Position control with PID regulation for a FES system: preliminary results.

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Abstract. For people with quadriplegia at C3 and C7 levels functional electric stimulations (FES) could be a solution to make precision movements using the wrist. Closed loop control for FES systems enables to improve precision, stability and diminishes the impact of external perturbations. The goal of this work is to present a control position of the wrist articulation whenever the movement is produced by FES. In this article, a control design is developed along with the results of its first evaluation process on three voluntary individuals without neurological damage. A PID controller is used and it is adjusted experimentally for each test subject. A Constant reference for the wrist extension angle at sagittal plane and time evaluation of 10 minute was used to probe de PID. For two subjects the regulators responded reasonably with low mean errors and low standard deviations. For subject 3 the designed regulator did not succeed in stabilizing the position as from minute 6 in the second test. Preliminary studies of this work suggest that it could be possible to continue with the study of the closed loop position control with PID strategy in some people with spinal cord injuries whose movements are assisted by FES.

1. Introduction
People with quadriplegia at C3 and C7 levels possess mobility of their arms but are not capable of clutching their fists strong enough to grasp, hold, and release objects. Therefore, they are unable to perform daily activities that are needed for their own survival, which leads them to depend on either other people or auxiliary systems to manage such activities. It is estimated that in Argentina, 50% of spinal cord injuries are at cervical level [7]. Functional electric stimulations (FES) have been widely used in such patients in order to increase the strength of their palms and thus achieve the flexion/extension of the wrist both in therapeutic treatments and neuroprosthetics. These systems can be configured individually for each user given that the type of control or residual movement varies from patient to patient.

In order to improve their performance, neuroprosthetic systems require a specific control of the articular position so that the movement trajectories can be achieved satisfactorily. At the same time, it is necessary to develop control strategies so that the FES equipment can give autonomy to the patients in their daily activities [1].

Initially, most of the FES systems adopted open loop control strategies [2, 3]. Presently, some therapists prefer this equipment because of the simplicity in its use and because they are able to adjust the levels of stimulation according to each patient´s needs in a simple way. However, the open loop result is not as satisfactory because the external load noise and the muscular fatigue cannot be eliminated [1].

Later on, closed loop controllers were designed to adjust FES systems parameters through feedback [4,6]. In these systems, an error signal is developed which results out of the difference between the real output and the desired one. This type of control improves precision and stability, and diminishes the impact of the external perturbations on the system. At the same time, the development of automatic controllers allows patients and those who assist them not to press switches to activate and control FES equipment. The proportional integrative derivate controller (PID) is a feedback control strategy that is widely used in industrial control systems. It is through this controller that the error between the measured variable and the desired point of adjustment can be corrected and minimized through the proportional (P), integral (I) and derivative (D) action. Therefore, in FES systems, for which precision and stability are essential, it is very important to correctly define the P, I, and D values. Traditional estimation of P, I and D is based on industrial experience through a manual tuning called Ziegler-Nichols method. The use of this method has not been fully successful for FES control systems [8], thus making other forms of tuning control systems necessary.

The goal of this work is to present a position control of the wrist articulation whenever the movement is produced by FES. A PID controller is designed and it is adjusted experimentally for each test subject at constant reference. An adjusted PID produces an accurate relative stability and a robust response time. In this article, the design of the controller and the results of its first evaluation process on voluntary individuals without neurological damage are presented.

2. Design methodology

In order to achieve the proposed goal, three volunteers with no neuromuscular damage and whose peripheral nerves were intact were tested. All subjects agreed to participate in the experimental protocol procedures. The methodological steps to design the PID controller were:

- Experimental determination of the model to be controlled: for the PID controllers design it was necessary to calculate the estimated model system to which the control was applied. According to the transfer function of the model it is possible to determine the parameters of the controller. In this case, the model is the muscle osteoarticular of the wrist whenever the extension of the right hand is produced by the action of the FES. This model has as the stimulating voltage as its input and the angular position of the articulation under study in the sagittal plane as its output.

