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Mechatronic system to assist rehabilitation therapies for shoulder and elbow joints: Design, kinematic analysis, building and HMI

Sistema mecatrónico para ayudar en terapias de rehabilitación para articulaciones de hombro y codo: Diseño, análisis cinemático, construcción e HMI

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Abstract

This work presents a novel application of a system to assist therapies during upper limb rehabilitation. The design and kinematic analysis of a device proposed is presented. Two mechanisms are driven by only one motor develop circular, arc and linear paths in order to move the shoulder and elbow joints in rehabilitation therapies. The first mechanism M1 position, velocity and acceleration are analyzed and its graphics respect to time are obtained. The main goal is to develop a mechatronic system which help to therapists during shoulder or elbow rehabilitation activities and be able to record the patient movements during the session. The methodology includes the study of art state, biomechanic analysis of shoulder and elbow joints, mechanism type selection and kinematic analysis in MATLAB® and its validation in ADAMS®. The main contribution is the proposal of an easy to use mechanism that develop three paths for upper limb rehabilitation. The amplitude and velocity of movements can be programmed, monitored and registered in a computational system and the information used to improve therapy.

Mechatronic, Rehabilitation, Shoulder, Elbow

Resumen

Este estudio presenta la novedosa aplicación de un sistema mecatrónico en la asistencia en terapias de rehabilitación de la extremidad superior, así como el diseño y análisis cinemático del modelo propuesto. Dos mecanismos impulsados por un actuador desarrollan trayectorias circulares, lineales y de arco, para la movilización de las articulaciones del hombro y el codo como apoyo en las terapias de rehabilitación. Para el mecanismo M1 se realiza análisis de posición, velocidad y aceleración y se obtienen y validan sus gráficas respecto del tiempo. El objetivo es desarrollar un sistema mecatrónico que ayude a terapeutas durante actividades de rehabilitación de hombro y codo y sea capaz de registrar los movimientos de los pacientes durante la sesión. La metodología incluye un estudio del estado del arte, el estudio biomecánico de las articulaciones del hombro y del codo, la selección del tipo del mecanismo y el análisis cinemático en MATLAB® y su validación en ADAMS®. La mayor contribución es la propuesta de un mecanismo de fácil uso que desarrolla tres trayectorias para la rehabilitación de la extremidad superior. La amplitud y velocidad de movimientos puede ser programada, monitoreada y registrada en un sistema computacional y la información usada para mejorar la terapia.

Mecatrónica, Rehabilitación, Hombro, Codo

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Introduction

The World Health Organization reported in 2006 that an estimated 10% of the world’s population lives with some form of disability (WHO, 2006). In Mexico, in the 2010 census produced by INEGI (The National Institute of Statistics and Geography), 5.1% of the population have some kind of disabilities (INEGI, 2010) and 58.3% of them have limitations walking and moving. Number of people with disabilities is increasing mainly due to growth population and aging as well. About 80% of people with disabilities live in developing countries; most of them live in poverty and have difficulty accessing basic health services, including rehabilitation services (WHO, 2006).

CRIQ (Integrated Rehabilitation Center of Queretaro) promotes measures to prevent disabilities, rehabilitation and in achieving the goals of equality and full participation of people with disabilities as well (DIF Queretaro, 2014). CRIQ has manual equipment for physical rehabilitation, Figure 1, which indispensably requires at least one therapist for each patient in rehabilitation. In general, automated equipment for aid limb rehabilitation therapies in health institutions in the Mexican state of Queretaro is scarce, mainly due to high costs. Moreover, it has been found that using robotic systems in rehabilitation therapies respect to manual therapies increase profits because they incorporate intensive tasks and interactive exercises (Burgar, Lum, Shor, & Machiel Van der Loos, 2000)(Heo, Gu, Lee, Rhee, & Kim, 2012). Advanced technology can enrich treatments and can help patients who cannot regularly travel to clinics for treatment; however, this is not superior to traditional treatments and cannot replace therapists (Levanon, 2013).

In this project, design and construction of an automatic system programmed by a therapist, assist patients in circular, linear and rocker movements of upper extremity is proposed. The purpose is to help the patient to mobilize the shoulder and elbow’s joints in the amplitudes and speeds indicated in therapy, primarily flexion and extension movements.

