Control System for Locomotory Prosthesis Configuration

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***Abstract*—** The current paper describes a control system designed for configuration of the locomotory prosthesis. The modeling and control system, which is the main subject of this paper, is designed to model, configure and control the intelligent prosthesis in absence of a patient, for research, developing or testing purposes. It offers a valuable help in determining the prosthesis' movements precision and reproducibility along with their conformity to the software modeled movements. It generates low level electrical signals, similar with the myoelectrical ones, which allow prosthesis tests and configurations to be made in laboratory conditions. The system has been tested on a simple active leg-prosthesis prototype and the results are presented.

***Keywords*—** Intelligent Prosthesis, Laboratory tests, Virtual Environment, Software Testing, Software Aided Design, Prosthesis Simulation, Myosignals, Systems configuration.

I. INTRODUCTION

Increased efforts to address the problems associated with unexploded land mines in some parts of the world have focused attention on the field of prosthetics and orthopedics.

Greater consciousness about amputee quality of life has also promoted research efforts to develop a new generation of products [1].

Some of the technology being explored for use in advanced prosthesis designs is being drawn from disciplines outside of conventional orthopedics and prosthetics development.

Intelligent prosthesis consists in complex systems designed to interact both with the patient and with the physical environment in a way that reproduce normal human movements [2].

II. MODELING, DESIGN AND CONFIGURATION ISSUES

The intelligent prosthesis' design emphasizes various problems that has to be solved in order to get both reliable and performance oriented solutions [3].

Restoring the functions of a taken off human limb is a difficult task, and most arms or legs prosthesis are able to perform only the simplest functions of the missing natural limbs [4].

However, it is expected that the technological progress shows its effects also in this area, assuring a breaking through these limitations and the improvement of the intelligent prosthesis, so that all the patients demands are fulfilled [5].

The research endeavors in the development of prosthesis take into consideration firstly its performance (including hardware and software points of view) and secondly, the prosthesis's true behavior both to the patient's straight commands (either through bio-signals, remote control or direct interplay) or indirect commands (e.g. the human walk's style and dynamic [2]) and to the environment's such commands (throughout sensors or resistance).

In the testing phase of intelligent prosthesis design, in order to reproduce the behavior of human arms or legs, it is important to test the prosthesis using complex command signal sets, similar with myoelectric biosignals. This is the main purpose of the system presented in this paper.

III. THE MODELING AND CONTROL SYSTEM

The modeling and control system, which is the main subject of this paper, is designed to model, configure and control the intelligent prosthesis in absence of a patient, for research, developing or testing purposes. It offers a valuable help in determining the prosthesis' movements precision and reproducibility along with their conformity to the software modeled movements.

The system, presented in Fig.1, consists of a Software component and specific interfaces to convert software data to human-like electric signals.

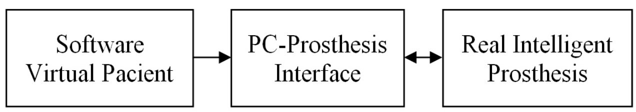


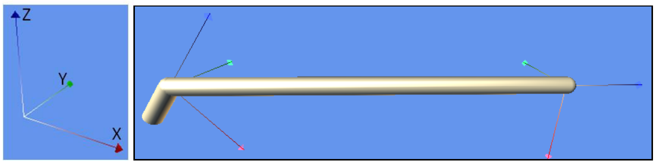
Fig.1 The modeling and control system diagram

The system allows a comparison between the real and simulated behaviours of the prostheses, aiming at solving the problems of the real prosthesis. The tests start only in a virtual environment, and, when the virtual prosthesis is free of errors, a real prosthesis is designed and its behaviour is compared to the behaviour of the virtual model.

The system allows connections to other additional programs, each of them covering a different aspect of limb simulation. For example, it is possible to analyze prosthesis according to the patient’s gender, age, height and weight.

A. Virtual Patient Software

Virtual patient/prosthesis application includes a graphic 3D module used for skeleton and humanoid representation. To reduce the quantity of graphical represented information without functionality regression the coordinate system associated to each bone is represented in a different color, like in the figure below.



a) b)

Fig.2 (a) Coordinate system's color convention;
(b) Bone representation.

