Design of an automatic device for rehabilitation of the fingers of the hand for people with ictus

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Abstract. The present research presents the construction of a robotic equipment used in the rehabilitation of the fingers for people after an Ictus, the equipment is constituted by a sliding crank mechanism in connection for each finger independently, the static and dynamic characteristic of the parts were designed with anthropometric measures. In addition, an architecture control based on PID-Fuzzy is proposed that achieves an adaptive control for each patient, which allows to have a software with personalized therapies for each patient, incorporates with a database for recording the stages in their rehabilitation according to the type of motor activity, number of repetitions and execution time; finally, the robotic equipment is evaluated in patients with follow-up in a defined time interval.

1. Introduction

ICTUS, also known as stroke, cerebrovascular accident, or cerebral infarction, is caused by a blood vessel blockage, it avoids receiving enough oxygen to the brain and dying [1]. There are two types of ICTUS caused by brain bleeding or a cerebral thrombosis [2]. ICTUS occurs after age 55 and the World Health Organization (WHO) predicts that by 2050 more than half of the population over the age of 65 will suffer from this medical emergency [3].

Currently, a person is affected by ICTUS every 5 seconds around the world. It is the second leading cause of death and the leading cause of disability in adults [1]. Each year there are more than 15 million cases of ICTUS, two out of ten people die and the rest suffer sequelae that are often very serious, in the young the sequelae are more evident than in the elderly, the consequences range from difficulties in motor skills: how to speak, read and write to walk or lose fine motor skills to perform hand movements. [4] [5] [6].

2. Kinematics of the Human hand

The hand is the upper extremity of the human being that fulfills various mechanical, sensory and even communication functions, so it is one of the main organs for the daily development of a person, the control of the movements of the hand is given by a finite number of the muscles with degrees of freedom for each finger, which are responsible for giving functionality to the hand, we can see in Figure 1.

The muscles mentioned above are positioned on the outside of the hand and wrist, specifically in the forearm, and the force that is generated by them is transmitted thanks to long, thin tendons that reach down to the fingers. [7]

According to a statistical comparative study of anthropometric measurements between mestizos, indigenous and afros in Latin America, the distal length of the fingers in men, considering the averages obtained for each sector of the phalanges corresponding to: thumb 72.5mm in the right hand
and 72.4mm in the left hand; index 104.2 and 104.5; mean 115mm and 114.6mm; annular 109.1mm and 108.9mm and pinky 88.5mm and 88.4mm, respectively.

Figure 1. Cinematics of the Human Hand.

In women, the average distal lengths are: right hand thumb 63.5mm and 62.6mm in the left hand; index 91mm and 90.7mm; middle 100.4mm and 99.2mm; annular 94.4mm and 94.2mm and pinky 75.8mm and 75.9mm; respectively [8]. According with these data and the need for a linear movement with parameterizable range, the crank rod slide mechanism was designed for the independent control of each of the fingers.

3. Mechanical Design
This section presents the mechanical design of the crank rod mechanism for each finger, under the principles of theoretical and computational mechanics, where each of the considerations is detailed in the static and dynamic analysis for each element.

3.1. Proposed mechanism
Considering the maximum force of a human hand of 70 N, [9] for the calculation of the forces exerted by each of the elements that conform the crank - rod - slide mechanism figure 2, the nodal static analysis method is used.

Figure 2. Servo Mechanism.
3.2. Nodal Static analysis

![Nodal Analysis](image)

**Figure 3.** Nodal Analysis (a) Node A - (b) Node B - (c) Node C

3.3. Node A

With this mechanism, we obtain an output force on the axis of rotation of 100.428 N as shown in figure 3 (a), which satisfies the estimate of 70 N of human force; also, if we consider that the axis of translation can obtain a maximum force on the articulation of 94.26 N by means of equation (1) and equation (2) respectively shown in figure 3 (a).

\[ F \times \sin \beta - F_{AB} \times \sin \theta - f_r = 0 \]  
(1)

\[ N - F_{AB} \times \cos \theta - F \times \cos \beta = 0 \]  
(2)

3.4. Node B

In figure 3(b), we have the mechanism at its critical point. The angle where the force generated by the servomotor is the maximum being close to collinearity in the crank rod sliding mechanism.