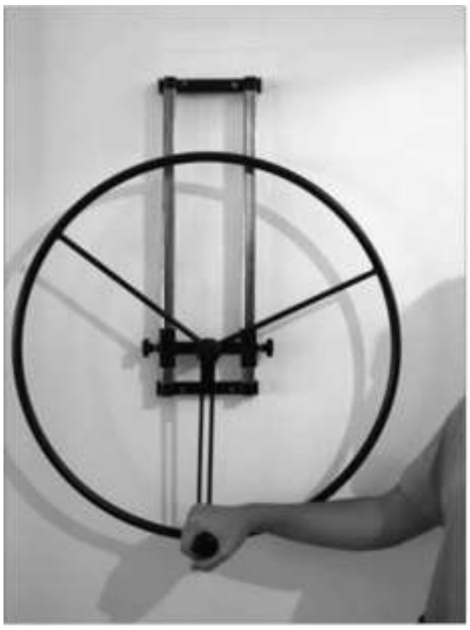


Figure 1 Wheel for shoulder and elbow mobilization (KinesioShop, 2014)

Background

In early 1980, the "Stanford Robotic Aid Project" Professor Bernard Roth Stanford and Inder Perkash, head of "VA Spinal Cord Injury Service" were co-investigators with professors Leifer Dr. Vernon Fickle, the proposed rehabilitation engineering whose goal was to develop a simple general purpose system that could assist individuals with disabilities to achieve independence in activities of daily living (ADLs, activities of daily living) (Burgar et al., 2000). Two exoskeleton systems were manufactured and joined to produce flexion - extension of the elbow and pronation - supination of the forearm in a slave master system. The movements of the master system were reproduced in the slave system via servo positioning systems. The top view shown exoskeleton developed called MIME, Stanford University (USA) Figure 2.

Figure 2 Mirror-Image Motion Enabler, MIME (Burgar et al., 2000)

In 2011 the "Robotic Arm Skate for Rehabilitation" project, developed in New Zealand (Wong, Jordan, & King, 2011) was presented. The device consists of a robotic skateboard for upper extremity rehabilitation; it is able to perform scheduled tasks on a computer, Figure 3. Four electric motors allow you to perform movements on a flat surface. Computer games based exercises encourage the participation of patients and their progress is monitored on the computer.

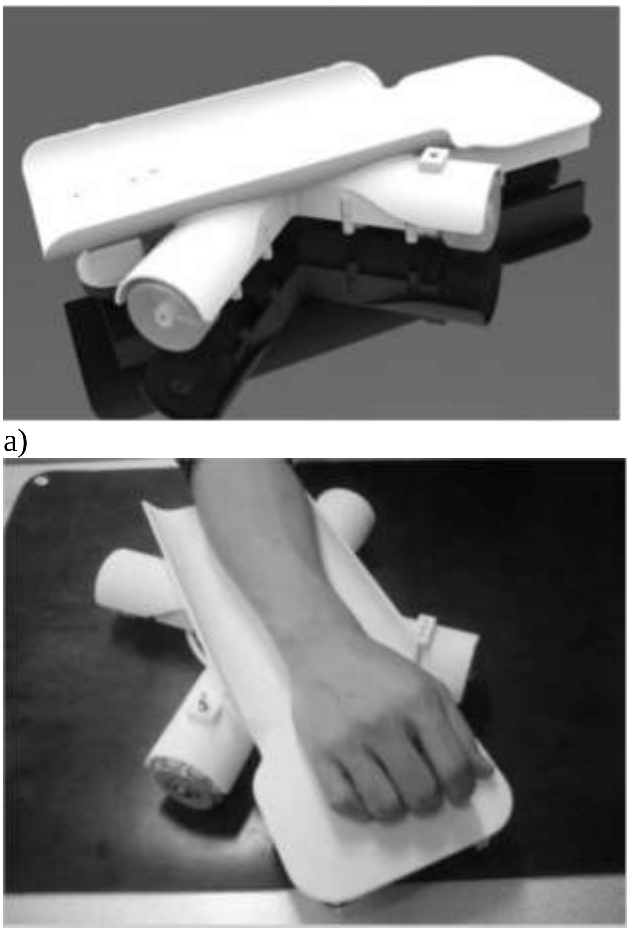

a)
b)

