



24th COBEM - 2017



24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-2186

PROPOSAL OF ACTIVATION AND POSITION CONTROL OF THE PROTOTYPE OF AN ACTIVE ORTHOSIS FOR LOWER LIMB

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Abstract. *In recent years, the number of people requiring motor rehabilitation treatment in the lower limbs increased. Due to the high number of patients and the long time the treatment demands, the use of robotic devices can increase the efficiency of rehabilitation treatments. In this context, we highlight the use of robotic orthoses. This work presents the development of proposals for activation and position control of an active lower limb orthosis, dedicated to the accomplishment of the movement of extension and flexion of the human knee. The mechanical structure of the device was developed at the Federal Institute of Espírito Santo and has a DC motor as an actuator, responsible for the execution of the movement. The developed proposal uses electronic sensors of position and limit of course, electronic circuit in closed loop and PID control.*

Keywords: *orthosis, robotic, PID control, automation.*

1. INTRODUCTION

According to the Brazilian Institute of Geography and Statistics (IBGE, 2012), 7% of the Brazilian population declares to have motor deficiencies. Considering the increase in the lifespan of Brazilians, the tendency is that in Brazil this number will increase even more (Araújo, 2010). One way of mitigating the negative effects or even restoring the mobility of an affected limb is through motor rehabilitation programs. Robotic rehabilitation is a growing area of research within biomedical engineering, dedicated to the application of robotic devices in modern rehabilitation (Botelho, et al., 2015). In some countries, such as Japan, most physiotherapists work in hospitals, which means that patients are deprived of continuous therapy at the time they are discharged from the hospital, aggravating their condition. In an aging society, a need for physiotherapy continues to grow, together with the number of people suffering from motor deficiencies caused by illness or accidents (Homma, 2002). In this context, we highlight the use of robotic orthosis. The term orthosis refers to orthopedic mechanisms positioned externally to an affected limb and its purpose is to restore, or potentiate, lost or weak functions of that limb. Robotic orthoses, which use actuators controlled by electrical signals, are classified as active orthoses and have been widely used in motor rehabilitation of upper or lower limbs, by performing repetitive movements in an automated way (Araújo, 2010); (Varoto, 2010). Several research groups have carried out work related to the development of equipment and strategies to aid, treat and evaluate patients who need motor rehabilitation. In Brazil, the works developed by Araújo (2010), Varoto (2010) and Santos (2011) can be observed in this area of research. This work presents the development of proposals for activation and position control

of an active lower limb orthosis, dedicated to the accomplishment of the movement of extension and flexion of the human knee.

2. EXPERIMENTAL PROCEDURE

The mechanical structure of the active orthosis prototype used in this work is shown in Fig. 1 below:

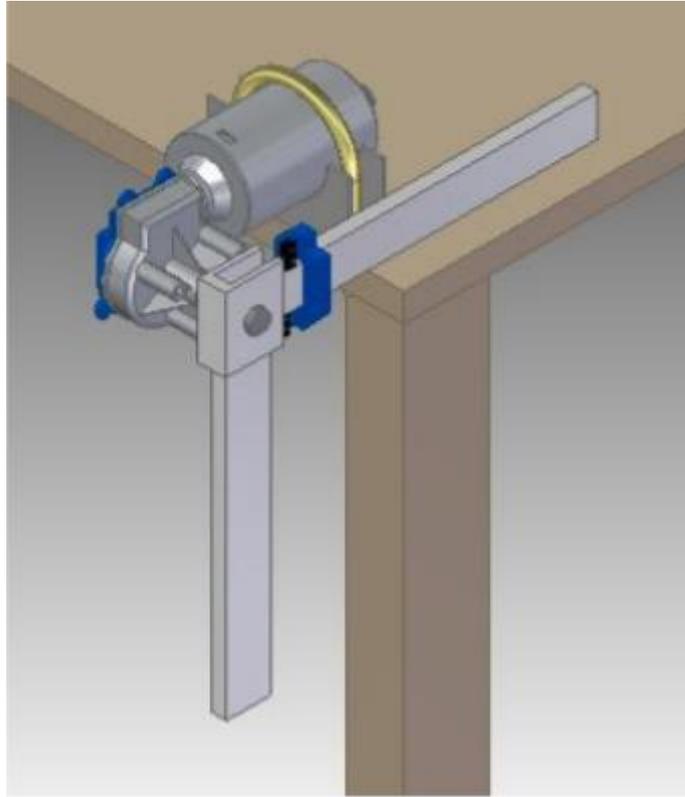


Figure 1. Prototype of an active orthosis.

The actuator is a Bosch ® CHP 9 390 082 031 DC motor. This motor features a gear unit with a screw and an irreversible worm gear, allowing rotation transmission in only one direction. The rotation direction is clockwise according to the manufacturer's specification, and was the same used during tests.