Each bone is graphically represented starting from its parent bone coordinate system. The bone definition includes length and rotations with specified rotation angles around X, Y and Z axes of parent bone. The bone contains a new coordinate system is computed from started system. To reduce the graphical information but keep the functionality, each axis of the coordinate system is represented in different color.

The new system is translated with the bone length along Z axis and then rotated with specified angles around corresponding axes in order Y-rotation, X-rotation and Z-rotation (Yaw → Roll → Pitch).

The software contains:

- a graphic 3D engine;
- an interactive system between the user and the graphic elements;
- a module for virtual prosthesis parameters administration;
- a module synchronizing the graphic scene components according to each new value of the prosthesis parameters;
- a set of functions for environment settings and design.

The software simulator for human body parts is an interactive open base for prosthesis design.

The 3D engine graphically shows a virtual prosthesis. We adopt two solutions for the engine:

- a powerful engine under DIRECTX [4, 5] creating a high quality scene;
- a less powerful engine, using VRML [1], enabling online tests.

The engine works under a WEB browser and it is accessible over the internet.

The software offer posibbilties to design and simulation of a prosthesis control system and a movement system in accordance with all the facilities of the prosthesis and with the patient's assets.

The designed system comprises:

- a virtual environment. It allows generating, configuring and modifying different work environments for the testing of the prosthesis;
- a module allowing virtual prosthesis description. The users can create different prosthetic architectures according to the patient's disability.
- a module allowing real prosthesis specifications. The module is necessary because the virtual prosthesis must have a behavior identical to the behavior of a real prosthesis, under the same simulated conditions (on different external stimulations). The virtual environment allows the connection to an external hardware which reads a set of virtual sensors corresponding to real sensors.
- a command module sending signals to a set of devices used in the movements of a real prosthesis, as a response to different kinds of external stimuli. The module works in real time and performs a continuous monitoring of the parameter states.
- a module implementing the control logic, usually by means of a software specification.
- a module for synchronizing and coordinating the evolution of the environment components.

B. Humanoid and Prosthesis Part Description

In the figure below is shown the control used for bone definition. Each bone can be either a human bone or an equivalent bone used in prosthesis design.

First option is a control used for bone name. Each bone has length, start geometry and end geometry. Each of these consists in two radiuses (one for X-axis and one for Y-axis).

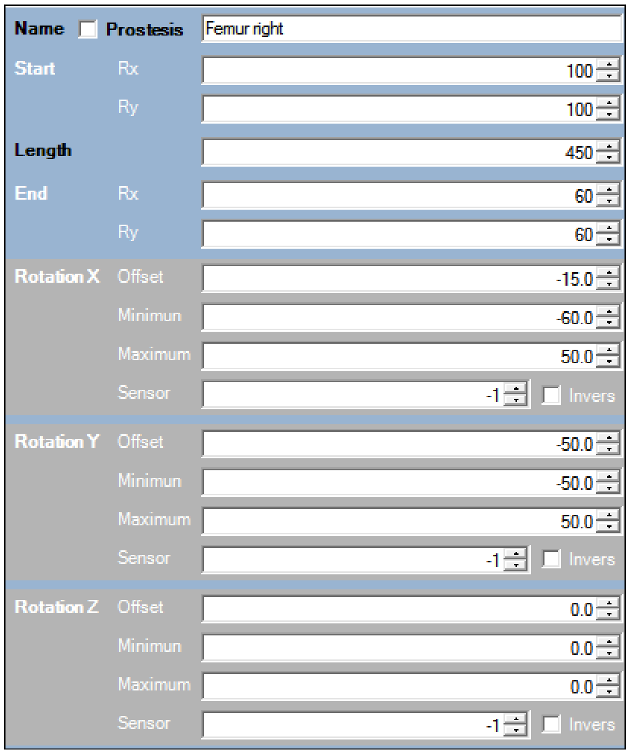


Fig.3 Bone definition

The rotation angle is limited between a minimal value and a maximal value. Also, the limits are used to compute output values.

