Proposal for the design and manufacture of a dynamic orthoses prototype for hand rehabilitation

Propuesta para el diseño y manufactura de prototipo de órtesis dinámica para rehabilitación de mano

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DOI: 10.35429/JTP.2022.22.8.19.29 Received September 15, 2022; Accepted December 10, 2022

Absreact

Objetivos The objective of this research is to propose a prototype design of the dynamic orthosis adaptation system for hand rehabilitation. For this, the following methodology was used: the biomechanical and architectural foundations and the functional patterns of the fingers of the hands were previously analyzed, later the test subject was chosen and the corresponding measurements were taken, to finalize the design and manufacture of the prototype. The dynamic orthosis prototype proposed in this research is controlled by servomotors coupled to rings with rigid links, which transmit movement at a certain speed, from the motor axis to the fingers, simulating the biomechanical movements of flexion and extension. The design of this device is focused on users who do not have movement in the phalanges, and thus prevent their muscles from atrophying. The contribution of this research is the development of an economic device that can partially or totally replace the physiological therapies of a patient with problems in the upper limb (hand).

Orthosis, Rehabilitation, Biomechanical

Resumen

El objetivo de esta investigación es proponer un diseño prototipo del sistema de adaptación de órtesis dinámica de rehabilitación de mano. Para ello se utilizó la siguiente metodología: se analizó previamente los fundamentos biomecánicos, arquitectónicos y los patrones funcionales de los dedos de las manos, posteriormente se eligió al sujeto de prueba y se tomaron las mediciones correspondientes, para finalizar con el diseño y la manufactura del prototipo. El prototipo de órtesis dinámica propuesto en esta investigación, se controla mediante servomotores acoplados a anillos con eslabones rígidos, los que transmiten el movimiento a una velocidad determinada, del eje del motor a los dedos, simulando los movimientos biomecánicos de flexión y extensión. El diseño de este dispositivo, está enfocado a usuarios que no tengan movimiento en las falanges, y así evitar que sus músculos se atrofien. La contribución de esta investigación es el desarrollo de un dispositivo económico que pueda sustituir parcial o totalmente las terapias fisiológicas de un paciente con problemas en miembro superior (mano).

Órtesis, Rehabilitación, Biomecánica

Citation: MONTIJO-VALENZUELA, Eliel Eduardo. Proposal for the design and manufacture of a dynamic orthoses prototype for hand rehabilitation. Journal of Technological Prototypes. 2022. 8-22: 19-29

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Introduction

In the last decades it has been observed that a patient's recovery has better results when he or she has a rehabilitation based on therapies, which are regularly applied by physiotherapists and specialised personnel (Merchant *et al*., 2017). Therapies with dynamic orthoses have demonstrated positive and immediate effects in the recovery of patients with pathologies or injuries associated with the movement of human body limbs (Lu *et al.*, 2022; Kwan *et al*., 2021; Martins *et al.*, 2019; Kora and Abdelazeim, 2019 and Katsuhira, 2018), however, this is a task that requires considerable financial investments by public health institutions, in addition to requiring trained human capital (Duncan *et al*., 2005).

Because of this problem, rehabilitation treatments, including orthoses, have been developed and refined. Orthoses are devices applied externally on the body or a body segment to improve its function (Vargas, 2017), and can be biomechanical devices or appliances, splints, technical aids and supports, which are used in orthopaedics, physiotherapy and occupational therapy (Gavilán, 2017), as they are a very effective method for the prevention and management of contractures; and are part of the comprehensive rehabilitation system (Chandler, 1983).

The purpose of a dynamic orthosis to increase motion is to provide continuous stretch to a stiff body part in one direction and allows the body part to move in the opposite direction (Middleton, 2019). Dynamic orthoses (orientation of the technological prototype of this research), serve to maintain stability, while providing dynamic corrective forces in a suitable position, functionally assisting the weak extensor muscles of the hand (Ayala *et al,* 2015), these can be fitted with actuators such as servomotors (direct current motors, whose shaft rotation can be controlled), adapted with rigid shafts, springs, elastics or rubber bands to provide direct dynamic assistance to the recovery limbs and often, elastic bands are used to provide stretch or other devices that help to perform the movement (Liu *et al.* , 2022; Sun *et al*., 2022; Sheikh *et al*., 2021; Ashmi *et al*., 2021; Xu *et al.,* 2021; Tsabedze *et al*., 2021 and Zhu *et al*., 2021).

