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Automatic tuning of myoelectric prostheses

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Abstract—This paper is concerned with the development of a software package for the automatic tuning of myoelectric prostheses. The package core consists of Fuzzy Logic Expert Systems (FLES) that embody skilled operator heuristics in the tuning of prosthesis control parameters.

The prosthesis system is an artificial arm-hand system developed at the National Institute of Accidents at Work (INAIL) laboratories. The prosthesis is powered by an electric motor that is controlled by a microprocessor using myoelectric signals acquired from skin-surface electrodes placed on a muscle in the residual limb of the subject. The software package, Microprocessor Controlled Arm (MCA) Auto Tuning, is a tool for aiding both INAIL expert operators and unskilled persons in the controller parameter tuning procedure.

Prosthesis control parameter setup and subsequent recurrent adjustments are fundamental for the correct working of the prosthesis, especially when we consider that myoelectric parameters may vary greatly with environmental modifications. The parameter adjustment requires the end-user to go to the manufacturer's laboratory for the control parameters setup because, generally, he/she does not have the necessary knowledge and instruments to do this at home. However, this procedure is not very practical and involves a waste of time for the technicians and uneasiness for the clients.

The idea behind the MCA Auto Tuning package consists in translating technician expertise into an FLES knowledge database. The software interacts through a user-friendly graphic interface with an unskilled user, who is guided through a step-by-step procedure in the prosthesis parameter tuning that emulates the traditional expert-aided procedure.

The adoption of this program on a large scale may yield considerable economic benefits and improve the service quality supplied to the users of prostheses. In fact, the time required to set the prosthesis parameters are remarkably reduced, as is the technician's working time. This is interpreted as minor costs for prostheses manufacturers and suppliers.

Key words: *fuzzy logic, human-machine interface, prosthetics.*

INTRODUCTION

The preliminary studies about the possibility of using residual muscles of a residual limb after amputation to move a prosthesis dated from the beginning of this century, but it was not until the late 1940s that the importance of myoelectricity in this field was understood (1–4). The first myoelectric hand was realized by Reiter in Germany, while significant improvements in these studies were made by Battye, Nightingale, and Whillis in England and by Popov in Moscow (5,6).

In the early sixties, Hannes Schmidl promoted the experimental application of myoelectric control at The National Institute for Accidents at Work (INAIL), Prosthesis Centre of Vigorso (Bologna, Italy). On the basis of this work, the first Italian myoelectric prosthesis was made in 1965 (7). At present, the INAIL Prosthesis Centre is one of most important clinics in

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Europe that is producing myoelectric hands and prostheses (see **Figure 1**).

The INAIL Research and Development department is now working to realize a hand prototype with feedback sensors and to provide the user with tele-assistance and telediagnosis services (8,9). Some other research concerning ''intelligent'' electrodes, as well as studies about lower limbs, is also being carried out. This article is concerned with the most recent prototype realized by the Centre: the MCA Auto Tuning system.

The project aims to develop a software package for aiding both skilled technicians and unskilled users in the setup process of a prosthesis control system.

At present, individuals are required to go to the manufacturer's laboratory for the prosthesis control parameter setup. This procedure is performed manually by factory technicians together with the prospective users. The operator interacts with the client asking him/her to perform muscle contractions while the technician records the corresponding sensor signals. Using the results of the above tests and past experience, the technician sets the control system parameters to optimize the performances of the prosthesis. The setup procedure should be performed several times during the life-time of the prosthesis, mainly because of environmental (e.g., temperature, humidity) changes, which still cause discomfort in users.

The key idea of this project was to incorporate the skill of expert technicians in an automated system based on easy-to-use software. The three most promising uses of the system are:

1. The system can be used by the prosthesis manufacturer technicians to automate the initial setup, permitting significant timesaving in the whole process of prosthesis delivery.
2. The software will be distributed to about 100 INAIL-affiliated centers stationed all over Italy, in which suitable hardware will be provided for users. In this way, persons with amputation can receive local assistance for prosthesis setup.
3. The most ambitious aim of the project is to provide an automated setup procedure directly in the home of the wearer. The system requires a personal computer (PC) and simple communication hardware to establish the PC-prosthesis link, as we will explain later. Since home computing systems are becoming as common as domestic appliances, it can be foreseen that the only thing required by the wearer for home assistance will be the communication hardware.

Some work has already been carried out on the methods of increasing prosthesis performances using computer systems (10). Our work is a further attempt in this field toward high performance and ease in prosthesis use. The key idea was to incorporate technicians' expertise of manual tuning of control parameters into a Fuzzy Logic Expert System, which is then integrated in a software tool.

Fuzzy Logic methodology (11–14) has been used in this task because of its capability to blend human qualitative knowledge into formal algorithms. These ''fuzzy'' algorithms may then be efficiently implemented in computer programs.