Considering equation (3) it is calculated the force in BC obtaining a force of -34.68 N in addition we observe the projection of a FABP vector perpendicular to the FBC vector which is the maximum projected force of the mechanism, useful for later calculation of the maximum torque and selection of the motor by means of equation (4) it is obtained FABP=106.48 N.

\[ F_{AB} \times \cos \gamma + F_{BC} \times \cos \alpha = 0 \]  
(3)

\[ F_{ABP} = \frac{F_{AB}}{\cos \varphi} \]  
(4)

3.5. Node C

It is convenient to analyze the force diagram figure 3 (c), in node C, as it provides us the force for the motor anchors.
From which the maximum forces were obtained $F_{Mx} = 24.34 \, N$ and $F_{My} = -0.81 \, N$

In addition, by means of equation (5).

$$ T = F_{BCP} \times d $$

A torque of 358.24 N mm is obtained, that is 11.9Kg cm. Therefore, the Hitec 755HB servo motor was selected, which has a torque of 12Kg cm.

4. Dynamic Analysis

In order to establish the position, speed and acceleration of the mechanism for different angles, the dynamic analysis in crank rod sliding mechanism is performed varying the angle of entry between the rod with reference to the base of the servomotor (Delta 1); this angular movement is established by means of the servomotor show in figure 4.

4.1 Position, Velocity and Acceleration

To determine the position, velocity and acceleration in this type of mechanism it is necessary to structure the closed loop vector equation, the same that will generate the maximum displacement of the slide taking into consideration the entry angle, followed in order to find the velocity equation, the closed loop equation is derived, expressed in a complex form, from where the equation (6) of the velocities of the mechanism as a function of the entry velocity is obtained.

$$ V_4 = -r_2\omega_2 \sin \theta_2 + r_2\omega_2 \cos \theta_2 \tan \theta_3 $$ (6)

Then to determine the acceleration, the closed-loop equation expressed in complex form is considered and derived twice respect to time obtaining the following equation (7),

$$ A_4 = -r_2\omega_2^2 \cos \theta_2 - r_2\omega_2 \sin \theta_2 - r_3\omega_3^2 \cos \theta_3 - (r_2\omega_2^2 \sin \theta_2 - r_2\omega_2 \cos \theta_2 + r_3\omega_3^2 \sin \theta_3) \tan \theta_3 $$ (7)

Graphing these two equations with the current dimensions of the mechanism using a MATLAB script with the final values found in the static analysis are: $r_1 = 112.8 \, \text{mm}$, $r_2 = 102.5 \, \text{mm}$, $r_3 = 119 \, \text{mm}$,
\( \delta = \) variable, \( \delta_2(\theta_2) = \) with a variation of \( 1^\circ \) between \( 0^\circ \) and \( 180^\circ \) and \( \delta_3(\theta_3) = \) variable, figure 5 schematizes the relationship of the crank angles \( \theta_2 \) and the crank handle \( \theta_3 \) of the mechanism which vary from 5 to 75 degrees with an increase of one degree in each.

\[
\begin{align*}
\text{Relation of angles} \\
\quad \delta_3 \text{ (degrees)} \\
\quad \delta_2 \text{ (degrees)}
\end{align*}
\]

Figure 5. Angle ratio.

Figure 6 represents the final linear position vs. the angle of rotation of the crank produced by the motor \( \theta_2 \) of the mechanism, which is the slide \( r_4 \) with a maximum travel of 17.3 cm, considering as starting point 0.3 cm, which generates a displacement of the slide of 17 cm. Sufficient length for the fingers displacement.

\[
\begin{align*}
\text{Final Position Graph} \\
\quad \text{Position (mm)} \\
\quad \text{Angle (rad)}
\end{align*}
\]

Figure 6. Joints Final Position.