In the literature reviewed, a wide range of orthoses applied to different body limbs is shown, ranging from conceptual designs of exoskeletons to assist lower limb rehabilitation (Zhou *et al*., 2021; Li *et al*., 2021; Wang *et al*., 2021; Peng *et al*., 2020 and Shi *et al*, 2019), mechanical design of an exoskeleton for upper limb rehabilitation (Grosso and Tibaduiza, 2009), and recently, dynamic orthotic designs for upper limb rehabilitation with control systems (Wong *et al*., 2022; Wang and Barry, 2021 and Medina *et al*., 2021) and artificial intelligence (Pattanshett and Khan, 2022; Huang and Wang, 2022 and Velez *et al*., 2021).

Problem statement and rationale

Disability in an individual is understood as any restriction or absence of the ability to perform an activity in the manner or within the range considered normal (Asún, 2017). More than one billion people worldwide suffer from some form of disability, and between 110 and 190 million adults have significant difficulties in functioning (WHO, 2017). In 2014, in Mexico, 3.8 million women and 3.3 million men had a disability, and 33% of this figure had difficulty moving or using their arms or hands (Instituto Nacional de Estadística y Geografía, 2016).

In Mexico, the number of people trained in the fabrication and fitting of prostheses and orthoses is limited. In context, by 1982 the only school dedicated to this speciality in the country closed and currently some institutions in Veracruz and Querétaro are joining efforts to develop the professional career of prosthetists and orthotists, however, the development of this area is still stagnant (Vázquez, 2016).

The World Health Organisation (WHO) states that for every 500 people with disabilities, there should be one professional prosthetist or orthotist (Gómez, 2021). Taking the data established by INEGI and the recommendation established by the WHO, there should be at least 2000 professionals in this speciality area, however, there is only around 15% of the demand.

It is necessary to generate development projects in innovation based on the argument of being able to assist the performance of hand mobility, which, being impaired, impedes the performance of daily life activities.

ISSN 2444-4995

For this reason, through the development of this orthosis, it will be possible to replace the complete or partial functionality of the flexion and extension movements of the fingers of the hand. Based on the above, the aim is to develop an external aid of the dynamic rehabilitation orthosis type, which seeks to supply or complement the altered biomechanical performance at hand level, thus allowing the flexion and extension movements of the phalanges to be carried out by means of a system integrated into the orthosis based on servomotors, to facilitate the performance of the upper limb.

Research objectives

The general objective of the research is to propose a prototype design of a servomotor-controlled dynamic rehabilitation orthosis adaptation system for upper limb finger flexion and extension movements, to strengthen the hand of people with early stage injuries, through low-cost technologies (integrated control devices, servomechanisms and additive manufacturing).

The specific objectives are:

– Select the test subject for the determination of the geometric and biomechanical parameters of the hand.
– Model the device using Computer Aided Design (CAD) software, Solidworks 2016.
– Manufacture the model using additive manufacturing techniques.
– Simulate the rotational speeds of the servomotors using Proteus Design Suite software.
– Connect the servomotor control system with Arduino.
– Integrate the mechanical and electronic parts to generate the prototype.

Theoretical reference

The origin of orthotic and prosthetic practice can be traced back to antiquity with early orthopaedic craftsmen using leather, textiles and metals as fabrication materials for splints and bone repair, based on humanity's physical need for functional and cosmetic integrity in response to limb loss (Edelstein and Bruckner, 2002).

Although these early practitioners were innovators in this area, during the 19th century their craft developed very slowly (LeTourneau Prosthetics, 2017), with significant records until 1905, when Whitman Brace invented the first full foot orthosis made of heavy metal (Bin, 2019). It was during World War I when the ten leading prosthetics firms in the United States met to determine the state of the art in prosthetic technologies and manufacturing methods, leading to the creation of the Artificial Limb Orthotics and Manufacturers Association, an event considered to be the turning point in the development of orthotics and prosthetics in this country (LeTourneau Prosthetics, 2017).

Between 1945 and 1976, the Veterans Administration, universities, private companies and other military research units were contracted to conduct numerous prosthetics and orthotics research projects (Thompson, 2019). Increased demand for services in orthotics and prosthetics led to improved components, materials and clinical skills from 1960 onwards (LeTourneau Prosthetics, 2017), with composite materials, such as fibreglass and thermoplastics, being introduced to the field (Terekho and Chistyakov, 2021). The field of prosthetics and orthotics is constantly changing, with newer technology and materials being incorporated into everyday practice, and research in the field is increasing as interest in restoring or simulating lost human function becomes more of a reality with scientific and technological advances (Kelly et al., 2007).

An emerging technology in the field of orthotic fabrication is additive manufacturing (contemplating 3D printing), which reduces part manufacturing costs by reducing material and time to market, as well as increasing design freedom, potentially resulting in weight savings and easier assembly (Williams et al, 2016). Additive manufacturing processes take information from a computer-aided design (CAD) file that is subsequently converted into a stereolithography (STL) file, in this process, the drawing made in the CAD software is approximated by triangles and slices, which contains the information of each layer to be printed (Wong and Hernandez, 2012). Multiple research and development of orthotics are currently related to additive manufacturing (Patel and Gohil, 2022; Brognara *et al*., 2022; Wang *et al*., 2020; Banga *et al*., 2020; Liu *et al*., 2019; Alqahtani *et al*., 2019 and Banga *et al*., 2018).