Basically, a Fuzzy Logic Expert System is made up of a database of rules and an inference engine (see **Figure 2**).

The database of rules consists of a set of linguistic statements; such as, ''if a **premise** is fulfilled, then execute a corresponding **action.**''

This structure makes it easy to translate human knowledge, often expressed via common language phrases, into the fuzzy rule database. These rules are then applied by means of an inference engine to the actual information gained from the wearer. In this step, the actual premise is compared to all the rule premises stored in the database. The rules corresponding to the

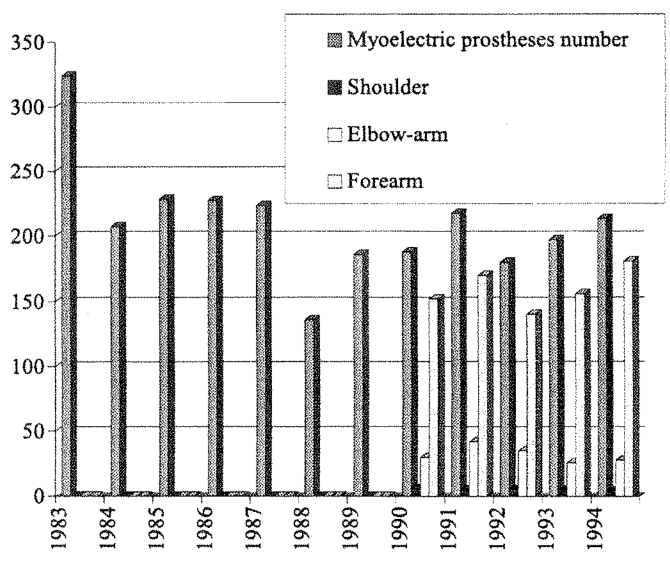

Figure 1.
Production of prostheses by INAIL Centre from 1983 to 1994.

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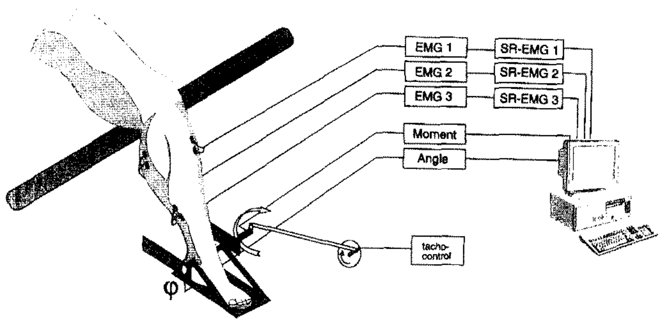

Figure 2.
General scheme of a Fuzzy Logic-Based Expert System.

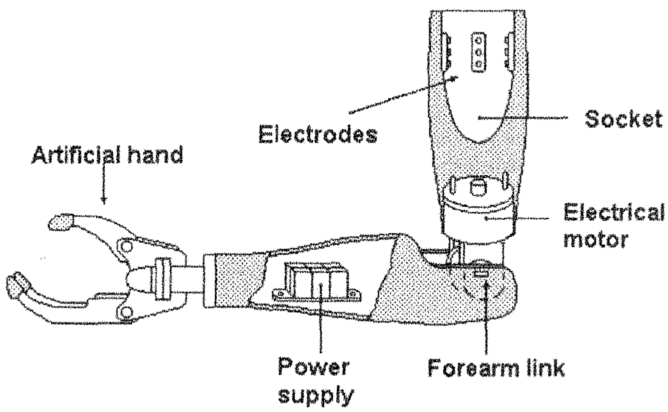

Figure 3.
Myoelectric prosthesis general layout.

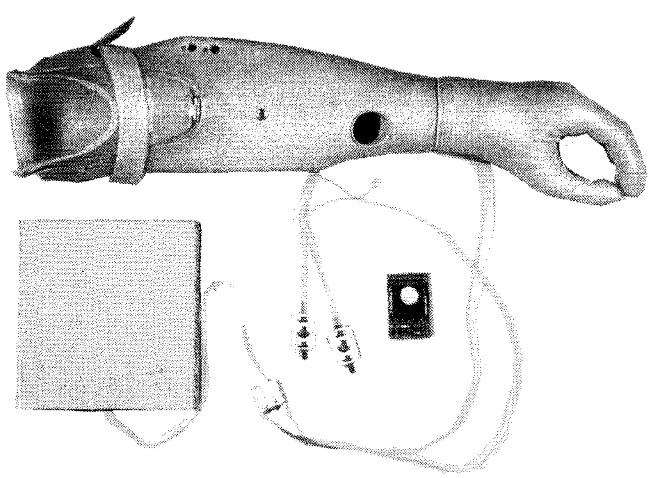

Figure 4.
The INAIL myoelectric prosthesis.

premises that agree, even partially, are chosen and the corresponding actions are merged together to obtain the final output.