- Design of the PID controller: Once the transfer function of the step before was estimated for each subject, the design of the controller was made and the parameters were calculated according to functioning premises of the complete closed loop system. A good relative stability and a robust response time according to the system to be controlled were established as requirements.

- Preliminary implementation of the closed loop regulators: In this step, the PID controllers designed on step before were implemented in a digital form. The control loop in real time was executed in each subject through a portable computer and an AD/DA data acquisition module. The control action inferred on the stimulating level of the FES equipment in order to keep the angular position of the articulation of the wrist as a reference constant value.

3. Design implementation
In order to make the design of the PID regulators and to evaluate their preliminary functions in real time an experimental platform was mounted and made out of (see figure 1):

- A Dorsiflex FES stimulator to achieve the articulation of the wrist movement. This equipment works with stimulation frequency of 23 [pps], biphasic pulses with positive rectangular and negative excursion and pulse width of 0.23 [msec]. This stimulator has an output from 0 to 130 volt (measured with no connection to a subject) regulated by a low voltage level selector. This selector may vary from 0 to 8 [V]. Stimulating pulses were applied through superficial adhesive conducting rubber electrodes. For the implementation of the closed loop, the Dorsiflex was adapted so that it could be commanded from a digital computer.
- An electro goniometer for the measurement of the sagittal angular position of the articulation of the wrist. This equipment uses the rotational position sensor Murata brand Model SV01A103AEA101R00 .
- A USB AD/DA data acquisition module Data Translation model DT9804. This module uses 16 bits conversors. The data acquisition was established at 5000 [Hz] for all cases.
- A portable Toshiba Satellite PSAG8U computer with MATLAB 7.1 software.
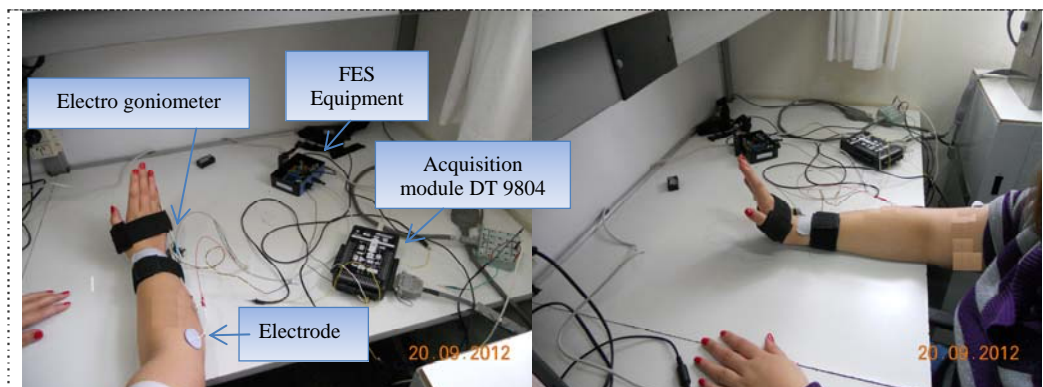
Figure 1. Photos of the experimental platform for the design and test of the PID controllers with subject 2.

*3.1. Experimental determination of the model to be controlled*
In order to estimate the transfer function of the model for each subject, the angular position of the right hand´s wrist was registered (extension movement) when the extensor carpi radialis longus and brevis muscles and extensor carpi ulnaris were electronically stimulated by the Dorsiflex system. The previously described electro goniometer was used by applying its centre on the biestiloideal line. The angular variation of the wrist was measured with this equipment in its sagittal plane.

The maximum stimulation voltage tolerated was established for each subject. They were requested to be relaxed without inducing any voluntary movements on the studied articulation.

The stimulation level along with the angular position was acquired by using the acquisition Data Translation module DT9804. The data was stored in the portable computer and later on processed by the Matlab software.