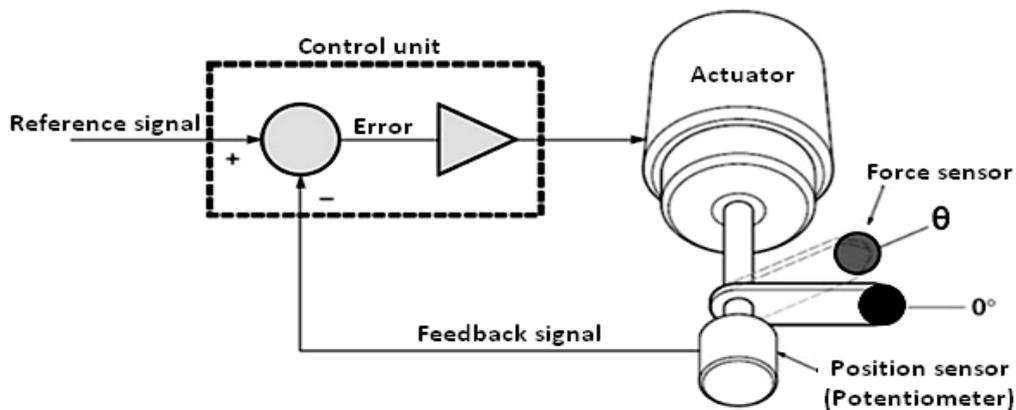


Figure 2. System's scheme featuring the control unit, the actuator and the sensor (adapted from Killian, 2000).

A closed-loop electronic circuit was developed to perform device control. The diagram of the developed circuit and its components are showed in Figure 3.

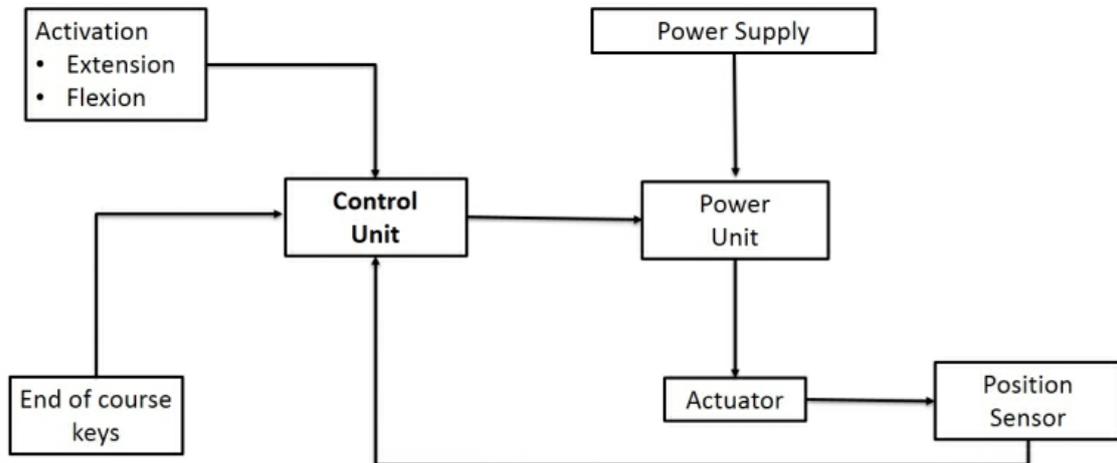


Figure 3. System diagram.

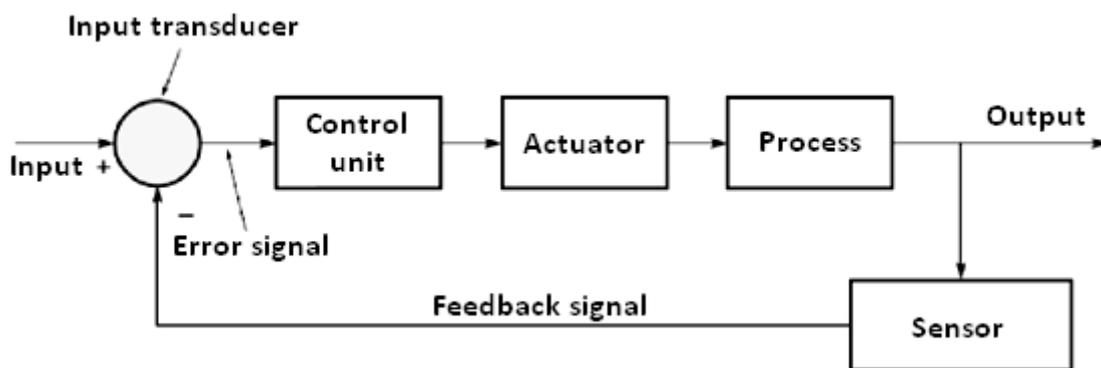


Figure 4. System's block diagram in closed-loop (adapted from Killian, 2000).

In the practice of lower limb rehabilitation programs, various strategies of movement or training are applied to be performed by the device combined with the user. The first tests consisted in an on/off activation of the device from 3 different movement strategies, elaborated according to the positioning of the movable rod of the device with respect to the vertical axis, shown in Table 1.