The MCA Automatic Tuning software works as follows:

1. The client connects the prosthesis hardware to a personal computer via the serial port and runs the program: MCA Auto Tuning.
2. The program acquires both sensor signals as well as client input. For example, the client is asked to sustain muscle contractions with "high," "medium," and "low" intensity, while the program acquires the corresponding sensor signals.
3. The program combines the above qualitative and numerical information with the expert human knowledge stored in the fuzzy logic database to compute the prosthesis parameter values.
4. At the end of the parameter tuning procedure, the program enables the new parameter values to be downloaded into the prosthesis control-system memory.

METHODS

INAIL Prosthesis Characteristics

The INAIL myoelectric prosthesis considered (see **Figures 3** and **4**) is a new generation multifunction prosthesis with three degrees of freedom, corresponding to the opening/closing movement of the hand, wrist pitch, and elbow flexion/extension (15). As the control of these degrees of freedom differs only in minor details, we concentrate on the description of hand control; that is the most crucial in terms of performance. In the more general case (i.e., when all the functions are enabled), the user may select which degree of freedom (hand/wrist/elbow) is under control:

- Using a double contraction of the EMG driving muscles
- Using a third EMG sensor (see **Figure 3**).

The prosthesis is controlled by surface electromyographic (EMG) signals from remnant muscles. EMG signals are acquired by skin-surface electrodes and processed by a small custom electronic board inserted in the prosthesis. The board is governed by the industry-standard microprocessor INTEL 87C196KC with input signal analog to digital (A/D) converter and pulse width modulation (PWM) for motor control facilities on chip, that enables low board space occupancy. The software parameters are stored in an electrically erasable programmable read-only memory (EEPROM), allowing either on-line or off-line tuning.

The system provides two kinds of movement. The first is linear proportional control, in which the finger velocity is kept proportional to muscle twitch. This mode allows a fine control of the hand motion, enabling the wearer to have a "natural" grasp of objects. The second kind of movement corresponds to "on-off" control of the hand, in which the motor moves at fixed velocity in the presence of a non-zero EMG signal. This movement is easily controllable by users through remnant muscle contraction, but fine grasps cannot be achieved.

Several parameters enable a customization of prosthesis control in connection to user characteristics (such as muscular tone or amputation level) on which the EMG signal magnitude depends, and accordingly, the control action on the motor that actuates the hand.

As each user has his or her own characteristics, an "ad hoc" tuning session is necessary before final delivery of the prosthesis. Moreover, it is often necessary to repeat the setup procedure during the lifetime of the prosthesis, due to changes in environmental conditions and wear and tear of mechanical components.

The following subsections introduce the parameters that mainly characterize the macroscopic prosthesis behavior and which will be considered in the auto-tuning procedure.

Noise ($n0$)

This value is a measurement of electromagnetic noise that is coupled to the electrodes. The macroscopic effect of this noise is an unintentional prosthesis movement; therefore, the maximum noise value is recorded, and this value is subtracted from the A/D converter output in order to eliminate such undesirable behavior. In practice, the expert operator manually sets $n0$ equal to zero, then asks the wearer to keep the residual limb muscle that drives the prosthesis motionless. The expected EMG signal should be null and, therefore, a non-null measured value has to be added to $n0$.

The MCA Auto Tuning program performs the same task: first the program user interface instructs the client to remain motionless, then the software acquires the EMG signals values and sets $n0$ equal to a proper value based on the EMG signal maximum, which is nothing other than the electromagnetic noise.

It is very important to set $n0$ equal to a proper value, otherwise the prosthesis could vibrate even if the client remains motionless, and the motion control could be difficult.

Inactivity Threshold (I)

The I parameter consists of an EMG signal threshold below which the acquired signal is not processed. Generally, owing to physiological reasons, there is a cross-influence between the muscles on which the EMG electrodes are attached and the neighboring muscles that may generate spurious EMG signals, and therefore, unwanted movements.

This spurious signal, also known as *physiology noise,* should be distinguished from noise $n0$, because the first is related to an unwanted cross-relation between neighboring muscles, while the second is related mainly to electromagnetic noise or unwanted contraction of the muscle that directly drives the prosthesis.

Usually, this spurious signal is somewhat lower than that generated by intentional muscle contraction; therefore, the solution simply consists of using signal threshold under which the signal is cut off.

In order to tune this parameter, the client is asked to move the muscles that are not attached to EMG sensors, then the MCA software computes the I value depending on the magnitude of the corresponding spurious signals. The details of this procedure, which is based on fuzzy logic, are explained in the next section.

Minimum Threshold (m)

The m parameter represents the minimum value of energy required to move the electric motor. Due to motor or system friction asymmetry, two m thresholds (opening and closing) have been used.