A ten-minute-long register was perform on each subject by separate in which the level of stimulation was raised up to the maximum tolerated level, in step-like stimulus and in random increases and decreases of the stimulating voltage. The obtained data was processed in the system identification toolbox of the Matlab software in order to obtain an estimated the model of the system. This system is represented by the stimulation level as the input and the angular variation of the wrist (extension movement) in its sagittal angle as the output. In the utilized toolbox the estimation by error prediction, with Gauss-Newton search method and determinant minimization criteria (maximum 20

iterations) were selected. Part of the data of each registry was used to calculate the model and the rest of the data was used to validate it. In figures 2 and 3 the described method can be observed for subject number 1.

Figure 1. Obtaining the models for subject 1 using the system identification toolbox of Matlab.
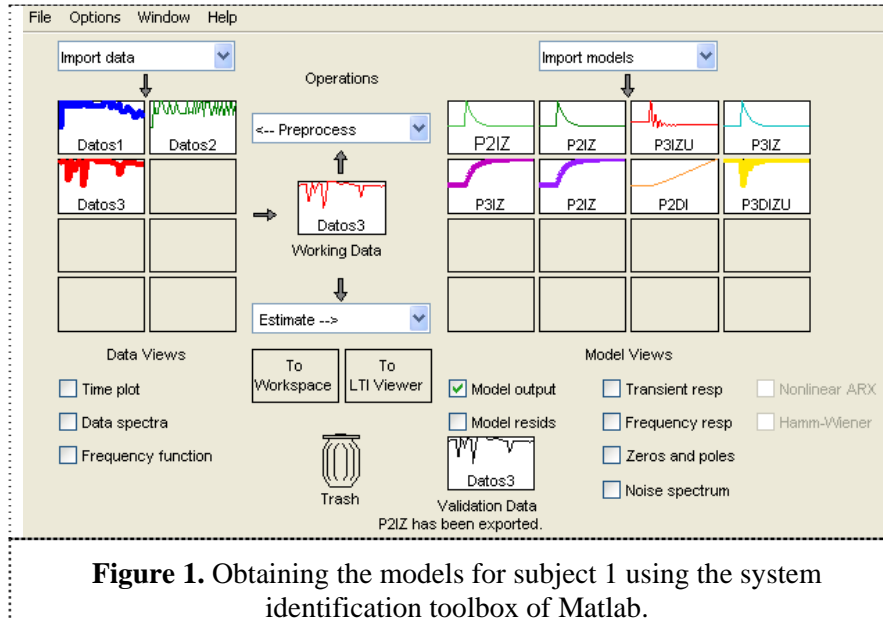
The model was approached by a four order transfer function G(s) as in equation (1) with one pole in the origin, dead time (Td), one real zero (-1/Tz) and gain (Kp).

$$G(s) = \frac{K_p.(T_z.s+1).\exp(-T_d.s)}{s.(T_{p1}.s+1).(T_{p2}.s+1).(T_{p3}.s+1)} \tag{1}$$

The model given by the toolbox that caused the least number of errors using the validation data was chosen for each subject. On Table 1 the time constants, gain and delay chosen for each subject are shown based on the generic function G(s).

Figure 2. Validation of the models for subject 1 using the system identification toolbox of Matlab.
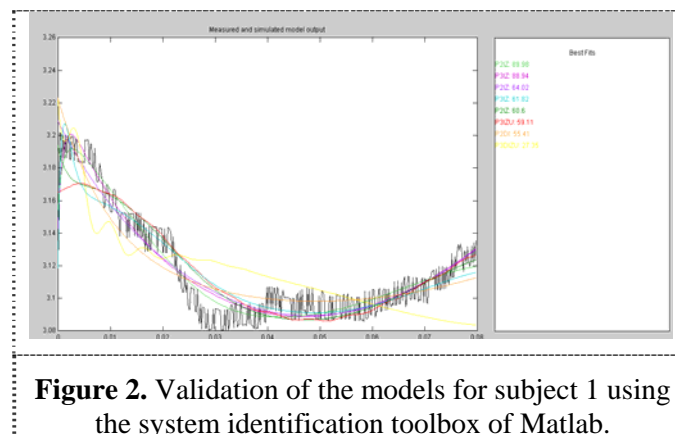
Table 1. Time constants, gains and delays of the transfer functions chosen for each subject.

