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Rapid Prosthesis Design Based on Movement Decomposition

Ionescu Valeriu and Zafiu Adrian

Abstract—**The human body is a complex system because of the way our neural system works in both acquiring data from the exterior and providing an adequate response in real time. Because of this, the development of an artificial prosthesis that matches the behavior of the biological sensorial system, the motor capability (such as size and weight) has had only limited success and high production costs. This paper presents a novel architecture that reduces the cost and development time of prosthetic hand, improves the quality of the selected signals used for prosthetic control and insures flexibility for the implementation of future prosthetic modifications.**

Index Terms— **prosthesis design, remote access, prosthetic design system, Surface-ElectroMyographic Sensor, cost reduction, movement decomposition**

I. Introduction

The development of prosthetic hands is a complex process that in recent years took advantage of the evolution in micro-technologies and surgery, in many cases disregarding the implementation costs. In order for a solution to have industrial success, it has to combine good sensorial and behavioral characteristics with a low production cost. Also, the solution has to be easily adapted to a large number of patients. The necessity of a lower cost usually has a negative feedback effect on the number of used sensors, the quality of materials, system weight, etc.

This paper presents in the beginning an overview of several aspects regarding the prosthesis development process and outlines the areas that lead to high development costs.

Starting from the outlined aspects, a new architecture for the hand prosthesis design process is proposed afterwards that has the advantages that: reduces the cost and development time of prosthetic hands, improves the quality of the selected signals used for prosthetic control and to insure implementation flexibility for future prosthetic modifications.

II. Neural Signal Structure

Neurons employ different types of electrical signal to encode and transfer information, as responses to stimuli, such as light, sound, or heat. The use of electrical signals presents a series of problems in electrical engineering when sent over long electrical wires. Neurons have quite long axons therefore a system of action potentials (which are also called "spikes" or "impulses") is present in the nervous system that allows sending electrical signals over great distances.

The action potential of a given neuron is of type all-or-none, because it occurs fully or not at all. If the amplitude or duration of the stimulus current is increased sufficiently, multiple action potentials occur (as seen from the responses to different current intensities in Fig. 1); therefore the intensity of a stimulus is encoded in the frequency of action potentials rather than in their amplitude.

This arrangement differs from receptor potentials, whose amplitudes are proportional to the magnitude of the sensory stimulus, or synaptic potentials, that varies according to the number of synapses activated and the previous amount of synaptic activity.

The signal sources for the human hand are multiple and have a complex structure, with the following main nerves: radial (supplies the dorsal muscles to most of the back of the hand); ulnar (the only unprotected nerve that does not serve a purely sensory function, innervating muscles in the forearm and hand); median (it runs down the arm and forearm, with no motor innervations in the upper arm, and innervates most of the flexors in the forearm).

This leads to sources of "noise" (that need filtering) coming from nearby muscles that may not come only from the interference due to the thermal or electrical noise but also the presence of other neural signals. This may lead to problems in determining the positioning of biomedical sensors and the need for intramuscular (surgically implanted) sensors.

In order to control the artificial hand, the filtration stages shown in Fig. 3 are usually used, as shown in [2] [3].

The digital system that acquires data from the Surface-Electro Myographic Sensors (placed on the patient's hand) has to filter chains of impulses, in order to extract conscientious commands.

At a higher processing level in the control architecture for the prosthetic hand, due to the signal structure of action potentials encoding, the identification requires pattern recognition software (such as neural networks or fuzzy logic). The long training process of this software, previous to its hardware implementation, is essential.

The filtration stages range from low-level (hardware) to high-level (software):

- To increase the signal-to-noise ratio of the efferent neural signals recorded. The use of specific algorithms ("blind deconvolution" algorithms, cross-time-frequency representations, or principal component analysis) is necessary in order to decompose the neural signals eliminating the noise components;