Figure 3 Robotic Arm Skate for Rehabilitation. a) Platform CAD Design, b) Actual Prototype (Wong et al., 2011)

Methodology

In the upper extremity rehabilitation, different movements are performed, among the most important circular and linear paths performed with arm and mobilize mainly the shoulder, elbow and wrist mobilization may be found. There are instruments that assist in achieving the mentioned movements; they can be passive or active as shown in Figure 1**.**

Shoulder Physiology

The shoulder is the proximal joint of upper extremity and is the most mobile of all joints of the human body. Because it has three degrees of freedom, it can guide the upper limb respect to the three planes of space (Kapandji, 2006). In the transverse axis in the frontal plane including B, it allows flexion and extension movements performed in the sagittal plane A. Figures 4 and 5. In the anteroposterior axis, included in the sagittal plane A, allows the movements of abduction and adduction. On the vertical axis, it directs the movements of flexion and extension made in the horizontal plane (cross), with the arm abducted 90 ° (Kapandji, 2006).

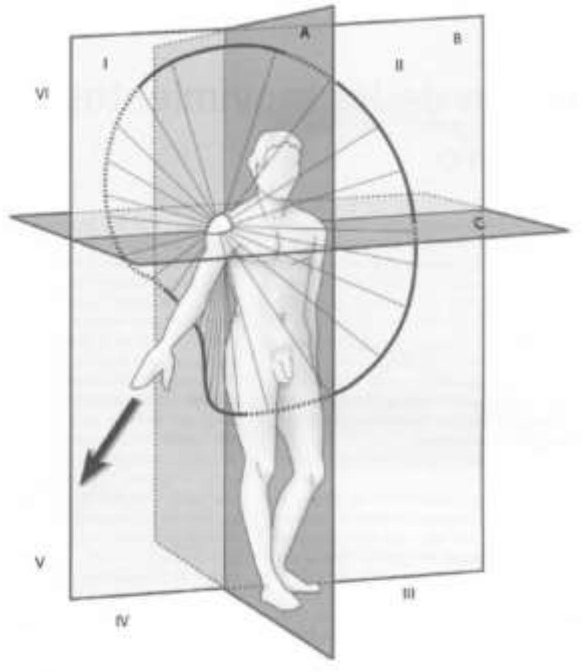


Figure 4 Body Planes, Sagittal Plane A, Plan B and Plan Front Transverse C. (Kapandji, 2006)

Elbow flexion-extension

The elbow is the middle joint of the upper extremity, makes the connection between the arm and forearm. Thanks to that achieved by the shoulder orientation can zoom in or out of the body active extremity: the hand (Kapandji, 2006). Anatomically, elbow has only one joint, but the physiology distinguishes two distinct functions: flexion-extension and supination. Elbow’s flexion has amplitude of 145 ° maximum, Figure 6.

Design

The Project ―Mechatronic System for Rehabilitation Therapies Shoulder-Elbow Joint Assistance‖, ―SIMATREHC‖ is represented in the block diagram in Figure 7. It consists in a mechatronic system, which has two mechanisms.

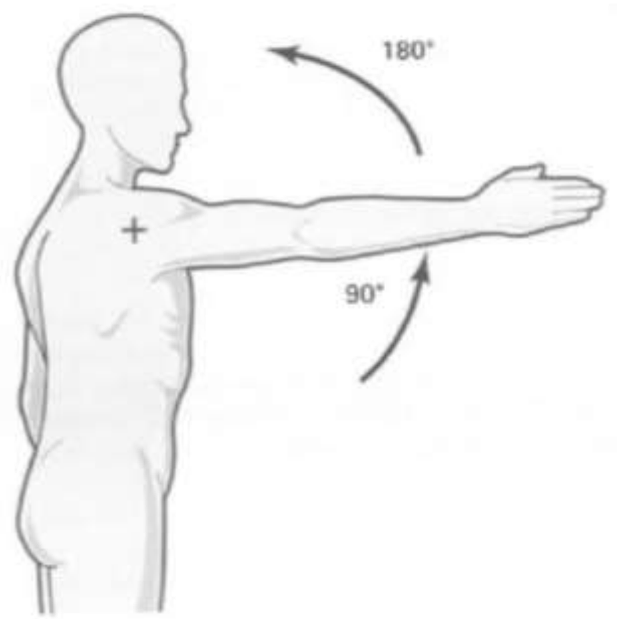


Figure 5 Shoulder flexion and extension movements performed in the sagittal plane (Kapandji, 2006)