Figure 7 (a) contains the graph between the speed of the servo motor vs. the angle of the crank \( \theta_2 \), according to the program is determined a degree of variation of the crank, so that in this case the maximum speed of the mechanism is 0.23 rev/s with \( \theta_2 = 60^\circ \), bearable for muscle rehabilitation of the fingers.

Figure 7 (b) represents the maximum acceleration of the mechanism as a function of the angle of the crank \( \theta_2 \), which has a maximum acceleration of 8.23 cm/s².
5. Electronic and Software Design

The electronic design provides the control of the five interconnected Hitec HS-755HB servos moreover the servos are connected to the computer between an Arduino Uno controller board in charge of the movement of the system that integrates the acquisition of the data of the joints controlled with LabVIEW software, this allows the synchronized control of the servos movements.

The diagram of the connections for electrical system that controls the servos in LabVIEW with the Arduino control card one is illustrated in figure 8.

The servos are controlled by Arduino Uno Board, it sends the data to the computer for all the 5 Hitec HS-755HB servos powered with 5V. The Software LabVIEW sends the movements to be activated with the Arduino board.

The Robotic Equipment has a software that incorporates personalized therapies which have the ability to adapt to the range of motion of each patient, with exercises that have different degrees of difficulty, also concentrates all the information of the patient in a database that measures the progress throughout the therapy all this is accessible through an HMI in the computer as shown in figure 9.
6. CONTROL Design

6.1. PID Self-Tuning

Self-adjusting values for a PID controller are usually based on the mathematical model of known systems. Real-time tuning or estimation of values is used for systems that are very complex. The most suitable parameters can be obtained under full load and no-load operating conditions. For instance, for gain (P) it must be in the Pmin and Pmax range under no-load and full-load conditions, respectively.

Therefore, if the proportional gain (P) increases, as a consequence the rise time and the steady state error will be reduced. In addition, being (P) too large will have extreme oscillation, otherwise being (P) too small there will be a steady state error [10].

Having a pretty big error, then (P) should be working on the largest number to get a quick time increment, Pmax. Otherwise if the error is very small, it has (P) to be Pmin to keep the minimum stable state error; for this reason, a Fuzzy self-tuning PID controller has been selected for this application. The proposed control diagram is shown in Figure 10.

$$K_p(t) = K_p^0 + \Delta K_p \left(1 - \gamma \left(E(t), E'(t)\right)\right)$$

Where: $K_p^0 = P_{min}, \Delta K_p = P_{max} - P_{min}$ and $\gamma = \text{adjustment factor}$

Adjustment factor $\gamma$ is determined by fuzzy rules, based on the same consideration, for (I) is important for the stable state and detrimental for the transient state. Then it has to be increased for the integral constant (I) together with the error reduction and the error derivation.

To obtain the value of the integral constant ($K_i$), have:
\[ K_i(t) = K_i^0 + \Delta K_i \left( 1 - \gamma(E(t), \dot{E}(t)) \right) \]  

(9)

Where: \( K_i^0 = I_{\text{min}} \) and \( \Delta K_i = I_{\text{max}} - I_{\text{min}} \)

Also, for differential gain (D) if it is a large value it can increase the speed response and can cause a steady state error. Then, (D) must be decreased along with the error and the error derivation [11].

To obtain the value of the proportional constant \( (K_D) \), have:

\[ K_D(t) = K_D^0 + \Delta K_D (1 - \gamma(E(t), \dot{E}(t))) \]  

(10)

Where: \( K_D^0 = D_{\text{min}} \) and \( \Delta K_D = D_{\text{max}} - D_{\text{min}} \)

6.2. Fuzzy PID

For the adjustment of the controller parameters, the adjustment factor \( \gamma \) is obtained by means of blurred theory. Therefore, you must set the reference variables, which are the position error and the position error difference.