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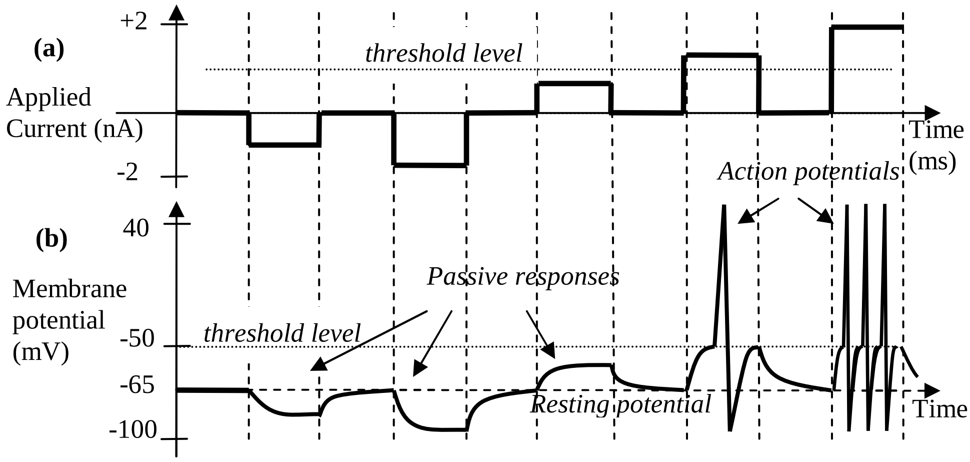

Fig. 1 The intensity of a stimulus (a) is encoded in the frequency of action potentials (b) only if a threshold level is crossed [1]

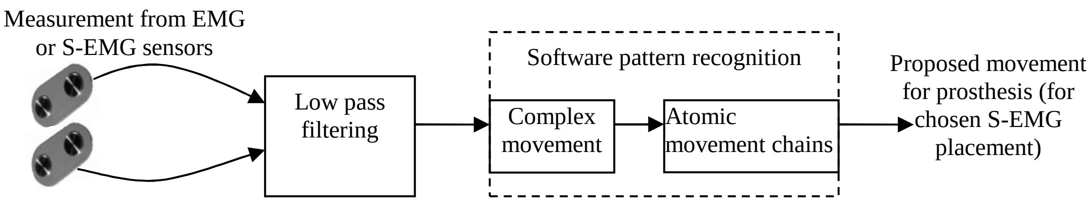

Fig. 2 System architecture for task discrimination

- A system for the extraction of different time and frequency parameters ("neural features") from the neural signals, used for the pattern recognition;

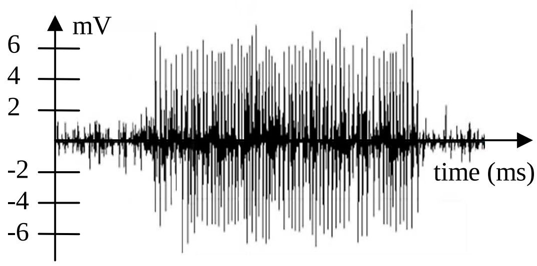

Fig. 3 Signal used for testing the filtering and discrimination techniques

- A software system for the discrimination of the task desired (based on neural networks or fuzzy) that should identify and compose an anatomically correct action for the hand.

As a final consideration, all commands given by the nervous system give feedback from multiple sources such as muscle status feedback or peripheral skin sensors. This mechanism may be implemented in the prosthetic design by using feedback sensors (with a certain increase in overall cost) or by software limiting the movement of the prosthetic hand to an anatomically correct movement sequence.

III. System Architecture

Based on the previous analysis, the systems architecture presented in this paper allows the patient (though the use of computer software and a data acquisition system needing the supervision of only a medical technician) to send the data to a remote processing location in similar fashion to a telemedicine system architecture [4], [5]. This allows local centers (or even mobile medical assistants) to interact with the patients, whereas the data will be processed and supervised by qualified specialist doctors in a central location.

This will also allow the development of a limited number of high performance/qualified supervising centre, instead of multiple local centers with lower quality equipment (thus reducing development and implementation costs), insuring data centralization (different cases can be easily compared and studied in parallel) and the reduction of costs for the patients for accessing high performance medical facilities through the use of internet connections.

This is an original architecture, as no other similar architectures have been proposed for this design area.

A general view of the proposed system architecture is presented in the Fig. 4.

The architecture has two major components: server side and client side:

The client side: Its role is to read the biosensor data, to transmit it to the server through internet and display a graphical representation of the interpreted data received from the sensors. Its components are:

1. Biosensor data acquisition board for reading the data from the sensors and transmitting it to the client computer that will interpret it and relay it to the server. In order to improve the connectivity and to ensure a future-proof solution, a PIC-MAXI TCP-IP development board was used. The biosensor choice will be presented further in the paper.