The association between a degree of freedom and a sensor value is modeled using a value differed by -1 in the "Sensor" field. The used sensor value can be normal (as is) or like binary complement (0 becomes 1 and 1 becomes 0). All these settings are grouped under the “Bone editor” control, presented in Fig.3.

The important advantage of this approach is high definition granularity, enough to create a correct skeleton for each patient, even if there are some asymmetries or bone deformation.

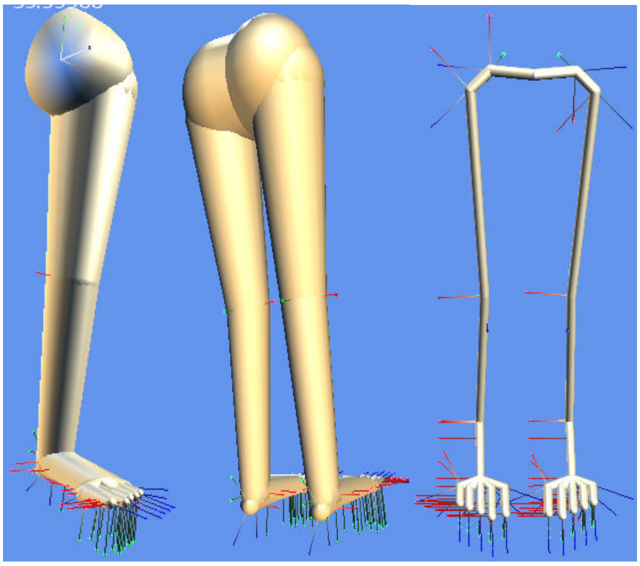
The entire skeleton that can be easily adapted to particular situation.

The application allows a very good skeleton representation. The “start” and “end” bone geometry are very useful because the final representation follows the human proportion.

C. *Humanoid Representation*

In our application we create a start skeleton that can be easily adapted to particular situation.

Our efforts concerns legs representation, but we define all the body. A full representation gives us and to the patient a global image of the future body. Fig.4 contains different leg representation.



a) b) c)

Fig.4 3D models of the leg and skeleton:
a) left leg, b) both legs, c) skeleton

Also, the software is able to represent an amputated limb and associated prosthesis, as a replacement of a full limb. The prosthesis – adapter system, as an “artificial bone” which replaces the mising part of the bone, has an adequate (software adjustable) length, in order to restore the limb functionality.

The humanoid representation data is stored in an XML file. Each bone has a node with a parent bone and a set of child bones (Fig.5).

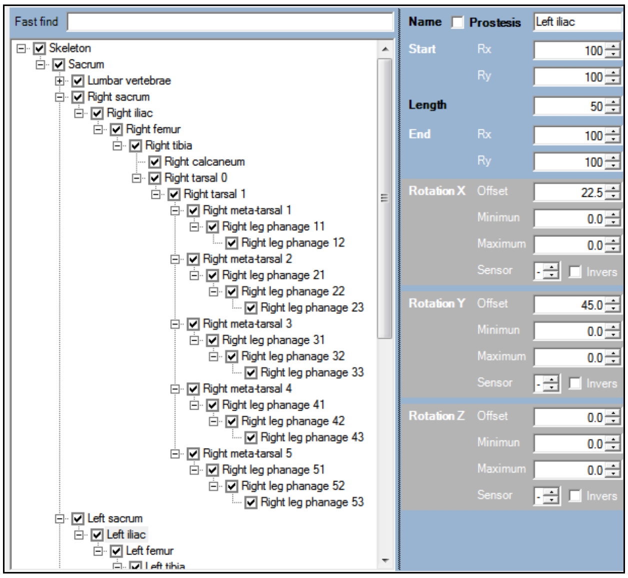


Fig.5 Humanoid representation

D. *Setting articulation limits*

Each articulation is augmented with inferior and superior rotation limit and with a sensor identifier. Each sensor is identified in virtual prosthesis using a unique associated identification number. A sensor identifier can be used for many articulations to create complex movements.

Virtual sensors simulate the interaction between the elements of the prosthesis. Such sensors detect collisions between the elements of the prosthesis and block illegal movements. The sensors are supposed to be hardware implemented and send values to the control module.