Table 1. Movement strategies.

Movement strategies	Angular variation
1	0° a 90°
2	0° a 45°
3	45° a 90°

Subsequently, proportional (P), proportional-integral (PI), proportional-derivative (PD) and proportional-integral-derivative (PID) controls were implemented. In this control, a setpoint (desired position of the device) is compared to the instantaneous position of the device. The *setpoint* was given manually through a potentiometer and the difference between the two values generated an error value. PID compensator equation:

$$u(t) = Kp e(t) + Ki \int_{t=0}^{\infty} e(t)dt + Kd \frac{de(t)}{dt} \quad (1)$$

Using an approach based on numerical methods for microcontroller implementation, the equation of the PID compensator becomes:

$$u[n] = Kp \times e[n] + Kd \times (e[n] - e[n - 1]) + Ki \times (f[n] + f[n - 1]) \quad (2)$$

The third and final control strategy was an online control system using a setpoint variable in time, generating real-time error response and graph plotting. For velocity control, it was necessary to set the trajectory limits. The potentiometer that is linked on the motor axis gives the position value but it also has a physical limitation which determines its maximum turning point. Therefore, it was determined that the angular position would be between 0° e 90°. Finally, two kinds of setpoints were made according to boundary conditions and several tests were performed for each in closed loop in order to get the best results of proportional (kP), integral (kI) and derivative (kD) parameters.

The variables of the control algorithm were monitored in real time, that is, in an online data acquisition system, both for position and speed control and for force control, with the aid of PLX-DAQ, a free tool for data acquisition and plotting of graphics conjunction along with Arduino®.

The first setpoint was a higher degree polynomial. For the determination of the polynomial, the following boundary conditions were used:

- Position: between 0°(start) and 90°(end);
- Zero speed in the beginning and end of trajectory;
- Zero acceleration in the beginning and end of trajectory;
- Trajectory total time: 30 seconds.

The polynomial obtained is:

$$S(t) = 0,0333 nT^3 - 1,6666. 10^{-3} nT^4 + 2,2222. 10^{-5} nT^5 \quad (3)$$

Where n goes from 0 to 3000 and T from 0 to 30.

For the second setpoint, the junction of a quadratic and linear function was used according to the following boundary conditions:

- Position: between 0°(start) and 90°(end);
- Zero speed in the beginning and end of trajectory;
- Zero acceleration in the beginning and end of trajectory;
- Quadratic function until a position of 50° and time of 15,81 seconds;
- Linear function from 50° until 90°;
- Total time: 30 seconds.

The quadratic equation used was:

$$y(t) = 0,2 nT^2 \quad (4)$$

The linear equation used was:

$$y(t) = 2,82 nT + 5,41 \quad (5)$$

Where n goes from 0 to 3000 and T from 0 to 30.

For force control, the sensor interacted with the control algorithm using the same parameters obtained for the time-changing setpoint as it must respond accordingly to real-time force input.

3. RESULTS AND DISCUSSION

Figures 5, 6 and 7 illustrate the angular variation of the movable rod over time during the execution of Movement Strategies 1, 2 and 3, respectively.

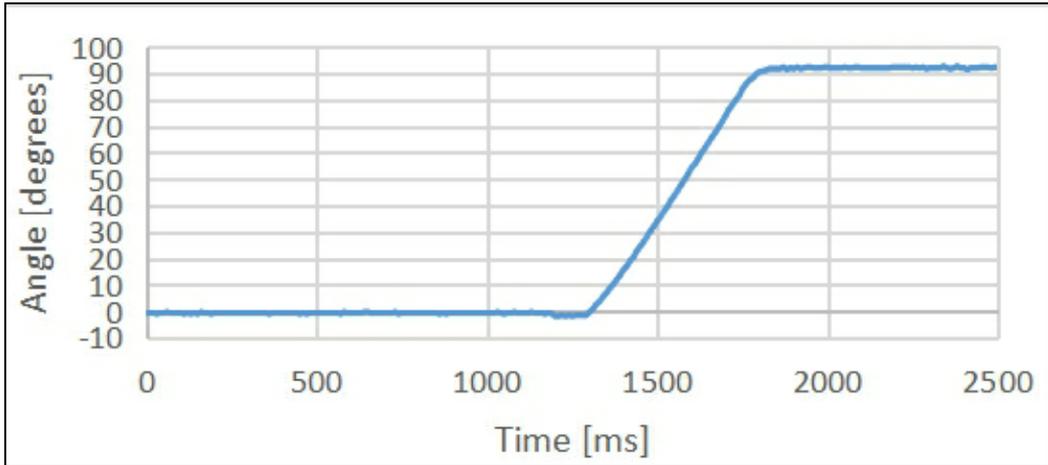


Figure 5. Angular variation of the device during the movement of extension by the Movement Strategy 1.