2. Graphical interface tool that allows the patient to see the feedback of his actions [6].

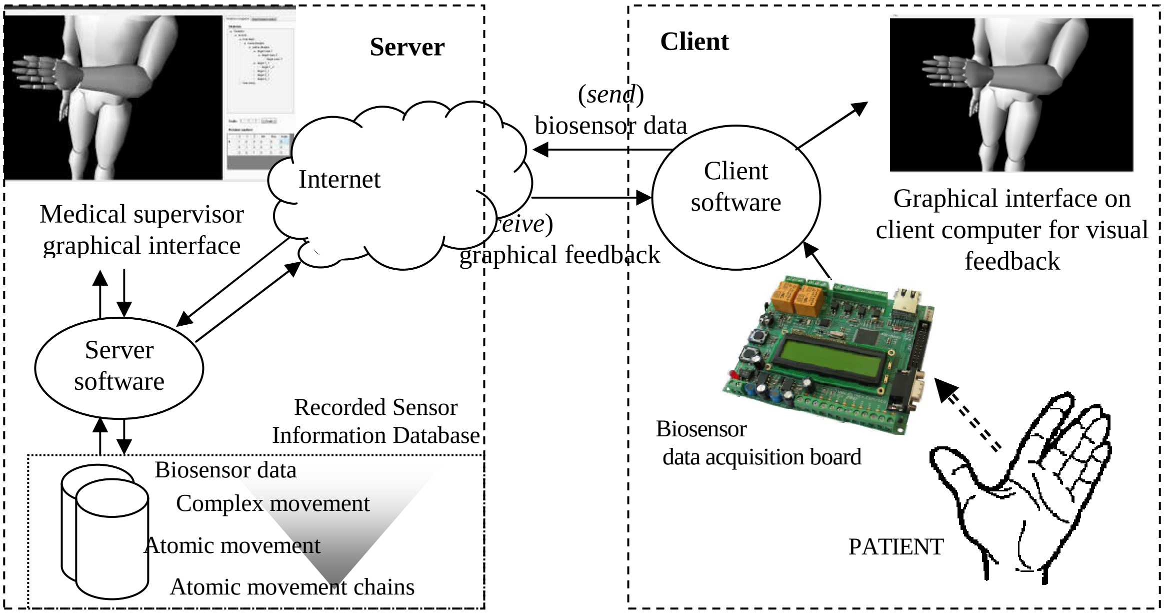

Fig. 4 The architecture of the telemedicine system for prosthetic design

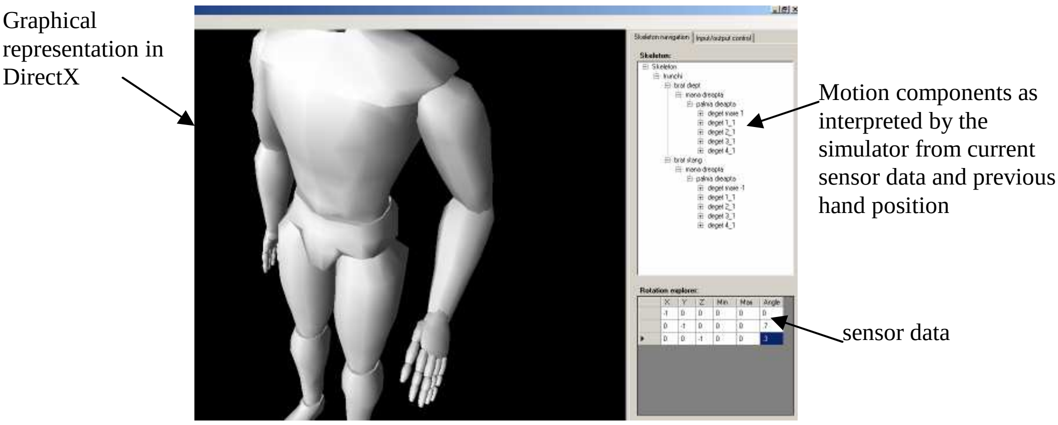

Fig. 5. Graphical User Interface allows visual feedback for the patient and doctor

The constraints for this implementation were that the hardware requirements on the client computer must not be excessive and the response should be adequate (real-time).Because real-time games have proven that real time communication is easy to implement with little bandwidth requirements the first implementations OpenGL and DirectX were early implementations but for faster development Microsoft XNA Game Studio was later used. The DirectX implementation of the user interface is presented in Figure 5.

The client interface also offers an interface for data submission as part of the initial EMG (Electro Myographic) tests. This interface allows the medical technician to select the muscles tested, in order to provide to the server database the information necessary to catalogue the sequence of tests.