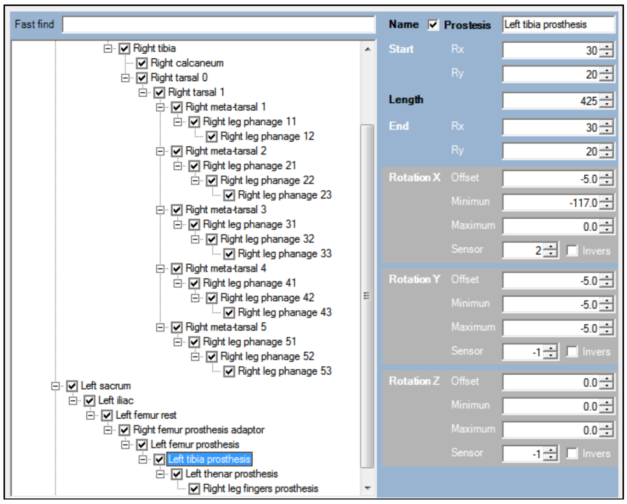


Fig.6 Settings for prosthesis’ articulation parts.

The virtual sensors also simulate the interactions between the prosthesis and the environment. This type of sensors comprise two categories: the real sensors model (like the pressure sensors placed on the compression part) and events from the real world (collision sensors that overload the simulated engines effects and do not allow illegal movements)

These sensors capture the new prosthesis parameters as a result of the interaction between the user and the 3D engine, and manage the collision tests.

The process of movement learning uses these sensors to create databases with movement sequences correlated with a time scale. The sensors are used in the validation process of the movement equations.

E. The PC-Prosthesis Interfaces

These interfaces are designed to convert bones positions data, from virtual patient, to human-like electric myosignals, which are able to control the movements of an active intelligent prosthesis.

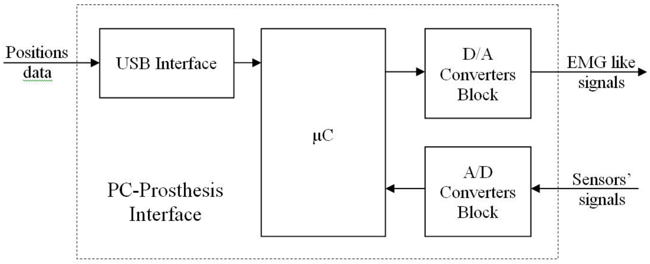


Fig.7 PC-Prosthesis interface block diagram

The block diagram of a generic PC-Prosthesis interface is presented in Fig.7. The microcontroller (µC) receives positions data from PC (generated by Virtual patient software) and send computed values to the prosthesis via a set of digital-analog converters block.

In Fig.8 is presented a myo-like signal, generated in this block, designed for knee motor actuation.

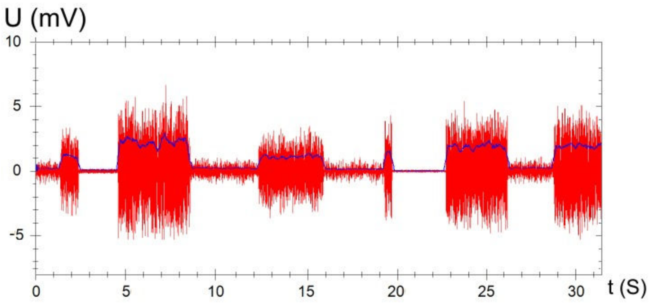


Fig.8 A myo-like electrical signal

A control myo-signal can be related to each of the prosthesis's degree of freedom. Doing like this, complex sequences can be achieved (like simultaneous modifications of multiple articulations), each of which having a certain weight (e.g.: 30% knee, 12% ankle etc.).

There are some prostheses and configurations for which a single signal can be used for achieving complex movements in-between the minimum and maximum limits. Furthermore, complex movements can be concatenated, such as the human walk can be processed either slowly or quickly, depending on the signal's intensity.

The feed-back (optional) is received from prosthesis's sensors through the analog-digital converters block. The acquired sensors' signals are digitally translated into domain [0...1].