	Kp	Tp1	Tp2	Tp3	Tz	Td
Subject 1	0.0126	1.476	6929.5	261.71	11403	0
Subject 2	0.076	0.234	7.35	$4.58\ 10^{7}$	$1.41\ 10^{8}$	0
Subject 3	0.098	0.0016	64.08	11312	2863.8	0

3.2. PID controller design
Based on the estimated model for each subject a parallel form PID regulator was designed with the generic transfer function as in equation (2).

$$C_{PID}(s) = K_p + \frac{K_i}{s} + \frac{K_d.s}{(1+s/N)} = K\frac{(Tz_1.s+1).(Tz_2.s+1)}{s.(1+s/N)} \tag{2}$$

In this controller a low pass filter was included in the derivative action in order to avoid high frequency noises. Each PID was designed so that the system would have a good relative stability and a robust response time. The design criteria adopted was 50degrees and a bandwidth of 4 [rad/sec]. The parameters K, Tz1 and Tz2 for each PID are shown on table 2.

Table 2. PID parameters (K, Tz1, Tz2 and N) for each subject.

	K	Tz1	Tz2	N
Subject 1	136.26	14	28	100
Subject 2	19.9	14	28	100
Subject 3	21.315	85	85	100

3.3. Closed loop implementation.
A real time close loop was implemented with negative feedback. This diagram block is shown in figure 3. A PESAG8U Toshiba Satellite portable computer was utilized, a USB data acquisition module data translation model DT9804 with AD/DA converters of 16bits, and a MATLAB acquisition toolbox. The sample frequency was chosen at 5000 [Hz].

The PID regulators described on the previous step were implemented in digital way using the Tusting transformation. The angular measure of the extension of the wrist in the sagittal plane and the electric stimulation were executed in the same way as in section 3.1.

The adapted Dorsiflex system was used. The level of stimulation of the Dorsiflex was changed by the digital value of the PID controller output. This digital value was transformed into a low-tension voltage by a D/A converter of the DT9804 module. This low voltage value replaced the Dorsiflex equipment level selector. In order to avoid abrupt changes in the levels of stimulation which could cause damage or pain in the subjects of study, before activating the close loop automatic regulation a voltage level increase ramp was implemented from 0 to reference value (0.5 V/sec increase). Subsequently automatic regulation was initiated through which the referential position was kept constant throughout the duration of the test.

4. Design evaluation methodology
The PID performance for each subject was evaluated as follows:

a) through the calculation of the relative stability of the system (PID design with estimated experimental model) for each subject . This stability, which is defined as each system´s margin to become unstable, was measured by the gain margins and phase margins in each case.

b) through the calculation of error and its standard deviation. These variables were measured by executing real time close loops in two different days for 10 minutes each. The two tests for each