3. Client network communication interface with two components: one that allows sending data collected from the acquisition board to the remote server for processing and simulation, and the other allowing the reception of the simulation results and their display on the local host.

The server side: it has the complex role of reading biosensor data from the client application while keeping track of multiple simultaneous communications; simulating prosthesis behavior based on the actuator data (stored in a database); generating the graphical data for the simulation running at the client side; and offering a user graphical interface for the doctor in order to monitor the simulation process and intervene if it is necessary. Its components are:

1. Server network communication interface is more complex then the client's interface. The interface is able to receive the biosensor data and keep track of multiple simultaneous communications. A limit of the number of simultaneous communications may be necessary as this may vary according to the server's simulation power (a larger value impacts the transmission latency as the server will provide data slower as it will have to perform multiple simultaneous simulations).

2. Medical supervisor graphical interface: allows the doctor to monitor the pattern recognition process performed by the server. The doctor offers a supervisory role: if it is necessary (for example certain signals during Electro Myographic tests have a low SNR ratio), the doctor can select a series of tests that should be redone by the remote medical technician. This allows the doctor to analyze data from several tests in less time.

3. Recorded Sensor Information Database is the final and the most important component that contains sequences of EMG data recorded from the patient and the chains of atomic

movements resulted from the analysis of this data. A pattern recognition algorithm selects the most likely zones for the placement of Surface EMG sensors.

Using Surface-Electro Myographic (S-EMG) Sensors ensures flexibility and their placement can be determined by a software application. For a certain position of the sensors, a single sequence of atomic movements (combining different properties of the measured EMG data) determines a movement of the prosthesis. If the placement of the S-EMG sensors is changed a different sequence of atomic movements may be selected for prosthesis command by the software.

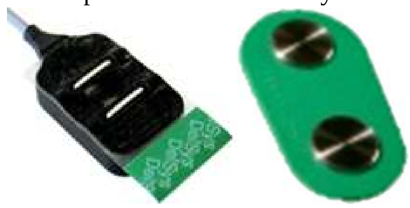

Fig. 6 Surface-Electro Myographic Sensors [7]

Surface EMG sensors have proven to be nearly as reliable as intramuscular EMG when an adaptive neuro-fuzzy inference system or neural network (when used in combination with the auto-regressive parameters [8]) is used for neural task discrimination. The accuracy of the training results ranges for SEMGs from 86% to 96%.

Surface EMG sensors are also preferred because if the patient does not handle well the prosthesis after the training period (necessary for the patient to get used to the prosthetic) the training process can be redone considering the new data with no extra costs for the patient (a surgical intervention is not necessary).

This is a sensitive part of the system as the algorithm used should identify the best movement data for a specific prosthetic.

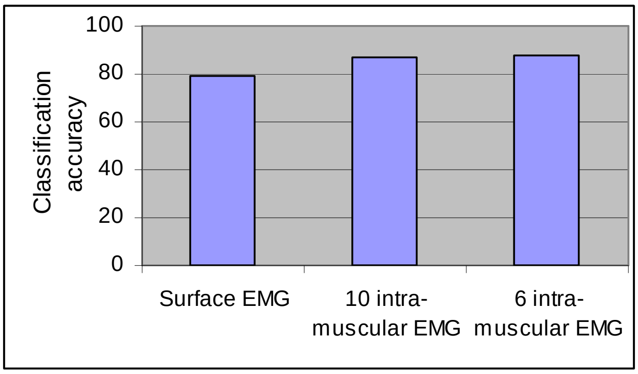

Fig. 7. Comparison of classification accuracies based on the surface EMG and intramuscular EMG [8]

The architecture's workflow is presented in the figure 8.

The first stage is the analysis of the signals of the hand performed by medical technician at the patient's computer.

The acquired data is sent asynchronously to the remote data server for analysis/processing.

The simulation results are downloaded in the prosthesis system and the patient can start the training using the local graphical interface.

If the training does not lead to optimal results, patient data can be re-sent and re-tested. All training data is monitored for future software improvement.