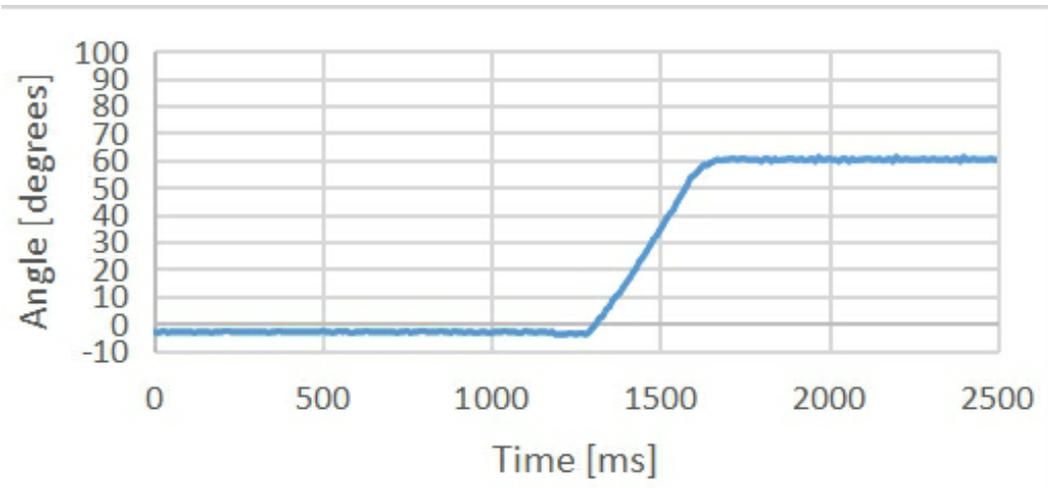


Figure 6. Angular variation of the device during the movement of extension by the Movement Strategy 2.

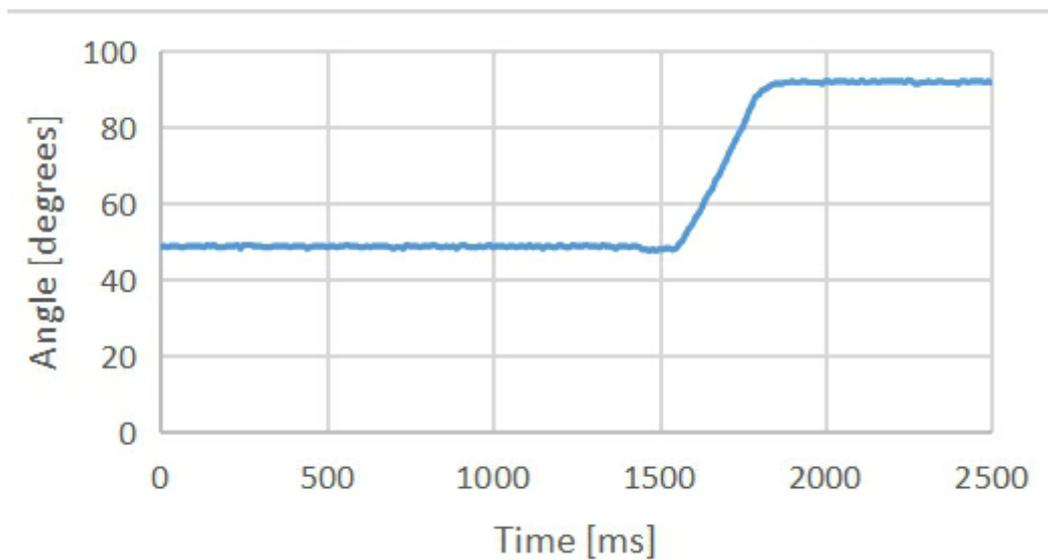


Figure 7. Angular variation of the device during the movement of extension by the Movement Strategy 3.

Small discrepancies are observed between the expected angular values in established motion strategies and the angular values assumed by the device upon stopping of the actuator movement. The inertia of the motor shaft, together with the inertia of the movable rod, are factors that contribute to the delay in the total stop of the shaft when the desired position is reached.

Figures 8, 9, 10 and 11 illustrate the angular variation of the movable rod over time during the execution of P, PI, PD and PID controls.