There are seven linguistic variables used in this document for each reference variable, which are large negatives (LN), medium negatives (MN), small negatives (SN), zero (ZO), small positives (SP), medium positives (MP) and large positives (LP).

The membership functions that represent these linguistic expressions are defined as the triangular type function. To process the reference variable more efficiently, the position error is a linear conversion of ±0.5 degrees to 0 ~ 1. At the same time, the position error difference is converted from ±0.174533 rad/s 0 ~ 1. The output factor is restricted to 0 ~ 1.

The fuzzy if-then rules shown in table 1 are defined below.

| RULE | Error | Adjusting Factor |
|------|-------|------------------|
| -1   | LN    | LN               | LP |
| -2   | LN    | SN               | LP |
| -3   | LN    | ZO               | LP |
| -4   | LN    | SP               | LP |
| -5   | LN    | LP               | LP |
| -6   | SN    | LN               | LP |
| -7   | SN    | SN               | SP |
| -8   | SN    | ZO               | SP |
| -9   | SN    | SP               | LP |
| -10  | SN    | LP               | SP |
| -11  | ZO    | LN               | ZO |
| -12  | ZO    | ZO               | LP |
| -13  | ZO    | SP               | LP |
| -14  | SP    | LN               | LP |
| -15  | SP    | SN               | SP |
| -16  | SP    | ZO               | SP |
| -17  | SP    | SP               | SP |
| -18  | SP    | LP               | LP |
| -19  | LP    | LN               | LP |
| -20  | LP    | SN               | LP |
| -21  | LP    | ZO               | LP |
| -22  | LP    | SP               | LP |
7. **Tests and Results**

The evaluation of the equipment begins with the collection of data from the patient, in addition to the initial positions of each finger, then the therapy consists of previously programmed exercises, from which you can obtain the number of repetitions, the execution time and the speed with each exercise is performed.

7.1. **Fingers Displacement**

In the figure 11 you can see the displacement made for a treatment of four weeks with 20 sessions, you can also notice that the patient's recovery is an average of 1cm per week or in 5 sessions.

![Figure 11. Displacement of the fingers along the therapy.](image)

7.2. **Repetitions number**

The number of repetitions is made according to the difficulty of the exercise and the progress that the patient has during the weeks, also it can be observed in the figure that for the first week the number of repetitions is between 1 and 3, for week 2 and 3 there is a quite remarkable progress with a maximum of repetitions of up to 26 and finally for week 4 there is a maximum of 32 repetitions in figure 12.

![Figure 12. Repetitions number along the therapy.](image)

7.3. **Repetition Time**

The execution time for each of the repetitions, depends on the degree of difficulty of the exercise and the recovery that the patient has during the weeks, it can be observed in the figure that for the first week the execution time is 3:30 with the first exercise and for week 4 in the same exercise is observed
a reduction of time to 1:28, so you can notice that there is a reduction of one minute during the week in figure 13.

![Execution Time of the therapies](image)

**Figure 13.** Execution Time of the therapies.

8. **Conclusions**
The robotic equipment is very useful for the recovery of damage to the hand in patients with Ictus, the experimental results obtained have demonstrated the smoothness of the proposed controller, which is reflected in the early recovery of patients and without causing any damage in each of the exercises for different types of therapies showing recovery of displacement in average of 1cm per week or in 5 sessions.

The design of the robotic equipment is based on anthropometric measurements and the degree of stroke in which the patient is, therefore, the software of the robotic equipment is adaptable to any type, and in turn incorporates personalized therapies with exercises of different types of difficulty, in addition to a database for the analysis and control of the patient's recovery in addition the number of repetition increase exponential between weeks 3 to 32 repetition during treatment.

The robotic equipment its helpful for patients with sequelae in the hand caused by the Ictus, especially in young patients, due to the fact that the sequelae in early ages are long term. Therefore, the device can ensure the recovery of a large part of the movement of the joints of the hand for the reinsertion into daily life and improve the quality of life of the patients describe in periodical reduce of time in each session 1 minute per week.

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