subject were performed under the same experimental conditions in different days, so that it could be observed whether the designed regulators at fixed parameters could keep the control in spite of the variability of the system. In each case the angular reference, real angular position, low stimulation voltage value and the error (the difference between the proposed reference and real angular position of the articulation of the wrist) was registered. Figure 1 shows two photos of the experimental set up of the control system applied to subject 2.
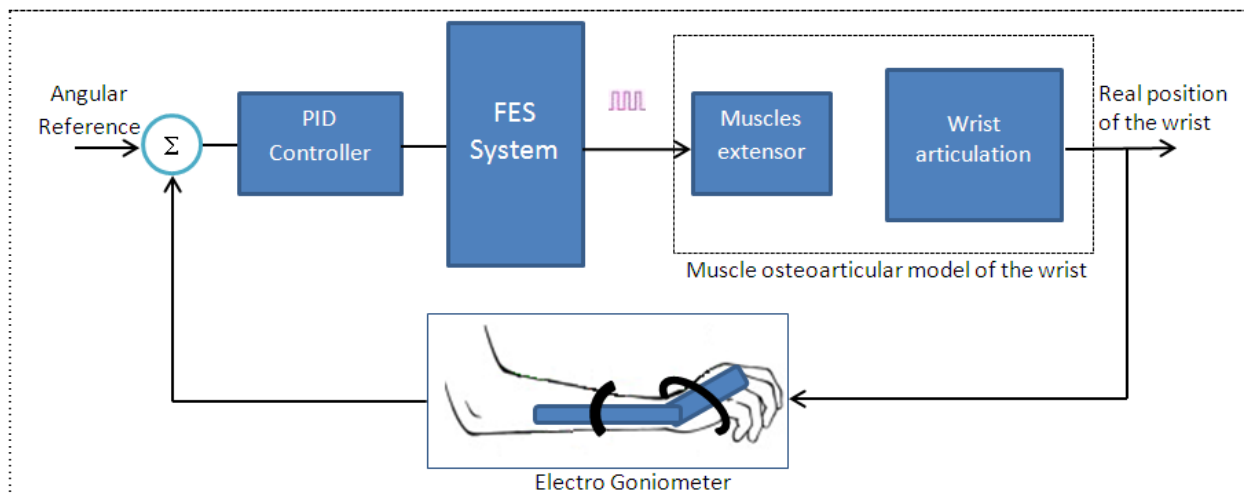
Figure 3. Scheme of the control setup in real time.