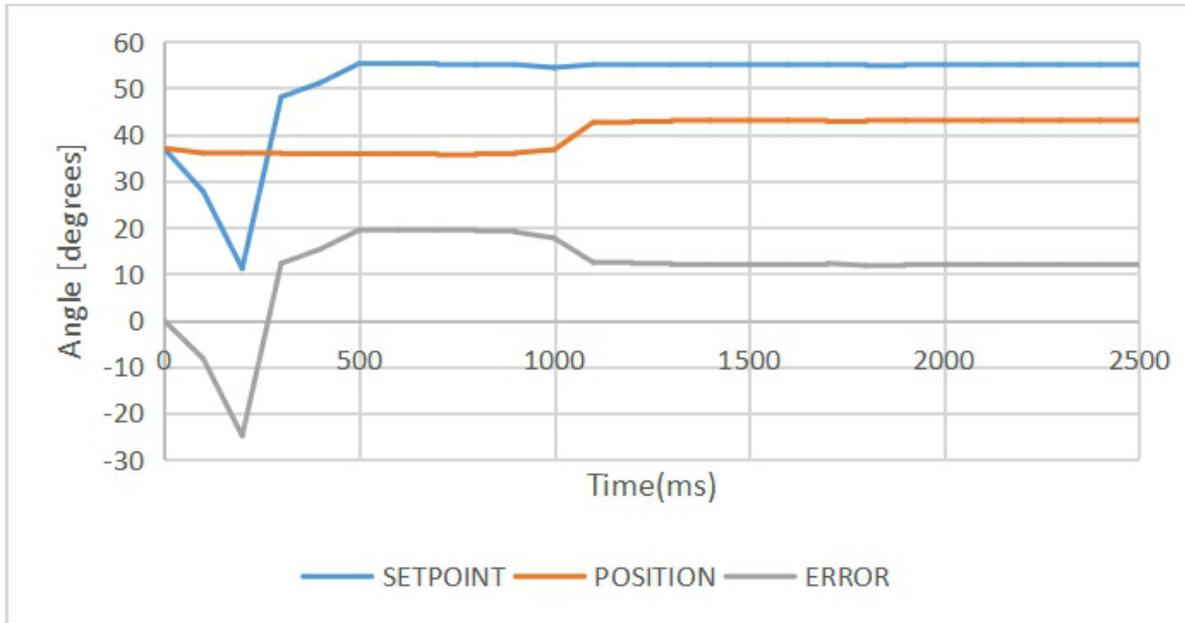


Figure 8. P Control. $k_P=0,2$.

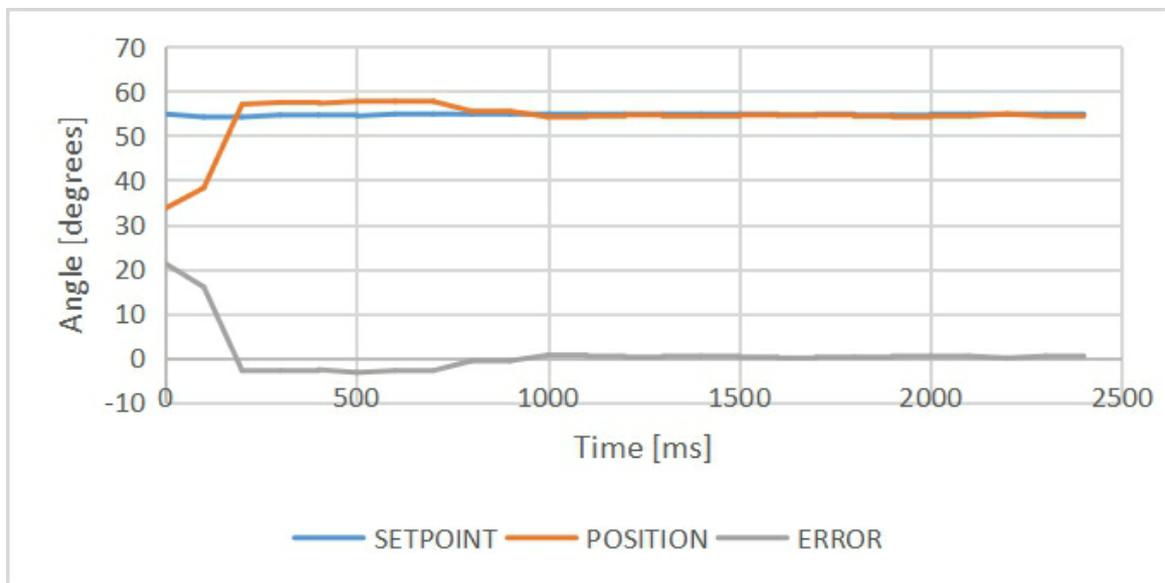


Figure 9. PI Control. $K_i=0,0000004$ and $K_p=0,5$.

