An angle measurement system of high resolution for the upper limbs using a low-cost servomotor

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Abstract. In the here presented study, the biomechanical design and coupling of a servomotor as measuring element for determining the angle of elbow flexion in humans is presented. This task requires a digital servomotor with a 12-bit low charge encoder type "contactless absolute", which makes the holding torque negligible. Because the servomotor is used as a sensor and not as an actuator, and is expected to produce the least possible resistance to the movement of the elbow, this is a crucial point. Additionally, the biomechanical design of the structure for coupling the servomotor was carried out considering the different movements of the arm and forearm, and the necessity to not interfere with the natural movement of the arm. The measurement resolution allows obtaining the flexion angle to an accuracy of 0.088; and integrated into the embedded system used to communicate with the servomotor, that allows obtaining and analyzing data and temporarily integrating information for counting repeats or measuring the speed of movements, among others. This system will also be useful to calibrate and compare other compatible biomechanical analysis models, where the same movement is analyzed.

1. Introduction

The acquisition of position information and angular speed of the human elbow is very important and useful for the design and manufacture of prosthetics and orthoses, and can support the study of patients undergoing rehabilitation, saving time and manpower, because the patient does not need to go to a medical center and no specialist is needed to take measures. Also angular movements occurring in daily life or in sports can be studied. For this purpose, a technique that implements an electromechanical system based on an embedded servomotor with a high resolution, but a low-cost encoder, which is not used as an actuator but rather as an angular position sensor receiving biomechanical information, is used. This information is adequately transferred to a computer, where the end user can analyze and use it for any of its possible applications. These signals offer the possibility of man-machine interfaces controlled by natural signals from the human body. Furthermore, they offer the ability to properly intervene in processes, on occasion providing support to people with physical disabilities and in rehabilitation, or to develop electromechanical systems to assist or to enhance physical skills for military and industrial applications.

Biomechanical signals, such as the angular position of the joints of the human body, are used in various applications, e.g. rehabilitation \cite{1}, medical monitoring, entertainment, military industry, product design, etc. Understanding these signals is essential to search for appropriate
techniques to acquire and implement these signals in systems and technical devices; as in this case, the measurement of the angular orientation of the human forearm with respect to the elbow, with which analysis can be performed to design orthoses and prosthetics, or to interact with virtual environments, etc. In similar cases to this technique like [2], where the absolute encoder AS5040 from Austria Microsystems with a resolution of 0.35 and a PIC16F877A were used. Angular position measurements of the knee were taken and the systems reliability was analyzed using a goniometer and comparing with motion analysis records. For the processing of the information a Matlab based interface was used. In [3], where the movement of the human forearm is captured by a reliable sensing system, based, as in [2], on the magnetic linear encoder AS5040 evaluating a noninvasive technique to estimate the angular position by using it as a digital goniometer tracking the orientation of the human limb. Also, there are different techniques, seeking to detect, estimate or measure joint positioning, as in the case of [4], where kinematic models are used in robotics and methods to continuously assess the orientation angles of the shoulder and the elbow based on inertial units and Kalman filter. These measurements were compared with those obtained by an optical tracking system showing that the error was always less than 8. In [5] a method is evidenced that estimates the angle of orientation of the human elbow through the processing of electromyographic (EMG) signals obtained from the surface of biceps and triceps aimed at optimizing while minimizing the error of the measured angle with respect to the actual angle. In [6], with the implementation of gyroscopes and accelerometers, a method is applied to obtain the orientation of a joint in static or dynamic state, using also speed and angular acceleration, as well as a Kalman filter to obtain the final estimation of the orientation. Angular positioning information is important and useful in various studies and applications making it necessary to find appropriate techniques, which offer reliable and easy to use information; thus requiring an electromechanical system able to monitor the angular position of the forearm relative to the elbow without limiting in any way the free movement of the individual. This system is based on the MX-12W servomotor from ROBOTIS line called Dinamixel [7], and which is not used as an actuator, but as an angular position acquisition device with a resolution of 0.088, capable of analyzing smaller displacements than the encoder implemented in [2] and [3].