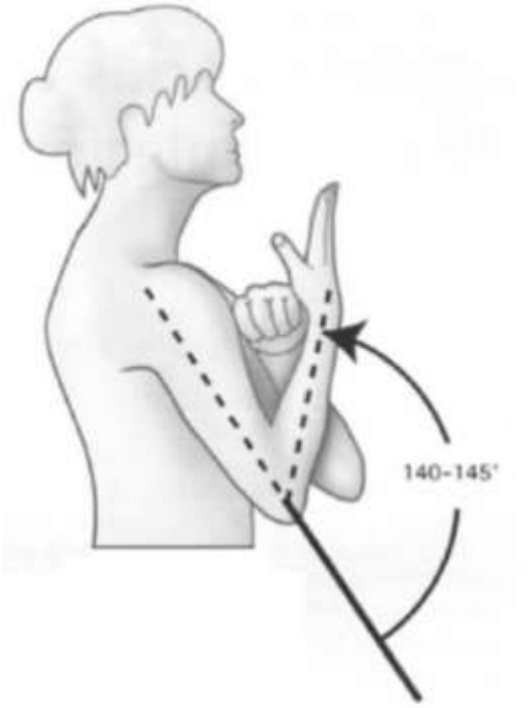


Figure 6 Elbow flexion-extension movements (Kapandji, 2006)

The slider-crank (R-RRT) type mechanism M1 performs circular paths with adjustable diameter and linear paths for mobilization of the elbow and shoulder mainly.

The four bars mechanism M2 performs rocker or arc paths to mobilize the shoulder. One advantage of the system is that it only requires an electric motor to drive both mechanisms, which generates up to six different movements with two system positions: horizontal and vertical (Sosa et al, 2012.). The engine is controlled by computer equipment through a power amplifier to generate movements with amplitude and speed set in therapy. Subsequently a monitoring and data acquisition will be added to record the performance of each patient rehabilitation sessions.

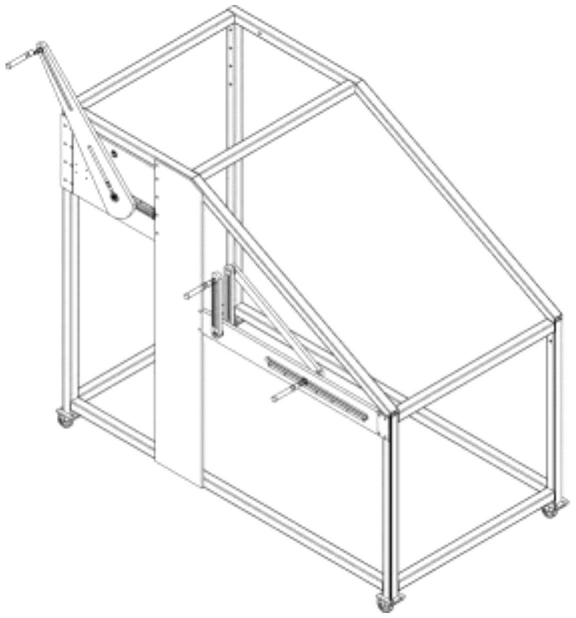


Figure 7 ―SIMATREHC‖ Project Block Diagram (Aguilar-Pereyra, 2014)