In other words, these parameters are an "offset" on the PWM motor control signal that compensate for the dry friction of the whole system (covering glove and mechanical resistance). Without these parameters, a considerable effort would be required by the user to effectively move the hand. These parameters are evaluated by means of a step-by-step procedure for opening and closing actions. In this procedure, the m value (e.g., the opening one) is progressively increased until the prosthesis moves. During this operation, the prosthesis works in "minimum modality," in which the user drives only the movement direction and the system calculates the *m* parameter. The MCA visual interface helps the user to set the *m* proper value through sliding bars, after informing him/her about the movements he/she has to achieve.

Maximum Threshold (*M*)

The *M* value assigns the upper power limit above which the motor gives the maximum power value. The threshold enables the user to reach the maximum prosthesis velocity even if the signal is weak. In order to calculate this value, the software acquires the user's EMG signals generated during maximum effort conditions.

Extensor Gain (*E*) and Flexor Gain (*F*)

These parameters assign the gains to be applied to extensor and flexor signals, respectively, and are used to scale out the EMG signals so that similar opening and closing actions of the prosthesis are achieved with approximately equal muscle-contraction magnitude.

In order to set these parameters, the client is asked to extend and, subsequently, to bend the prosthesis drive muscle with the same intensity. The MCA software then processes the signals acquired, using a fuzzy algorithm to increase the gain corresponding to the lower signal, to finally obtain equal behavior in the extension and flexion actions.

The Auto-Tuning System

The software package has been developed using Visual Basic 4.0 programming language for Windows 95 operating system. Visual Basic is an object-oriented programming language and an event-driven language. Other features in the graphic management enable the programmer to easily build user-friendly applications.

The system is hosted by a Personal Computer (PC). The minimal system requirements are an 80386 processor (Pentium is suggested), 4 Mbytes of memory (16 Mbytes suggested), 20 Mbytes free on the PC hard disk, with one RS232-serial port free.

The PC is connected to the prosthesis control system through the serial line. The connection has been tested for a 2-meter cable connector, which enables the subject to sit comfortably in front of the PC screen and to perform the required movements with the prosthesis.

The system is easy to use and enables the client to deal with the prosthesis setup procedure without help from an expert operator. The package is also useful to the expert technician, who can tune the prosthesis parameters in less time than it would take if it were done manually, and with evident economic advantages.

Congruity checking of the parameters is performed both after the automatic setup procedure (off-line) and during usual prosthesis working (on-line). If one or more parameters fall outside a validity range, the operator is informed that an error has occurred. The setup procedure also provides the "load default parameters" function, which allows the operator to load system memory with a default set of parameters that assures minimal prosthesis performance.

The MCA Auto Tuning software system is made up of two parts: one deals with general variables and processing routines; the second with the graphic-interface management. The general logical flow is represented in **Figure 5,** while **Figure 6** shows the interaction between program windows.

In particular, the global blocks refer to Fuzzy Logic system implementation and PC-microcontroller protocol management, respectively. The most relevant routines included in the first block are as follows: 1) **Define Membership Functions:** it allows Gaussian fuzzy sets (mean values and standard deviations) to be defined, uniformly distributed from minimum to maximum value representing linguistic variables (FLC input and output); 2) **Infer:** it implements the input/output FLC relation between input and output.

The most important routine included in the second block is **Acquire,** which carries out acquisition from microcontroller to PC. The most innovative part of the software is the one relating to Fuzzy Logic structure, which implements the Fuzzy Expert System. This expert system is called by two modules dedicated to calculating inactivity threshold *I,* and gains *E* and *F,* respectively.

Inactivity Threshold Fuzzy Logic Tuner

The Inactivity Threshold Fuzzy Logic Tuner is a single-input, single-output mapping: its input is a value resulting from spurious signal acquisition and filtering process while the output is the increment to be assigned to the parameter value.

The entity of the spurious signal and the increment are coded in the linguistic terms "very weak," "weak," "medium," "strong," and "very strong." These linguistic terms are defined using a fuzzy set with Gaussian-shaped membership functions (see **Figure 7**).

Similarly, the output variable (increment) is represented by five Gaussian fuzzy sets, which are labeled as "very small," "small," "medium," "big," and "very