For the simple prosthesis tested in this work, the sensors were configured to have the reference value corresponding to a digital offset of 0.5. The minimum sensor value corresponds to digital 0 and maximum to 1. This configuration is useful for the particular case of this prosthesis design and prevents the µC to work with negative values.

Additionally, in the µC there are implemented some auto-calibration facilities which permit to translate to the best reference the values given by sensors' signals, correcting some errors and adaptation to some specific conditions.

IV. The Synchronization Module

The middleware of the system is represented by the synchronization module. It interconnects all other modules. The entire real prosthesis or only parts of it are connected to the system, by using a hardware interface.

For testing, we use a kit of Velleman K8000 [7] connected to parallel port. The kit has 16 digital IO, 8 analog outputs and 4 analog inputs. The prosthesis model is implemented by using the virtual prosthesis editor.

The system synchronizes the real and the virtual prosthesis. Any adjustment of virtual prosthesis is transmitted to the real prosthesis and vice versa.

The movements of the real prosthesis are detected by the system and transmitted automatically to the prosthesis model which computes the new attributes of the model. The synchronization module sends new attributes as parameters to the graphics engine which repaints the graphic scene according to the real model.

Similarly, the interaction between the operator and the graphics engine triggers the modification of the scene, the synchronization module sends the new parameters of the virtual prosthesis to the model, the model computes appropriate commands that are transmitted by using the synchronization module and the hardware interface modifies the parameters of the real prosthesis.

Thus, all the time, the real prosthesis and the virtual prosthesis are in the same state.

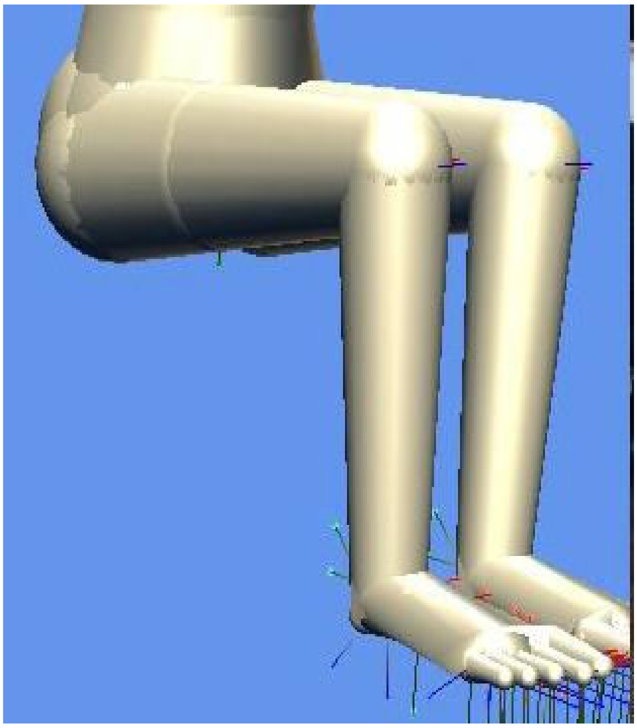
The system allows the storage of a set of movement sequences received from the real or the virtual prosthesis. This set of sequences can be transmitted to the real prosthesis, or to the virtual prosthesis, or to both, at the same time, at any time.

V. Evaluation and Tests

For the simple prosthesis we made some tests related to the movements' conformity with Virtual patient model and also on the auto-calibration facility of the PC-Prosthesis Interface.

In figure 9 are presented the testing results obtain for real prosthesis and virtual prosthesis.

(a)



(b)

(c)

Fig 9. The virtual prosthesis and the real prosthesis
(a) Human legs b) Virtual legs c) Test prosthesis

The simple prosthesis was connected to the modeling and control system and was tested to follow positions applied to the virtual model (Fig.10).