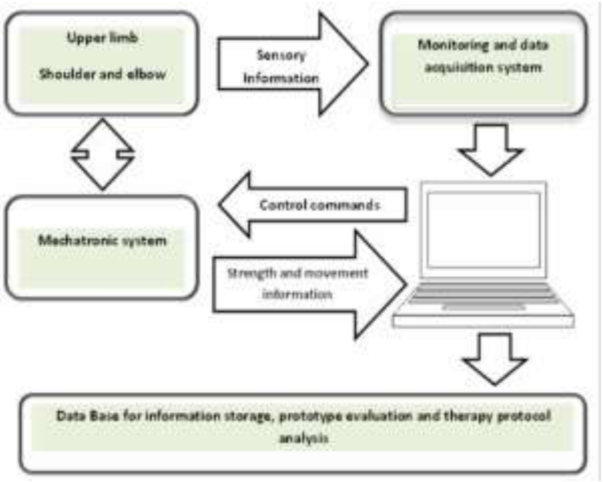
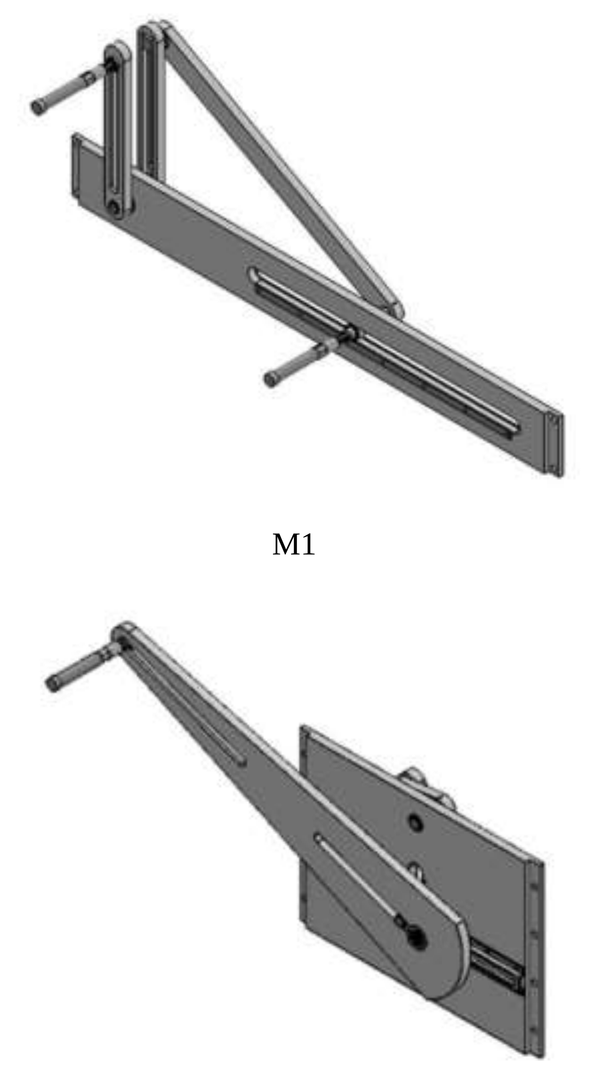


Figure 8 Complete System


M1

M2

Figure 9 The crank and slotted lever type mechanism M1. Four bars type M2

Mechanism M1 develops linear and circular paths and has grips that are installed and uninstalled manually according the movement requirements, Figure 9. The mechanism sizes were established based on the anthropometric measurements of the Mexican population (Chaurand Ávila, León Prado, & González Muñoz, 2007).

Kinematic analysis of mechanism M1

The kinematic analysis of the mechanism was preformed through vectorial analysis; it computes position (Eq. 2 and Eq. 6), velocity (Eq. 3 and Eq. 7) and acceleration (Eq. 4 and Eq. 8) of the points A and B respectively. Figure 10 shows the front view of the mechanism M1; the driver link 1 is the crank and its dimension is OA. The coupler link dimension is AB and the base link is fixed.

The first step performs a circular movement over point O, so that point A develops circular movement centered at point O and radius OA a path. Point B develops a linear path on the x axis, the amplitude of displacement depends on the angle θ turn the crank and is maximum for θ = π, 2π.

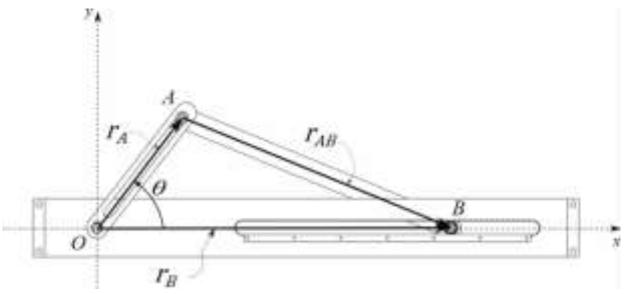


Figure 10 Front view of mechanism M1

If the links are represented by two-dimensional vectors and a framework **xy** originating at point O is defined because it is fixed, then the position, velocity and acceleration of points A and B are defined by the **r**A and **r**B vectors and their first and second derivatives with respect to time. The A point position is defined by the angle θ:

$$\mathbf{O} = 0\hat{\imath} + 0\hat{\jmath} = (0,0) \quad (1)$$

$$\mathbf{r}_\mathrm{A} = \mathrm{x_A}\hat{\imath} + \mathrm{y_A}\hat{\jmath} \quad (2)$$

$$= \mathrm{L_1}\cos\theta\,\hat{\imath} + \mathrm{L_1}\,\mathrm{sen}\,\theta\,\hat{\jmath}$$

$$\mathbf{v}_\mathrm{A} = \dot{\mathbf{r}}_\mathrm{A} = \dot{\mathrm{x}}_\mathrm{A}\,\hat{\imath} + \dot{\mathrm{y}}_\mathrm{A}\hat{\jmath} \quad (3)$$

$$= -\mathrm{L_1}\dot{\theta}\,\mathrm{sen}\,\theta\,\hat{\imath} + \mathrm{L_1}\dot{\theta}\cos\theta\,\hat{\jmath}$$

$$\mathbf{a}_\mathrm{A} = \ddot{\mathbf{r}}_\mathrm{A} = \ddot{\mathrm{x}}_\mathrm{A}\,\hat{\imath} + \ddot{\mathrm{y}}_\mathrm{A}\,\hat{\jmath} \quad (4)$$

$$= (-\mathrm{L_1}\ddot{\theta}\,\mathrm{sen}\,\theta - \mathrm{L_1}\dot{\theta}^2\cos\theta)\hat{\imath}$$

$$+(\mathrm{L_1}\ddot{\theta}\cos\theta - \mathrm{L_1}\dot{\theta}^2\,\mathrm{sen}\,\theta)\hat{\jmath}$$

where L1 is the magnitude of the vector rA, is the angular velocity and is the angular acceleration.

Because the movement of point B is along axis **x** and the length of vector **r**AB is constant, the component of point B in axis **y** is cero and its position, velocity and acceleration are:

$$(x_B - x_A)^2 + (y_B - y_A)^2 = AB^2 \quad (5)$$

$$\mathbf{r}_B = x_B\hat{\imath} + y_B\hat{\jmath} \quad (6)$$

$$= \left(x_A + \sqrt{AB^2 - y_A^2}\right)\hat{\imath} + 0\hat{\jmath}$$

$$\mathbf{v}_B = \dot{\mathbf{r}}_B = \dot{x}_B\,\hat{\imath} + \dot{y}_B\hat{\jmath} \quad (7)$$

$$= (-L_1\dot{\theta}\,\mathrm{sen}\,\theta + L_1\,\omega_2\,\mathrm{sen}\,\theta)\hat{\imath} + 0\hat{\jmath}$$

$$\mathbf{a}_B = \ddot{\mathbf{r}}_B = \ddot{x}_B\,\hat{\imath} + \ddot{y}_B\,\hat{\jmath} = \quad (8)$$

$$\Big(-\ddot{\theta}_1 L_1\,\mathrm{sen}\,\theta - L_1\dot{\theta}^2\cos\theta + \alpha_2\,L_1\,\mathrm{sen}\,\theta -$$

$$\omega_2^2\sqrt{AB^2 - y_A^2}\Big)\hat{\imath} + 0\hat{\jmath}$$

where:

$$\omega_2 = \frac{-L_1\dot{\theta}\cos\theta}{\sqrt{AB^2 - y_A^2}} \quad (9)$$

$$\alpha_2 = \quad (10)$$

$$= \frac{-L_1\ddot{\theta}\cos\theta + L_1\dot{\theta}^2\,\mathrm{sen}\,\theta - L_1\,\omega_2^2\,\mathrm{sen}\,\theta}{\sqrt{AB^2 - y_A^2}}$$

Results

Because the movement of point B is along axis **x** and the length of vector **r**AB is constant, the component of point B in axis **y** is cero and its position, velocity and acceleration are: Design of mechanisms M1 and M2 are presented in Figure 9. Figure 11 shows the kinematic simulation results in MatLab® of movement equations for points A and B of mechanism M1, with lengths OA = 301 mm and AB = 625 m~~m, circula~~r and lineal paths are developed. Results of position, velocity and acceleration simulation of points A and B for constant angular velocity ω= π rad/s in driver link 1 are shown in figures 12 and 13.This results have been validated with the program Adams® with the model developed in Solidworks®.