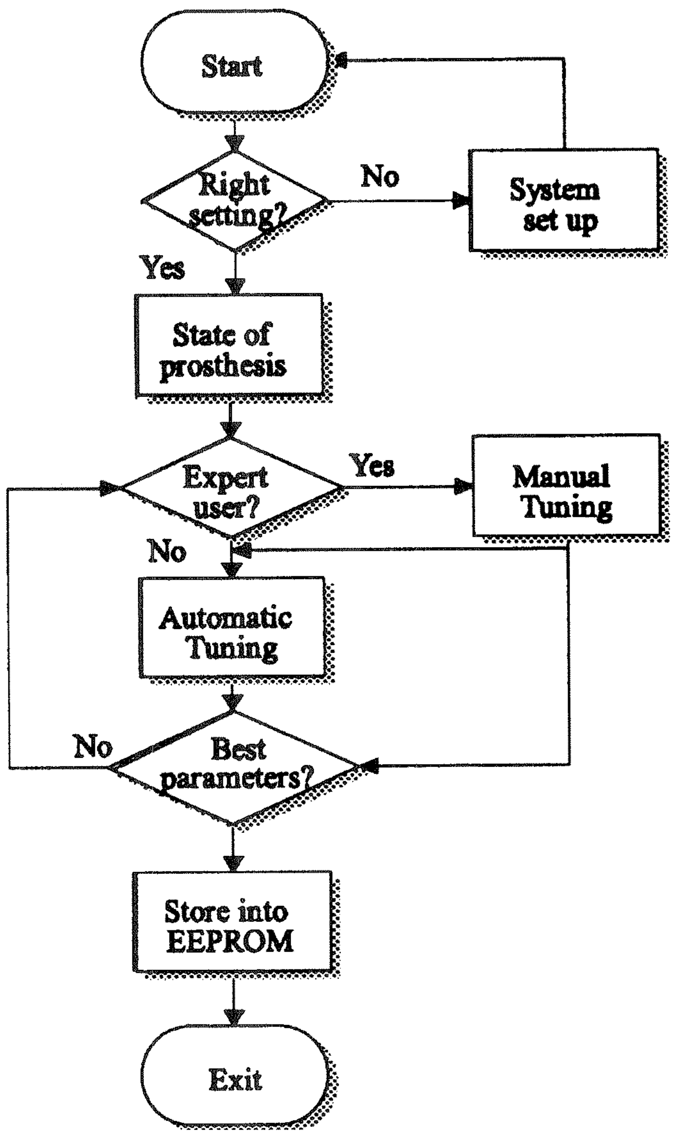

Figure 5.
MCA Auto Tuning logical flow.

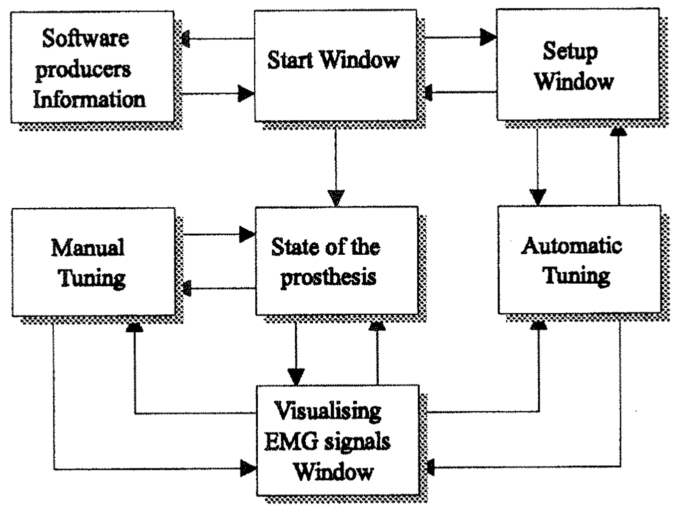

Figure 6.
The MCA Auto Tuning graphical interface windows.

big,'' respectively (see **Figure 8**). The Fuzzy Expert System is based on a set of rules that represents expert operator knowledge (**Table 1**).

Extensor Gain and Flexor Gain Fuzzy Logic Tuner

The Fuzzy Logic system implemented to tune E and F gains has two inputs, the EMG signals e and f, respectively, and one output: the increment to be assigned to the gain corresponding to lower signals so that the final signals have similar magnitudes. Every input variable was described by three fuzzy sets (**Figure 9**).

Output variable (increment) is represented by five Gaussian fuzzy sets, which are labeled as ''very small,'' ''small,'' ''medium,'' ''big,'' and ''very big,'' respectively (**Figure 10**). The set of rules that resulted from expert operator knowledge is presented in **Table 2,** while the fuzzy control mapping surface obtained is presented in **Figure 11.**

Parameter Coupling

Some of the above-described control parameters are coupled; therefore, the setup procedure has been carefully designed to minimize such interactions.

The first parameter considered in the MCA software procedure is the noise $n0$ because it is the ''free'' property (every other parameter depends on it, while it is independent of all of them). After evaluating the noise $n0$, it is possible to acquire the noise-free EMG signals and then evaluate the Minimum threshold m and Inactivity threshold I parameters. After m and I are computed, it is possible to calculate the E and F gains to equalize extensor and flexor signals. After the signal equalizing, it is then possible to acquire signals corresponding to sustained forceful contractions and then calculate the optimal Maximum threshold.