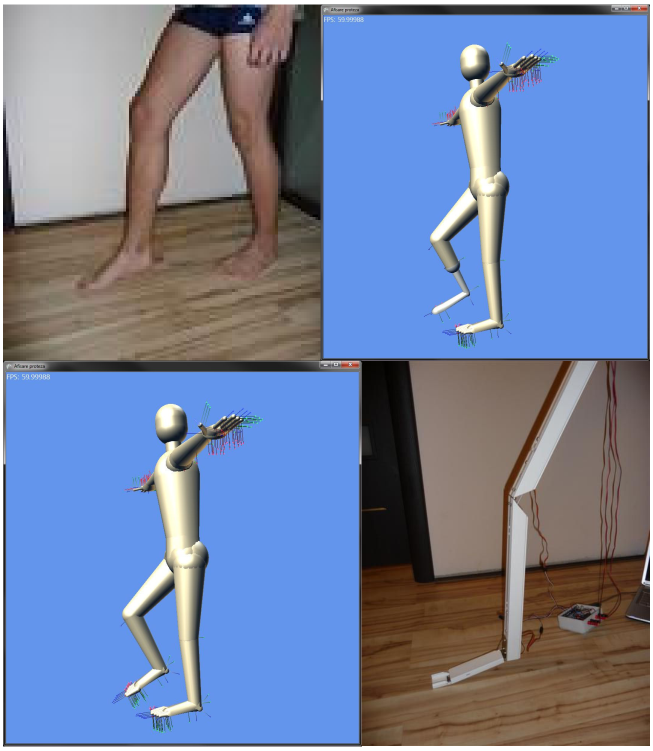
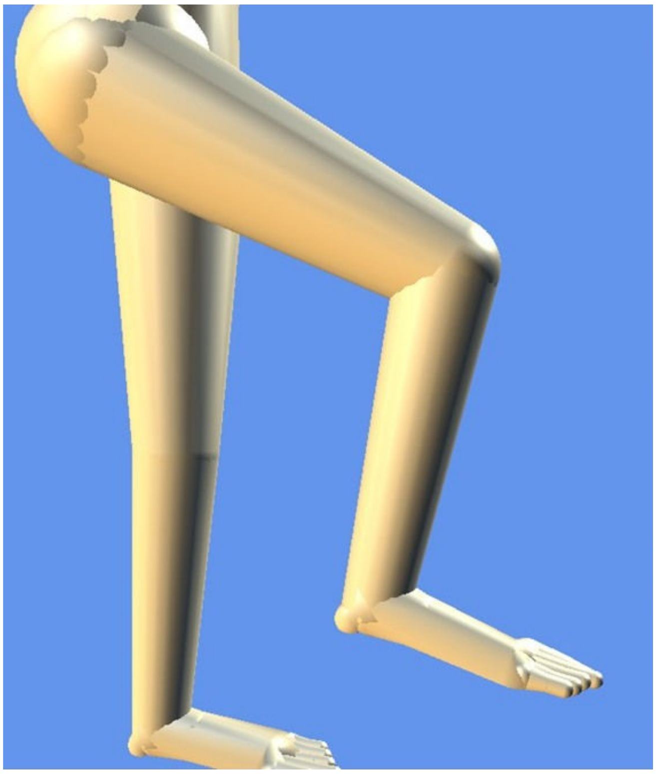


Fig. 10 Others results obtain with the real prosthesis



(a)

(b)

Fig.11 The virtual model (a) and the simple prosthesis (b) under the position tracking test

(a)

(b)

Fig.12 A human leg movement (a) and the simple prosthesis one (b) under the position tracking test

The simple prosthesis was proved to be able to follow the positions changes applied to the model.

A. Auto-calibration test

Let's assume the aforementioned example for the sensors' signal calibration, based on the simple prosthesis presented figure 10. Following the tests, Table 1 below contains the articulation's position before and after the auto-calibration.

Based on data inside the table 1, a subsequent graphical representation of the auto-calibration tests is presented in figure 10.