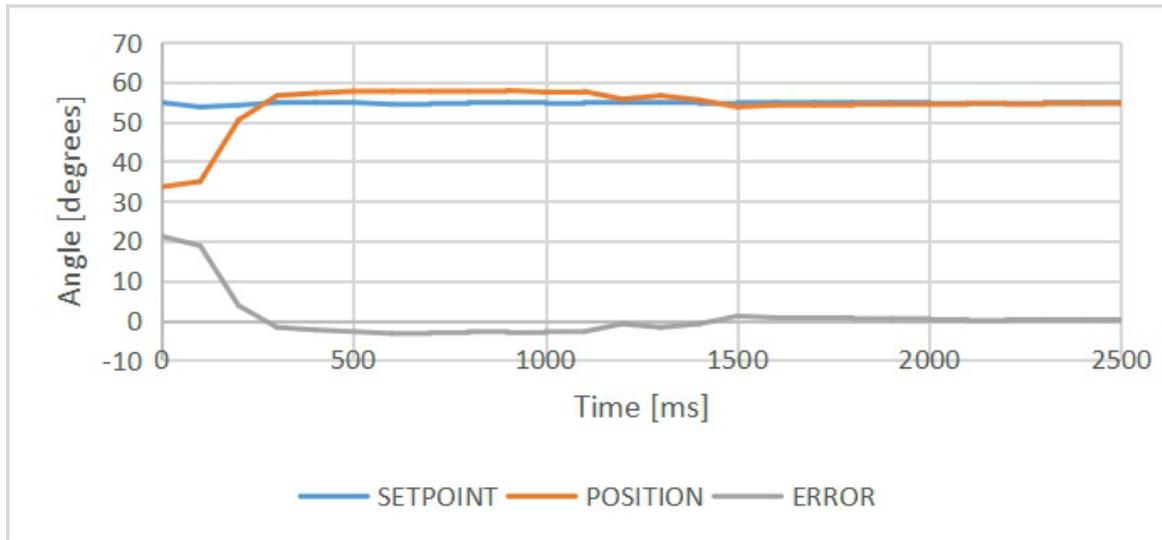


Figure 10. PD Control. $K_d=5000$ and $K_p=0,5$.

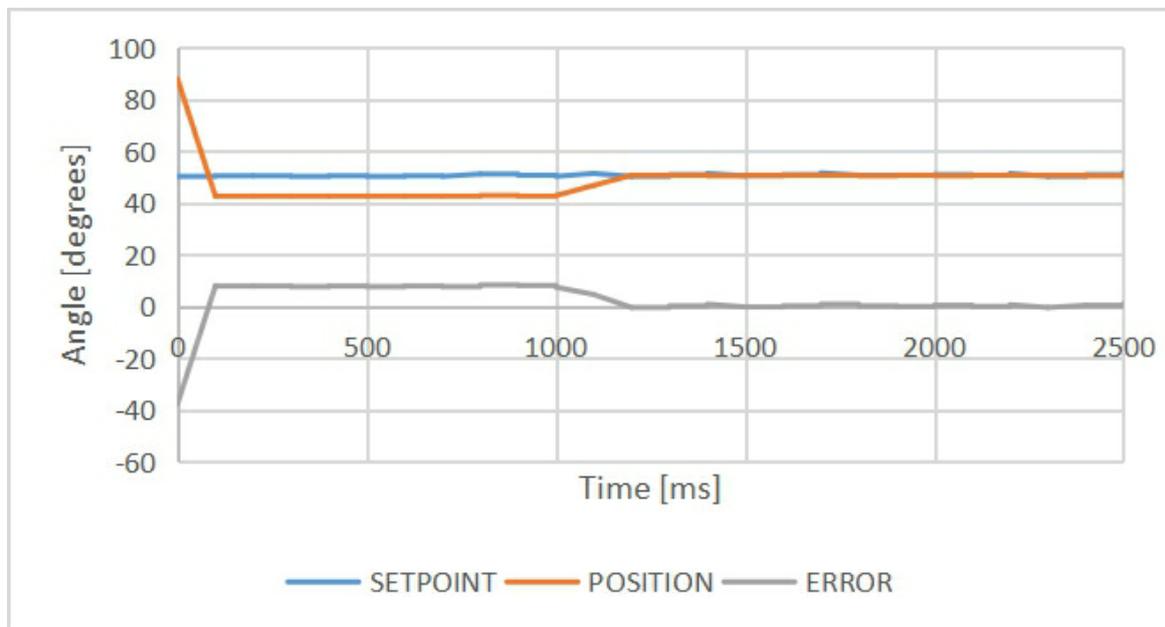


Figure 11. PID Control. $K_i=0,0000008$, $K_p=0,2$ e $K_d=8000$.

In the P control, the rod moved smoothly but had a considerable stationary error. For PI control the system became a little oscillatory and the rod took a longer time to reach the setpoint. For the PD control, a delay was also implemented in the algorithm so the motor could follow the controller signals easier and the system had a good response. In the PID control the system became heavily oscillatory and constants adjustments became harder. In the implementation of the P, PI, PD and PID controls, it was observed that the PD was the most satisfactory control, presenting lower stationary error and better stability when compared to the other controls implemented. The PID control was relatively effective, however, showed oscillation around the setpoint. A hypothesis for such a problem is the method of implementation of the PID used.