Software Testing

The testing was carried out in three different ways: by using a proper electrical circuit to simulate constant

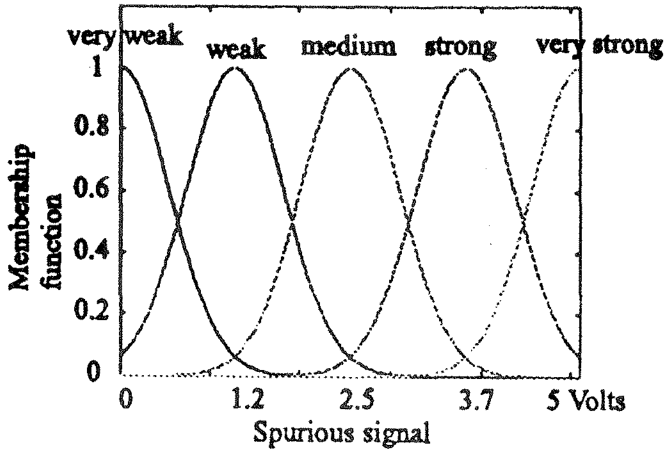

Figure 7.
Membership function degree to represent spurious signal (input variable).

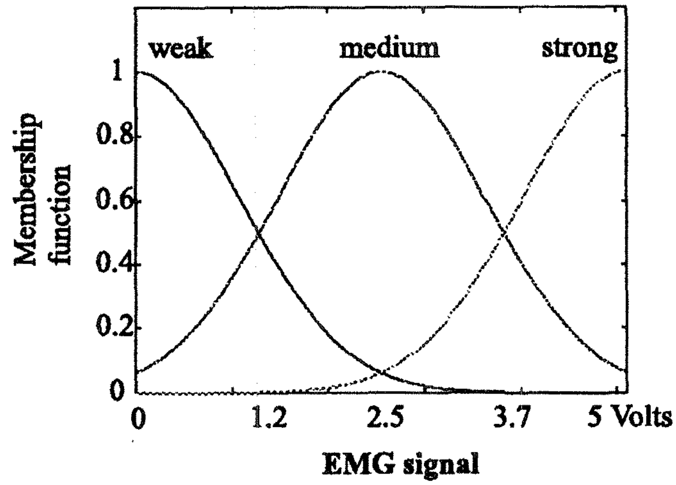

Figure 9.
Membership function degree to represent EMG signals (input variables).

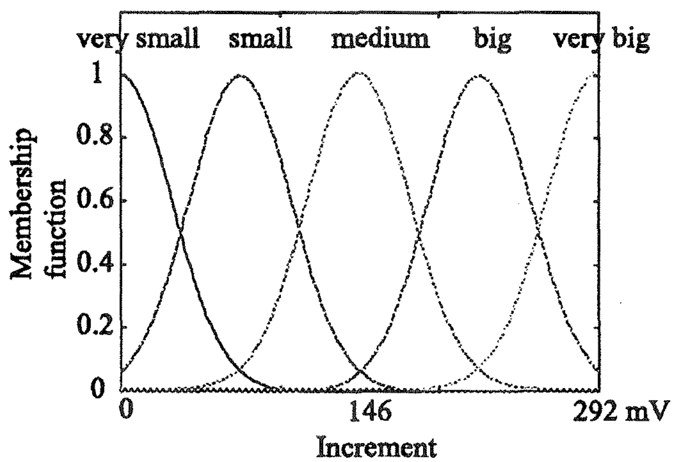

Figure 8.
Membership function degree to represent inactivity increment (output variable).

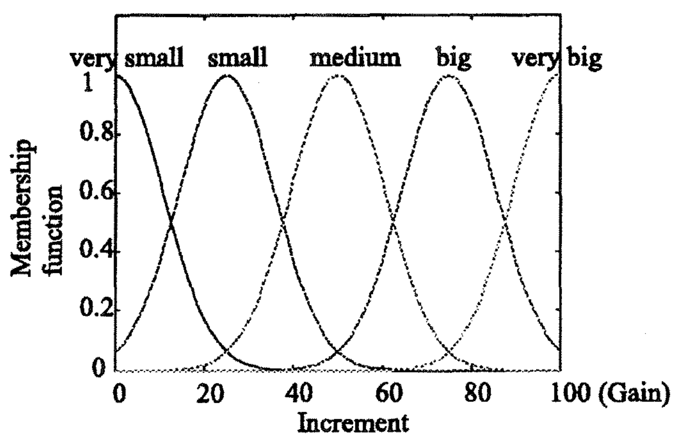

Figure 10.
Membership function degree to represent increment (output variables).

EMG signals, then placing skin-surface electrodes on an INAIL technician and, finally, by carrying out experimental trials with prosthesis users.