Reliable information of biomechanical signals is of great importance in the rehabilitation of patients who suffered strokes. As shown by the World Health Organization [8], those can cause apoplexy and other damages and should be treated quickly to achieve the best possible recovery. So, different techniques have been created to support this rehabilitation based on biomechanical signals. In [9] a robotic training device based on surface EMG, which actively promotes the resumption of muscle signals, is implemented for hand rehabilitation in patients suffering from stroke. This system can be adjusted to different finger sizes, thus fitting many patients. In [10] they use a game, controlled by EMG, to rehabilitate patients in a didactic manner; and in [11] a robotic exoskeleton is meant to help people with arm and forearm problems in their daily lives. This exoskeleton has one degree of freedom and the control supports the movement of the elbow by manipulating the angular position based on biological signals that reflect the intention of the movement. Other consequences of brain injuries, such as hemiparesis and hemiplegia are also treated with various techniques, where, as shown in [12], the evaluation of motor skills plays a critical role. In case of hemiplegia, devices as shown in this article can be used to specifically detect the motion decrease of the elbow. Also it serves as a reference to generate myoelectric signals-based control. In addition, models of muscle monitoring can be created, as in [13], where EMG is used to study the elbow in dynamic situations including position and angular velocity. It is worth mentioning that all the hardware elements used in the development of this idea are inexpensive, thus allowing the necessary testing, the data analysis and the interpretation of the outcome being replicable and using it as an educational tool within courses of undergraduate and master level. Finally, the system developed and integrated in this work includes the adaptive
biomechanical design, the prototyping and manufacturing, the coupling with the servomotor and the program for the embedded system that allows translating the flexion information into meaningful information for the biomechanical analysis. Such initiatives aim at integrating low-cost technologies in applications that enhance the acquisition of information in rehabilitation systems, sports or the monitoring of physical activity in general, and thus, can have an impact on the customers' quality of life.

2. System Description

2.1. Servomotor
The MX-12W is a high precision servomotor with the ability to measure positioning, torque, internal temperature and engine speed. It will be used to detect the angular position in the same way as with a digital goniometer and will also be used to measure the speed. MX-12W was selected due to its hardware, since its weight and size is useful in a system that will be used for measuring biomechanical signals. Although it will be non-invasive method, the individual will have to wear the electromechanical system like a garment. It has a positioning resolution of 0.088, which enables high-precision measurements with an input range of 0 to 360 and an output of 12 bits. It has a span of 360, which is more than sufficient for the required measurement, given that the angular movement of the elbow is not more than 150 according to [14]. Its physical dimensions are 32mm x 50mm x 40mm and it weighs only 54.6 grams.

2.2. Electromechanical system and control
For the correct measurement of the angular position, five pieces were used that were designed with CAD software and molded using a DREMEL 3D printer from Robert Bosch Tool Corporation. These pieces give rigidity to the structure allowing the servomotor to rotate regarding the degree of freedom of the elbow and allowing the mechanism being adjusted for different sizes of arm and forearm. The pieces shown in Figure 1 (a) are linked through the servomotor and they will also be fixed with screws to two plaster casts that are located directly to the arm and forearm, respectively. Furthermore, the embedded system of the servomotor, the OPEN CM09.04, which processes the information, is used for receiving data. Figure 1 (b) show the complete electromechanical system, which has not yet been attached to the connecting elements of the arm and forearm. To control the servomotor a brief treatment of the signal, which is already integrated, is required.

Figure 1. (a) Arm piece and forearm piece (b) Arm piece with the embedded system
3. Results

3.1. Control

Figure 2 shows the prototype system which will monitor the angular displacement. In this case it was set to be placed in a healthy person measuring 1.75 m in height.

![Prototype system](image)

**Figure 2.** Prototype system

3.2. Data acquisition

Figure 3 shows the acquisition of the elbow movement in several repetitions and three speeds by the same person. An external LED was used to indicate the time each flexion took, that is to say 1 (Fast), 3 (Normal), and 4 (Slow) seconds, respectively. It was observed that the data acquired by the system allows deriving relevant information for biomechanical analysis, such as the number of repetitions per minute, the speed of the movement of flexion and extension, and the continuity in the movement. This data is useful in the development of physiotherapy aimed at rehabilitation or analysis of performance increase in spots activities, because it allows traceability in the time and in the development of the activity, and eliminates the need for supervision.

![Position data](image)

**Figure 3.** Acquired position for a test subject

A comparison of the angular position of arm and forearm in three different individuals is shown in Figure 4. It can be observed that, although the same external indicator was used to mark the moment of the movement, there are different response times, which is also an important issue for biomechanical analysis and reaction time measurements.
4. Conclusion

This work is based on a measuring technique to monitor the angular position and speed of the human elbow using an electromechanical system, built with an intelligent, high resolution, but low-cost servomotor. Furthermore, the mechanical part of the device was fabricated with a 3D printer, taking the possibility of changing the size to suit different sizes of the arm and forearm into account; thus, offering the opportunity of conducting practical studies wherever data of the position or speed of the elbow is required for daily life tasks from people with lesions in this area, or disabilities, or to obtain reliable reference data from healthy people. In addition to using the servomotor as a sensor, rather than as an actuator, the system has an integrated OpenCM9.04 board for data processing and sending. Future work aims at the improvement of the biomechanical system to measure other joints, bearing in mind that implementation in the knees is also possible.

The here presented application is aimed at offering an accurate measuring system and traceability of an exercise that is commonly used to determine the physical condition of patients in rehabilitation or the progress in muscle response in athletes. The main objective is that by developing a low-cost system, where the mechanical parts become public domain, it will be possible to offer alternative measurement methods to persons or entities that do not have access, for cost reasons, to traditional systems; and besides, to allow direct supervision by physiotherapists or coaches during the exercise.

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