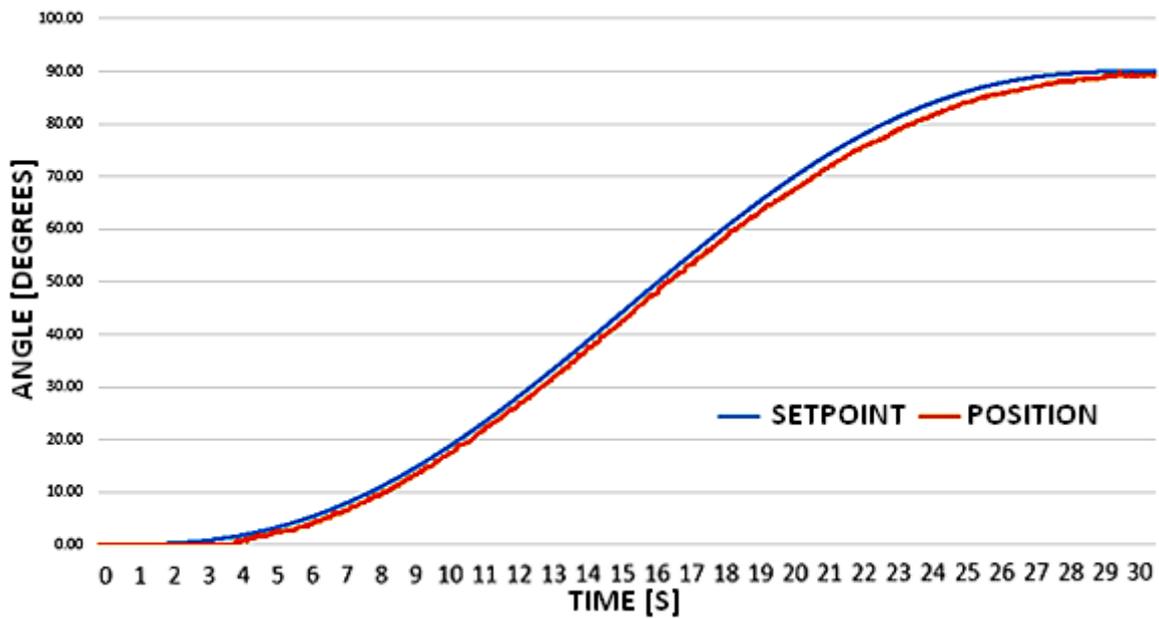


Figura 12. Control response for the first variable setpoint.

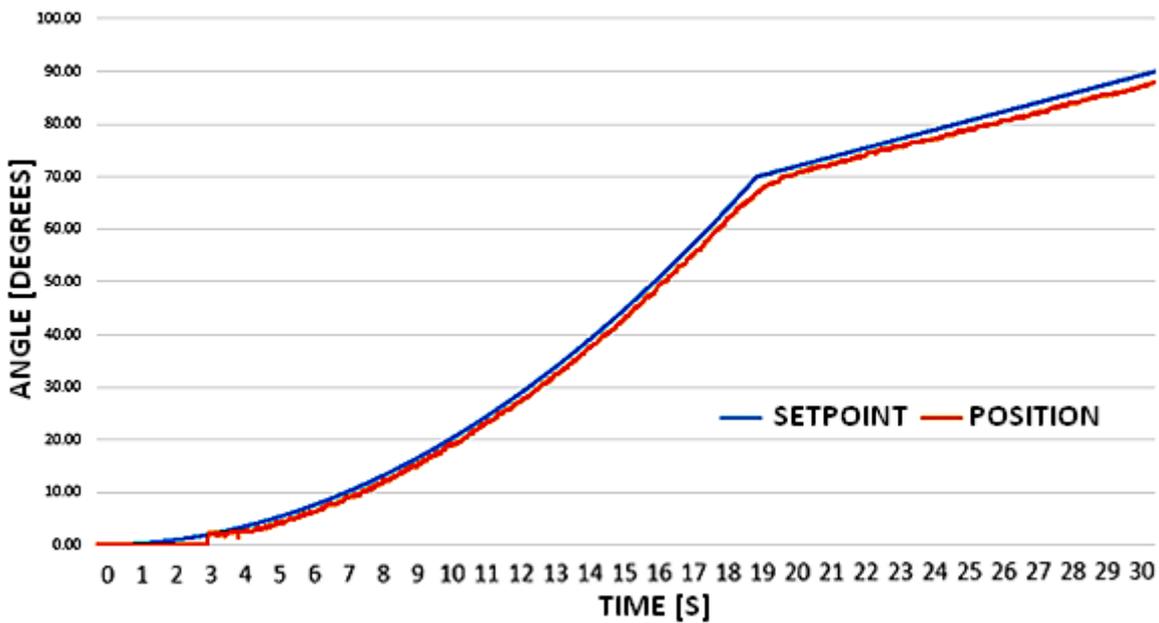


Figura 13. Control response for the second variable setpoint.

For position and velocity control the best k_P , k_I and k_D combination obtained was 30, 0.0005 and 2 respectively. With these constant values, it was possible to obtain a position response, as shown in the orange curves above, that was near the variable setpoint given. The motor itself has inertia, internal losses and a minimum PWM value to which it responds only above, that explains why its movement is a bit away from the setpoint and hence the control method is not perfect. However, for the control objective proposed, the response is sufficient and accurate enough.