First, a dedicated electrical circuit was used in order to simulate constant EMG signals. The results were satisfactory except in the case of *E* and *F* gains. The incorrect behavior is evident when EMG signals are similar and very high because the expected output is zero while the real output is different from zero, as shown in **Figure 11.** Therefore, the rule database, as well as the fuzzy sets obtained by expert heuristics, was refined during experimental setup. The new system has five fuzzy terms (''very weak,'' ''weak,'' ''medium,'' ''strong,'' and ''very strong'') describing the input variables; consequently, the number of rules is increased from 9 to 25. With respect to **Table 2,** the rule database changes, as shown in **Table 3.**

This finer granularity gave good results during the software test. The new mapping surface of the fuzzy tuner is shown in **Figure 12.**

The most important experimental test was that realized by using the same electrodes that are used in the prosthesis itself. The results from a test performedon an INAIL technician are shown in **Table 4,** in which

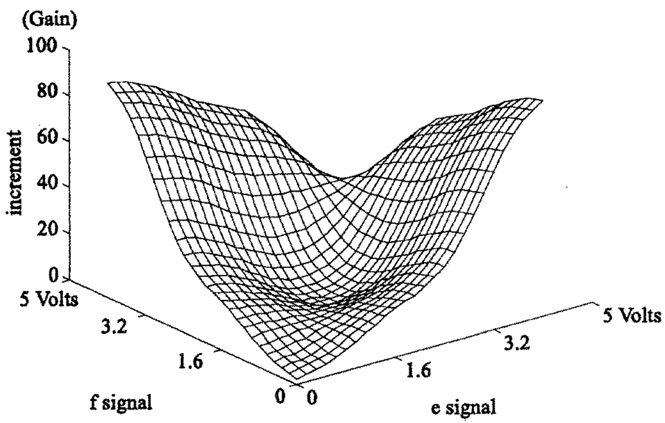

Figure 11.
Control law surface of E and F gains.

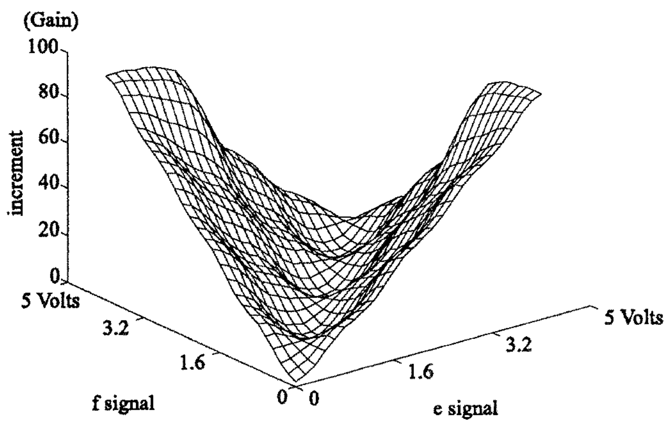

Figure 12.
Modified control law surface of E and F gains FLC.

the comparison between manual tuning and automatic tuning is shown. Differences between automatic and manual tuning are comparable with those achieved with manual tuning by different INAIL operators; therefore, these results are to be interpreted as positive performance of the system.

Further experiments on subjects are shown in the Appendix. The comprehensive results show good performance of the MCA software in the auto tuning of the prosthesis control parameters.

Table 1.
Fuzzy rule set for the inactivity Fuzzy Login Tuner.

If	Then
1. spurious signal is very weak	increment is very small
2. spurious signal is weak	increment is small
3. spurious signal is medium	increment is medium
4. spurious signal is strong	increment is big
5. spurious signal is very strong	increment is very big

CONCLUSIONS

The software package presented (MCA Auto Tuning System) is a tool that may be useful for both expert operators and persons with amputation. The expert technicians may exploit the user-friendly environment provided by the MCA software in their work, while clients are no longer required to come to the prosthesis manufacturers' laboratories for control system setup.

Moreover, the MCA software project will be carried on toward directions other than those sketched here. First, the software will enable the acquisition of a software database in which every prosthesis working condition, notably the user amputation level, will be related to ''optimal'' prosthesis control parameters. This database may be used for factory parameter initialization before performing prosthesis setup, allowing a time reduction in the tuning procedure.

Another direction of work will consist in the distribution of MCA software to all persons using tele-assistance services on data-transmission networks, in order to decrease mobility needs and assistance costs.

Although the most relevant control parameters are treated in the auto-tuning procedure, there are secondary parameters that are not considered in the MCA software. A further improvement of the project will be the extension of the automatic tuning procedure to those minor parameters.

As a final comment, one can note that the area of myoelectric prostheses, and in particular myoelectric hands, appears rather active both for new control approaches (16,17) and advanced robot interface applications (18,19). This may be very interesting in consideration of technology transfer and knowledge integration between heterogeneous research areas.

Table 2.
Fuzzy rule set for the Extensor and Flexor gains fuzzy logic tuner.