As seen in the architecture's workflow, the first stage is the analysis of the signals of the hand performed by medical technician. Because of the differences in the human hand structure from person to person, the analysis is a rather long process (up to six hours or more depending on the number of nerves/muscles tested) that implies the following tests [1] [9]:

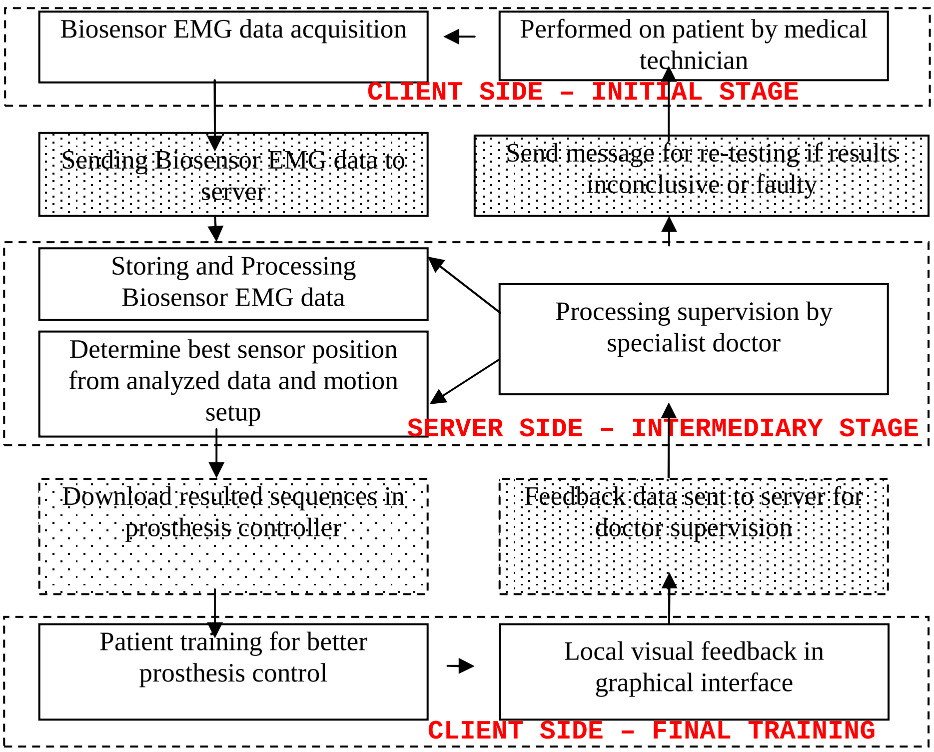

Fig. 8 The workflow of the proposed architecture

Nerve conduction studies: small electrical pulses are given to the nerves that go over the muscles through small electrodes. The nerve is then stimulated with that will activate the muscle. The time it takes for the stimulus to reach the muscle (called the conduction velocity) is recorded on a machine. The common nerves tested are the median nerve and the ulnar nerve, and the test takes from 15 minutes and one hour. The results obtained from these tests are useful but cannot be used alone as basis for the prosthesis movement (an electroneurogram (ENG) has problems with SNR, dimensions, and drifts [3]).

Electro Myography tests: uses two electrodes, one placed on the skin near the muscle to be analyzed and the second is pushed into the muscle to be tested, and measures the muscle activity. It takes a long time ranging from 45 minutes up to 2 hours. The patient has to recover after these tests as infections may appear due to the insertion in the muscle of the second electrode.

These tests are important as the recorded data constitutes the basis for the analysis that will determine the sequence of signals that the patient can control most easily in a reliable way. In a hospital, the training requires the presence of both a doctor and a technician; however most of the actual testing is performed by the technician and does not require the presence of a doctor, especially if the data will not be needed for sensor implant surgery.

In our proposed architecture the doctor can access the data downloaded in the server by the client software remotely through the use of a graphical interface, thus allowing him to analyze a greater number of patients from a single access point in the normal working hours (even if the patient is in a different time zone).

Regarding the structure of the database, it is necessary to note that in order for a robotic prosthetic limb to function several components must be designed for the patient's body:

- Biosensors that detect signals from the nervous or muscular systems;
- Sensors that provide feedback for the prosthesis movement (ex. force meters and accelerometers);
- An actuator that performs the actions of a muscle in producing force and movement;
- A controller that gathers data from the biosensors and sends the commands from the patient's body to the actuators of the device. The controller must correctly identify the feedback from the mechanical and biosensors to the user. This is essential for the intelligent prosthesis and must be the result of a good training process.

The architecture presented uses a high-end server to analyze the biosensor data and identify, by using a software simulator – based on a large database of pre-existing samples – the best function for the controller in order to give the correct actuator response. The server performing the data analysis/simulation will communicate with the client computer through the internet.

The natural movements of a limb (be it hand or leg) are formed of base actions (movements) described by chains of commands that must be given to each element that composes the prosthesis.