Table 1

Input[V]	**1.17**	**1.43**	**1.64**	**1.91**	**2.21**	**2.42**	**2.66**	**2.86**	**3.06**
Before (1.01V .. 3.38V)									
Normalized[%]	7%	18%	27%	38%	51%	59%	70%	78%	86%
Position[deg]	**-101**	**-77.3**	**-57.4**	**-31.9**	**-4.93**	**-4.05**	**-3.03**	**-2.19**	**-1.22**
After (0.82V .. 3.45V)									
Normalized[%]	13%	23%	31%	41%	53%	61%	70%	78%	85%
Position[deg]	**-87.1**	**-65.0**	**-47.1**	**-24.1**	**-4.71**	**-3.91**	**-3.00**	**-2.24**	**-1.36**
Shift (After-Before)									
Normalized[%]	6.6%	5.5%	4.6%	3.5%	2.2%	1.3%	0.3%	-0.5%	-1.3%
Position shift[deg]	**14.6**	**12.2**	**10.2**	**7.77**	**0.22**	**0.13**	**0.03**	**-0.04**	**-0.14**

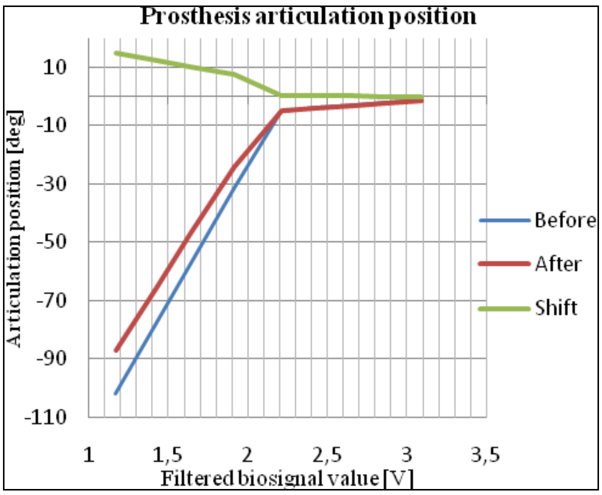


Fig. 11 Auto calibration effect over prosthesis articulation position

VI. Methods used for Prosthesis Implementation

The conception of the prosthesis is modular in order to allow the continuous development of the application scale and the hardware structure, through the possibility of developing and implementing new interfaces and programs depending on the environment in which it will actuate and the missions that it will have to accomplish. Therewith it is possible for the prosthesis to be delivered in different variants and at prices which increase depending on the abilities the user will ask for.

The interactions between the prosthesis and the environment are looked upon as a dynamic coupled system in which the “outputs” of the prosthesis are transformed into “inputs” of the environment, and its “outputs” into the “inputs” of the prosthesis. The “outputs” of the prosthesis are the actions intentioned by the patient, transformed into inputs of the environment and of the patient through the execution elements of the prosthesis. The outputs of the environment and of the patient are transformed into entering data for the prosthesis through the sensors implemented on the prosthesis. We have to mention that there are cases in which the input of the prosthesis does not completely describe the state of the environment and fails in the tentative of describing it. There are some solutions to implement artificial human limbs.

These solutions rely on electrical or mechanical devices such as:

- Servo motors
- Stepper motors
- Solenoids
- The nitinol wire
- The artificial muscle

Servo motors can be applied to movement and locomotion, but the disadvantage lies in that they have high rpm and low torque. Stepper motors may be used in the locomotion movement, steering and positioning control and they can be controlled using digital circuits. The solenoids and the nitinol wire are also inappropriate for a smooth control of the movement. These mechanics based solutions pose some disadvantages. They are very heavy and the complexity can be very large, which can make the control of these devices very difficult. There are many types of artificial muscle eap (electro-active polymers):

Ionic EAP

- Ion-exchange polymer metal matrix composite

- Triple layer made of polypyrrole and solid polymer electrolyte

- Freeform fabrication of polyacrylamide and polyacrylic acid cross-linked gels

- Carbon nanotube EAP

Dielectric EAP

- Electronic driver - high voltage DC transformer

- Electroding material / conductive carbon grease

- Polymer material as an acrylic polymer type

PH activated polymers - PAA - PVA base activated EAP

VII. Conclusion

A software-hardware system designed for intelligent prosthesis configuration and testing, under research and developing conditions, was developed, described and tested under different circumstances.

Physical tests were made on simple active leg prosthesis, able to reproduce the movements of a human leg, with no load or under light one. Also, auto-calibration tests were run on the PC-Prosthesis Interface, to verify its ability to adapt to sensor conditions changes.

Both types of tests were successful and we concluded that the system development effort was useful and the research results are very promising.

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