If	And	Then
1. *e* signal is weak	*f* signal is weak	increment is very small
2. *e* signal is weak	*f* signal is medium	increment is small
3. *e* signal is weak	*f* signal is strong	increment is very big
4. *e* signal is medium	*f* signal is weak	increment is small
5. *e* signal is medium	*f* signal is medium	increment is very small
6. *e* signal is medium	*f* signal is strong	increment is big
7. *e* signal is strong	*f* signal is weak	increment is very big
8. *e* signal is strong	*f* signal is medium	increment is big
9. *e* signal is strong	*f* signal is strong	increment is very small

Table 3.
Fuzzy rule set for the improved fuzzy logic tuner of the Flexor and Extensor gains.

If	And	Then
1. *e* signal is very weak	*f* signal is very weak	increment is very small
2. *e* signal is very weak	*f* signal is weak	increment is small
3. *e* signal is very weak	*f* signal is medium	increment is medium
4. *e* signal is very weak	*f* signal is strong	increment is big
5. *e* signal is very weak	*f* signal is very strong	increment is very big
6. *e* signal is weak	*f* signal is very weak	increment is medium
7. *e* signal is weak	*f* signal is weak	increment is small
8. *e* signal is weak	*f* signal is medium	increment is small
9. *e* signal is weak	*f* signal is strong	increment is medium
10. *e* signal is weak	*f* signal is very strong	increment is big
11. *e* signal is medium	*f* signal is very weak	increment is medium
12. *e* signal is medium	*f* signal is weak	increment is small
13. *e* signal is medium	*f* signal is medium	increment is very small
14. *e* signal is medium	*f* signal is strong	increment is small
15. *e* signal is medium	*f* signal is very strong	increment is very small
16. *e* signal is strong	*f* signal is very weak	increment is big
17. *e* signal is strong	*f* signal is weak	increment is medium
18. *e* signal is strong	*f* signal is medium	increment is small
19. *e* signal is strong	*f* signal is strong	increment is very small
20. *e* signal is strong	*f* signal is very strong	increment is small
21. *e* signal is very strong	*f* signal is very weak	increment is very big
22. *e* signal is very strong	*f* signal is weak	increment is big
23. *e* signal is very strong	*f* signal is medium	increment is medium
24. *e* signal is very strong	*f* signal is strong	increment is small
25. *e* signal is very strong	*f* signal is very strong	increment is very small

Table 4.
Parameter values resulting from automatic and manual tuning by using electrodes.

Parameter	Manual Tuning	Automatic Tuning
$n0$	005	014
m	100	131
I	25	20
E	100	64
F	64	86
M	120	147

APPENDIX

Experimental Results

In this section, we introduce experimental results acquired during a test session on clients at INAIL centre.

The results from the first experiment are shown in **Table A-1.** As the test was definitely the first one performed on a subject, automatic tuning was executed twice. The difference between the two automatic runs is negligible, and the absolute difference with respect to manual tuning is considered to be quite good, and close to the difference between the manual tuning by two technicians operating on the same person.

After this first experiment, some more methodical tests were performed on other INAIL centre clients. The results from those tests are shown in **Tables A-2–A-5.** The MCA system has been considered quite good in both performance and reliability.

Table A–1.
Automatic tuning and manual tuning test on subject with amputation (first case).

Parameter	Manual Tuning	Automatic Tuning 1	Automatic Tuning 2
$n0$	001	003	011
m	100	99	83
I	30	31	31
E	255	255	255
F	128	128	128
M	150	230	230

Table A–2.
Subject A.

Parameter	Manual Tuning	Automatic Tuning
$n0$	000	000
m	166	165
I	013	016
E	064	071
F	064	064
M	100	102

Age: 17. Sex: Female. Date 8/5/97. Kind of accident: Congenital malformation. Amputation level: third distal humerus.

Table A–3.
Subject B.

Parameter	Manual Tuning	Automatic Tuning
$n0$	003	005
m	166	165
I	025	031
E	064	084
F	064	064
M	130	144

Age: 15. Sex: Female. Date 8/5/97. Kind of accident: Domestic accident when aged 2. Amputation level: Transradial-third proximal. **Note:** The subject sometimes confuses the muscles she should contract to drive the prosthesis. For this reason, the I value for manual tuning is kept lower than usual, which is the one given by the automated procedure.

Table A–4.
Subject C.

Parameter	Manual Tuning	Automatic Tuning
$n0$	005	005
m	166	165
I	015	016
E	085	090
F	064	064
M	120	133

Age: 28. Sex: Male. Date 8/27/97. Kind of accident: Accident when aged 25. Amputation level: Transradial-third distal.

Table A–5.
Subject D.

Parameter	Manual Tuning	Automatic Tuning
$n0$	001	001
m	166	165
I	015	019
E	064	064
F	085	095
M	120	122

Age: N.A. Sex: Male. Date 9/8/97. Kind of accident: Accident.

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