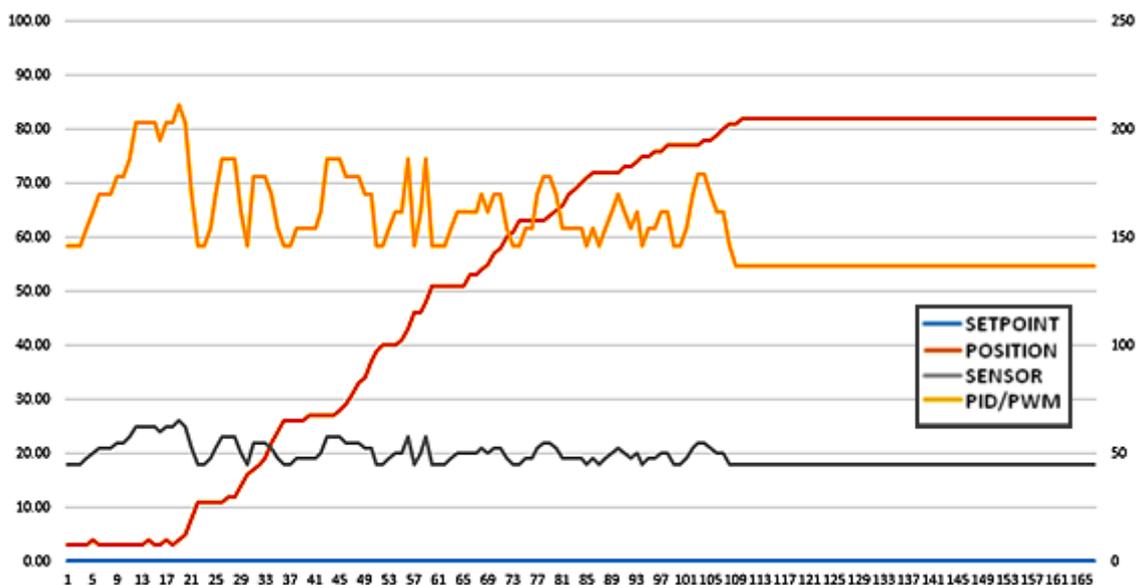


Figura 14. Response for force control.

In this force control system, the force sensor changes its value from zero once a force is applied, which means that when the sensor value is zero, no force is applied and when the value changes to an analog value between 1 and 1023 a force is applied accordingly. The objective, in an assistive strategy, is to move the rod so that the sensor value becomes zero taking away the effort made by the patient. The setpoint value is shown in the blue curve as a constant zero value. The darker orange curve gives the angular position of the rod and it varies between approximately 0° and 90° as the test was conducted with the rod moving between this range. The yellow curve gives the PWM/PID response (control action) and it is related to the sensor value, the gray curve, as the rod has to move depending on the sensor response. If the sensor value is higher (high peaks) it means that the error is a value more distant from the setpoint so the PWM/PID answer is higher as the rod has to move to compensate a bigger error value. If the sensor value is lower (low peaks) the PWM/PID response is lower as the rod has to move less to compensate a smaller error value.

4. ACKNOWLEDGEMENTS

We'd like to thank the Federal Institute of Science Technology and Education for this great opportunity of research and for laboratory and equipment support.

5. REFERENCES

- Araújo, M. V., 2010. "Desenvolvimento de Uma Órtese Ativa Para os Membros Inferiores Com Sistema Eletrônico Embarcado". UFRN, Rio Grande no Norte, Brazil.
- Botelho, T., Soprani, D., Carvalho, C., Mut, V., Frizzera, A. and Ferreira, A., 2015. "Control of a Lower Limb Robotic Exoskeleton using Impedance Control". In: *Proceedings of the 1st International Workshop on Assistive Technology (2015)*, Vitória, Brazil. 23-26.
- Cavanaugh J. T. and Killian, S. T., 2012. "Rehabilitation following meniscal repair" *Current Reviews In Musculoskeletal Medicine*, [s.l.], v. 5, n. 1, p.46-58, mar. 2012. Springer Nature. <http://dx.doi.org/10.1007/s12178-011-9110-y>.
- Homma, K.; Fukuda, O.; Nagata, Y. 2002. "Study of a wire-driven leg rehabilitation system". In: *Intelligent Robots and Systems, 2002. IEEE/RSJ International Conference on*. IEEE, 2002. v. 2, p. 1451–1456.
- Instituto Brasileiro de Geografia e Estatística: Cartilha do Censo 2010 - Pessoas com Deficiência. Brasília, Brazil (2012).
- Killian, C. T., 2000. "Modern Control Technology: Components and Systems". 2. ed. [s.l.]: Delmar Thomson Learning.
- Santos, D.P. dos, 2011. "Projeto Mecânico de Exoesqueleto Robótico para Membros Inferiores" USP, São Paulo, Brazil.
- Varoto, R., 2010. "Desenvolvimento e Avaliação de um Protótipo de Sistema Híbrido para Membro Superior de Tetraplegicos". USP, São Carlos, Brazil.

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