of functions and the similarity to a natural hand.

It is found that in order to make the use of the EMG command language easier, it is necessary to re-establish a new hierarchy for the 3-bit patterns. The most crucial/common/useful commands should have the easiest pattern ("200", "100", "220", "110", "222", "111", "122", "112"...).

VI. CONCLUSIONS

In this paper a novel EMG interface for multifunctional upper limb prosthetics is presented. The new EMG language is based on a three-bit ternary logic and supports up to 18 effective commands. The paper introduces the statistical analysis behind this EMG interface and discusses on calibration and command identification procedures.

Since the MANUS project is a global approach to upper limb prosthetics, a training process and the supporting Virtual Reality training platform is also presented. The whole concept has been subjected to experimental trials. The results show that the MANUS EMG command language can be effectively implemented for commanding our multifunctional prototype, however a thorough clinical evaluation is still to be performed.

All the subjects of the evaluation tests were able to perform a variety of EMG commands in a very short training period that show the promising characteristic of the MANUS proposal.

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