5. Results

The calculated relative stability for each system (PID designed with estimated experimental model) for each subject is shown on Table 3. The parameters on this table are gain margin (GM), phase margin (PM) and critical gain (Kc). Figure 4 shows the measured values for subject 3.
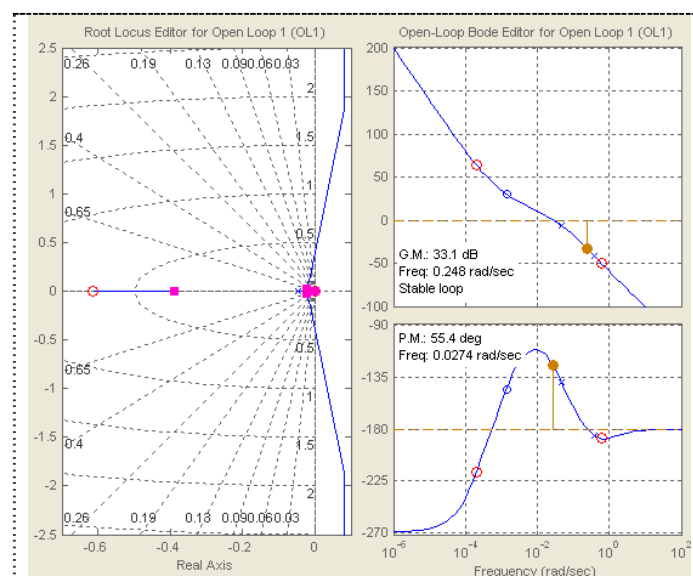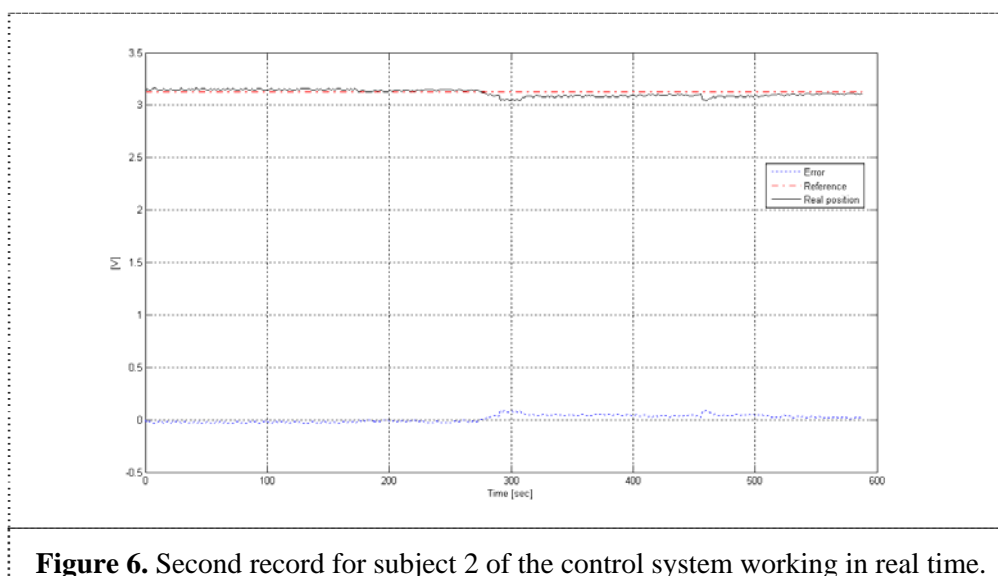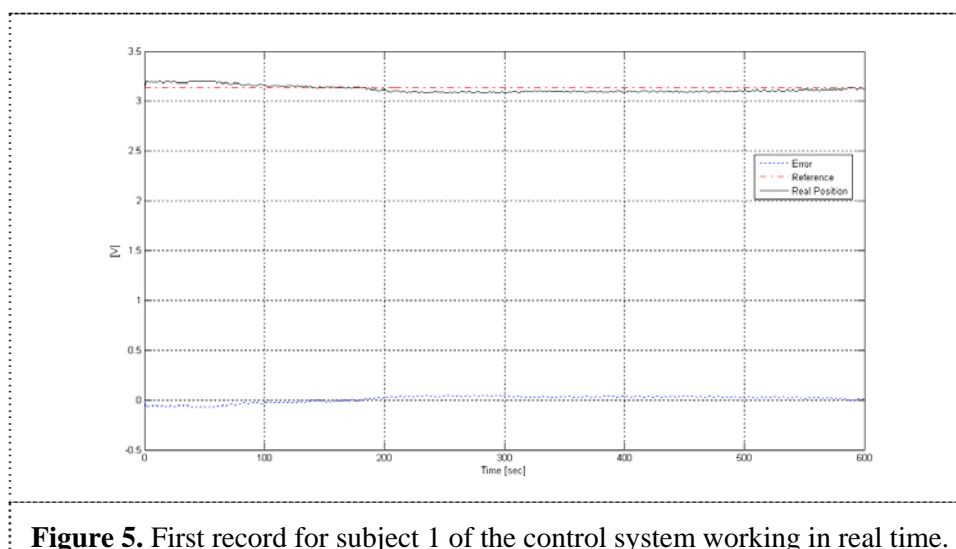

Figure 4. Measured phase gain and phase margin for subject 3.

Table 3. Calculated relative stability for each system
(PID designed with estimated experimental model for each subject).

	GM [dB]	PM [deg]	Kc
System 1	41.9	45.1	124
System 2	33.1	55.4	24.9
System 3	21.4	57.1	11.7

Figures 5 to 7 show the signals of the closed loop system at real time for all subjects. Table 4 shows the mean error and their standard deviation for each test in real time.

Figure 5. First record for subject 1 of the control system working in real time.

Figure 6. Second record for subject 2 of the control system working in real time.

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Table 4. Mean error and their standard deviation for each test in real time closed loop.