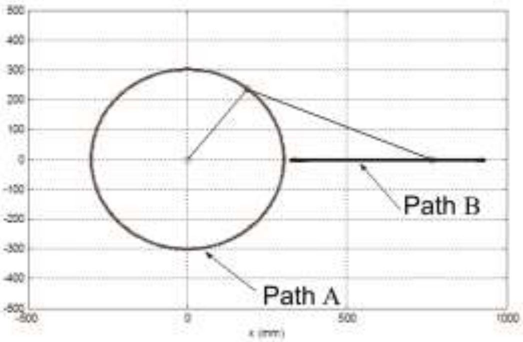


Figure 11 Simulation results in MatLab® of mechanism

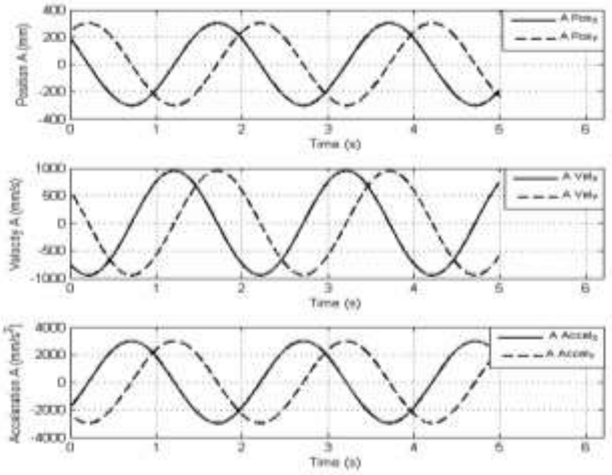


Figure 12 Simulation results in MatLab® of position, velocity and acceleration of point A of mechanism M1

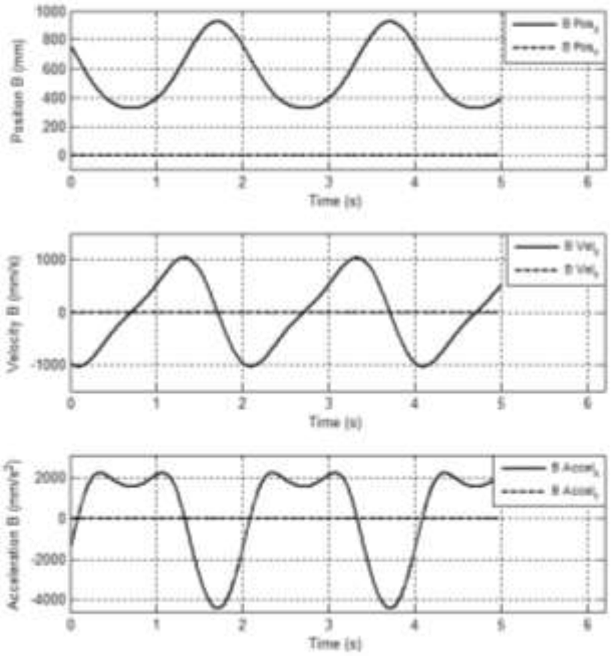


Figure 13 Simulation results in MatLab® of position, velocity and acceleration of point B of mechanism M1

Interface for programming and monitoring

The movements of mechanism are programmed by therapist through of an interface. Single movements can be executed in mode jog, a velocity limited has been established. The interface allows execute repetitive movements with amplitude, velocity and number of repetitions established previously. Figure 14 shows the human-mechanism interface developed in software LabVIEW®.

Figure 14 Interface for programming and monitoring developed in LabVIEW®

The user interface for mechanism control has three displays, through of that user, who can be medic or therapist, sets the values of parameters for mechanism movements. The user can observe the development of mechanism in a display for monitoring. Three aspects of this rehabilitation system development are, in importance order, safety, efficacy and efficiency.

The user interface has three operation modes: Configuration, Teaching and Programming. In Configuration mode, parameters for digital communication between computer and control system are set. Test of performance and safety and movements monitoring can be executed to evaluate limit switch and emergency stop. Functions for Teaching and Programming modes are shown in Table 1 and Table 2.