The database creation, based on movement decomposition, is performed as follows:

1. the complex movement of a limb is recorded;
2. the complex movement is broken into atomic parts that target each of the device's actuators;
3. the variation of the parameter (or parameters if there are elements with more freedom degrees) is determined;
4. the parameter variation is correlated in time in order to obtain an atomic movement;
5. the number of atomic movements found must be minimized in relation to the maximization of the number of complex movements resulting from the combination of atomic movements. Therefore the atomic movements that produce the maximum number of complex movement chains must be selected;
6. the resolution of the biosensor system is identified according to the patient's possibilities;
7. several complex atomic movement chains (the resulted complex movement) are chosen – the criteria is that the movement must be easily controlled consciously by the patient;
8. the final relation is made between the resulted complex movement combinations and the biosensor data by attributing movement combinations to specific sensor patterns;

The scope of the two coding levels: "biosensors → complex movement" and "complex movement → atomic movements" is to extend the coverage area of the control and command system: minimize the number of sensors needed to determine a complex movement and reduce the implementation costs by reusing a large number of atomic movements.

On the other hand modular implementation of the logic integrated in the robotic prosthetic leads to a higher degree of adaptability and further reduced training costs. The system is therefore transformed in a general framework for designing intelligent prosthesis.

IV. Implementation Results

Currently the system is implemented at experimental stage, with accent on the development of the graphical interface and the data acquisition and processing components.

During the testing, several aspects were observed regarding the synchronization between the biosensor data, simulation data and the graphical feedback read from the server when tests were performed in high latency networks. In this regard the variations in network latency had a negative effect on transmission quality and also on the visual feedback. Timestamps were included with the simulation packages in order to reconstitute the simulation data correctly at the server side. TCP protocol was used for data transmission as packet loss for the application is not acceptable. The initial nerve conduction studies and Electro Myographic tests were not affected as they do not require real time transmission.

The biggest drawback in automatic prosthetic design is the creation of a valid system of extracting the conscientious actions that a patient makes in order to control the prosthesis. If the starting data is not valid the simulation/training will not have optimal results. If, however, the system is correctly identified, it can be directed to perform a range as wide as possible of the patient's needs. Therefore the specialist's doctor's data analysis is compulsory.

A positive aspect of the approach presented in this paper is that the system has a high degree of adaptability. Its functionality can be adjusted and extended by modifying the software, still keeping track of limits of the hardware implementation. In time, as the patient gets used with the prosthetics, the resolution of the commands given will increase therefore the control on the values send to the device will improve. Accordingly, new complex movements can be then introduced, or present movements can be further refined.

At present the system implemented does not use authentication and the data sent is not encrypted therefore the load influence was not analyzed on the client computer or on the server – a further module for encryption and authentication may be necessary in the proposed architecture between the client and the server applications in order to prevent attacks with similarly structured packages [10].

V. CONCLUSIONS

This paper presented an original architecture of a telemedicine system that helps the design of robotic prosthetic limbs and patient training, helped by a graphical interface.

Prosthesis design is a complex process that takes a long time and implies many additional costs especially for the patient. The process can be simplified by designing a mobile hardware module able to acquire data from the patient's location and transfer it to a specialized medical center for processing and prosthesis design. The software installed on the patient's computer can handle data transmission through internet to the medical server and the local graphical representation of the prosthesis movement for patient training monitoring. The software in the specialized medical center handles the data received from the patient by storing it in a recorded movement database and performs software pattern recognition and data simulation for identifying patient's actions and designing the software that will be embedded in the patient's prosthetic. Data transmission from patient to server is performed in asynchronous mode in order to allow its analysis in convenient working hours for the doctor even if the patient is in a different time zone. The proposed solution, by using an architecture specific to telemedicine for the design process, helps to reduce design costs by:

-eliminating movement costs for patient and the lost time due to patient processing in a specialized medical center;

-cutting the costs for the development of local centers for patient processing by removing the need to install dedicated professional equipment and training specialist doctors to work in these centers;

-increases the number of cases a doctor can analyze by using computer to present the signals acquisitioned from the patient and by proposing a sensor implementation pattern as a result of computer simulation.

-allows patient training at home with the possibility of sending the training data to a medical center for remote monitoring.

-the implementation of the mobile unit available to the patient is light and simple medical technicians can be trained to install the software, to execute the initial Electro-Myography tests and to apply the surface biosensors to the patient for correct signal acquisition.

- the server system/software can be improved regardless to the client system/software as long as the exchanged data package structure remains the same.

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