	Subject 1 Test 1	Subject 1 Test 2	Subject 2 Test 1	Subject 2 Test 2	Subject 3 Test 1	Subject 3 Test 2
Mean Error	0.013	0.045	0.079	0.023	0.012	-0.064
Standard deviation	0.0321	0.0648	0.139	0.0275	0.0285	0.17
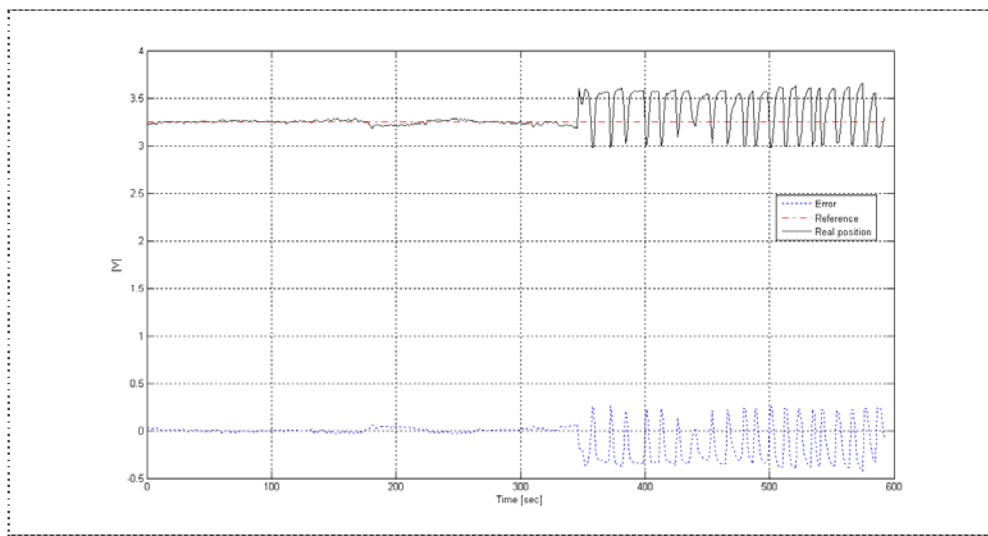
Figure 7. Second record for subject 3 of the control system working in real time.

6. Conclusion and discussion

The closed loops simulations with the experimental model and the designed controllers for each subject, showed a good relative stability was shown according to the values of gain margin, phase margin, and critical gain as detailed on Table 3. At the same time, subject 1 shows the highest relative stability whereas subject 3 has the lowest.

The muscle osteoarticular system of the wrist is a non-linear model, which varies with time because of the various causes that affect it such as muscular fatigue [4]. For subjects 1 and 2, at constant reference for the wrist extension at sagittal angle and during the period in which real time control was executed, the regulators responded reasonably in both tests with low mean errors and low standard deviations.

This suggests that by designing regulators with good margin of relative stability it is possible to control the proposed position in these two subjects despite the variability of the system to be controlled. In the case of subject 3, the first test can be included within the above conclusions for subjects 1 and 2. However, for test 2 (figure 7), the designed regulator did not succeed in stabilizing the position as from minute 6. The position remains oscillating around the reference value. In the simulation and according to the values on table 3, the PID for subject 3 had the lowest relative stability. This suggests the possibility of redesigning the controller so that a better relative stability can be achieved and repeat the experimental tests in real time. Another alternative solution for this subject, and in accordance to what other authors have presented before [4,5,6], is the application of non-linear control strategies such as fuzzy logic or neural network. In future, closed loop control strategies will be included in portable systems for home treatments of quadriplegic patients. These control systems will be implemented in micro controllers as it is simpler and less expensive to implement technologically PID regulators in them rather than non-linear control strategies. The preliminary

studies of this work suggest that it should be possible to continue with the study of the closed loop position control with PID strategy in some people with spinal cord injuries whose movements are assisted by functional electrical stimulation.

7. References

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