Teaching
Manual setting of current position
Setting of velocity for manual movement
Recording current position in registers
Cleaning position registers
Editing position registers
Turning on and off digital outputs (O1,O2)
Setting virtual limit for movements
Setting home position
Key—Play‖ for intentional execution
Recording movements graph
Recording movements data file
Emergency Stop routine

Table 1 Functions for Teaching mode

Programming
Setting movements sequences among positions
Beginning of movements at home position
Selection of positions from registers
Setting velocity for single movement
Setting time pause between movements
Turning on and off digital outputs (O1,O2)
Selection step by step or continuous mode
Forward or backward sequences execution
Key—Play‖ for intentional execution
Recording of graphic of movements
Recording of movement file
Emergency Stop routine

Table 2 Functions for programming mode

Safety functions for operation of mechanism

—Home‖Position: the initial position of mechanism should be at middle point of full range movement. This position, defined as —Home‖, corresponds to neutral position, in which flexors and extensors muscles activity is lowest.

Intentional Execution: to be able for moving the mechanism or turning on digital outputs of the system is indispensable to enable key —Play‖ simultaneously with the other function, it is to avoid accidental activation.

For example, for manually moving the mechanism, is necessary to turn the position control knob simultaneously with key —Play‖activation. This action can be described by Eq. (11).

$$FunPosition = CPosition \cdot Play \qquad (11)$$

where:

FunPosition is the function that sends the movement command to the motor driver.

CPosition is the virtual knob in the user interface which set the value of reference position for mechanism motor.

Play is a virtual key knob in the user interface which takes boolean values.

Functions that require intentional execution are: CPosition, CVelocity, Save, Reset and Turning on and off digital outputs.

Emergency Stop: when a virtual or real emergency stop button is activated, the emergency routine is executed, the mechanism movement is stopped and digital outputs are turned off. The emergency stop button is retentive and causes a fault in the system when is activated. This fault is eliminated by sequential activation of keys ―Play‖ and ―Clear‖.

Functions of Teaching mode

Manual setting of current position: Cposition knob set the value of reference for the angle of link 1 respect to ―Home‖ position; it is an intentional function. If the position of knob was lower than the virtual LowerLimit or upper than UpperLimit, the value of Cposition will take the value of the virtual LowerLimit or UpperLimit.

Setting of velocity for manual movement: the slider CVelocity establish the value of highest velocity for mechanism movements, the range is from 0-100% of motor highest absolute velocity; this function is intentional.

Recording current position in registers: the current position value, including initial position, is saved into a register by pressing key ―Save‖. The value of knob CPosition is recorded in a register of position array, the index begins in zero and increments its value every time that key ―Save‖ is pressed; this function is intentional.

Cleaning position registers: when key ―Reset‖ is pressed, all the array of position registers is saved with zeros, a zero is saved to the Index; this function is intentional.

Editing position registers: to change the value of a position register is necessary to select the value of ―Index‖ that corresponds to desired register using keys ―Prev‖ and ―Next‖, finally pressing key ―Save‖ and the new position value is recorded.

Turning on and off digital outputs (O1, O2): to set or reset digital outputs is necessary to activate the key that corresponds; previously key ―PLAY‖ should be activated because this function is intentional

Setting virtual limit for movements: to set virtual limits of movement, that are different of absolute limits, values for controls LOWERLIMIT and UPPERLIMIT should be established. This is a preventive action to configure movements in a smaller range tan full range. Recording movements graph: this function saves an image file of movements.

Recording movements data file: this function saves a text file of movements, it includes time, position and velocity for each sample. This function is executed automatically by pressing key ―STOP‖.

Finally, Figure 15 shows prototype built, it corresponds to Figure 8.

Figure 15 Prototype

Conclusions

Application of mechatronic systems can supply external forces for limbs mobilization in rehabilitation therapies; it cannot substitute human therapist in none case, moreover this kind of systems should be used under strict professional supervision. The proposed system allows three different movements with only one motor, which supplies the strength for controlled movements in position, velocity, acceleration and iterations. This Project has a wide scope, actual status, presented here, includes design and kinematic analysis of mechanism M1. Mechanisms design is based on movements with circular, linear and arch paths and the anthropometric measurements of the Mexican population. Mechanisms can be adjusted to different zises of shoulder and elbow. Future work includes dynamic analysis for torque required in motor, instrumentation for strength measuring and the full system evaluation.

Acknowledges

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