ISSN 2444-4995

Another major technology that has been evolving since 2005 and permeating prototype development is the open-source electronics platform Arduino, which combines software and hardware for multiple functions, including control commands through reading input (a sensor or a button) and converting an output (turning on/off a motor or a lamp), which has enabled adaptation to new application needs and challenges, including 3D printing, the Internet of Things (IoT), wearables and embedded environments (Moreno and Córcoles, 2018).

For the purposes of dynamic orthotics fabrication, Arduino is used as a controller for actuators including servo motors; a rotary actuator that allows precise control of angular position, velocity and acceleration, consisting of a suitable motor coupled to a sensor to feedback position from a set of gears and a control board, with the ability to be placed in any position generally from 0 to 180° (Chhabra *et al*., 2015). Multiple research and orthotics development is currently related to Arduino integration and servo motor control (Narote *et al*., 2022; Ozsahin and Ozsahin, 2022; Kashizadeh *et al*., 2022; Aljobouri, 2022; Smajic and Duspara, 2021 and Hernandez *et al*., 2021).

Methodology to be developed

The basis of this research is based on the analysis of the biomechanics, architecture and functional patterns of the fingers of the hands, based on Peña *et al*. (2012), Arias (2012), Viladot and Ruano (2001) and Smith *et al*. (1992). The methodology used in the development of the prototype is based on Becker Orthopedic (2022), Yung *et al.* (2018), Merchant *et al*. (2018), Palousek *et al*. (2014), Boyard *et al*. (2014) and Gehlot et al. (2018). This research has 6 main stages, described below:

Stage 1: Test subject selection. In this stage, a female subject was chosen to design the dynamic orthosis, based on the geometric and dimensional considerations of her hand. It is worth mentioning that the test subject does not present any type of injury, malformation or disability in her hand (healthy test subject).

Stage 2: Dimensional measurement of the test subject's hand. In this stage, with the help of a tape measure and paper replicas of the morphology of the test subject's hand, the dimensional data of the entire structure of the subject's right hand was obtained (Figure 1), following the methodology of Becker Orthopedic (2022).

Figure 1 Some dimensional measurements of the test subject's hand

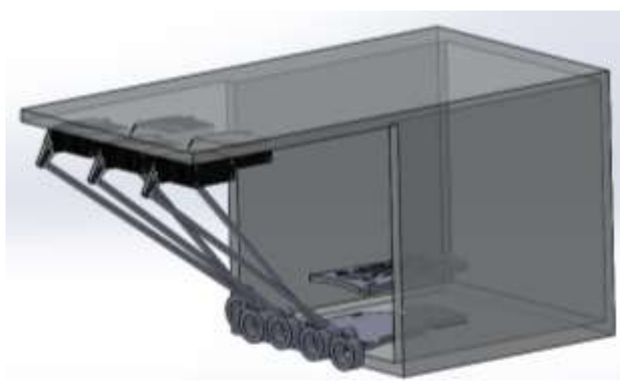

Figure 2 Mechanism assembly in Solidworks software

Stage 3. Design of the mechanism in Solidworks software. Once the dimensions and tolerances of the test subject's hand were collected, the mechanism was designed in CAD using Solidworks software (Figure 2), applying the joint methodology of Merchant *et al*. (2018) and Palousek *et al*. (2014). The elements of the assembly are shown in Table 1.

ISSN 2444-4995

Name of the part	Quantity
Lower bra	1
Upper clamp	1
Holding ring 1 (Thumb)	1
Holding ring 2 (Index, middle and ring finger)	3
Holding ring 3 (Little finger)	1
Cylindrical holder 1	1
Cylindrical support 2	2
Cylindrical support 3	2

Table 1 Integral elements of the dynamic orthosis mechanism

Stage 4. Manufacture of the final assembly. Each of the parts designed in CAD were passed directly to the MakeBot® software for additive printing simulation (Figure 3). Once the simulation parameters had been analysed and validated, each of the parts mentioned in Table 1 (Figure 4) were printed, based on the methodology used by Boyard *et al*. (2014). As a result, 2 parts printed in PLA material were obtained (Figure 5).

Stage 5. Electronic simulation and commissioning of servomotors. For this stage, the Proteus Design Suite software was used to determine the rotation and speed of the servomotor axes (Figure 6), using the methodology employed by Gehlot *et al*. (2018). Once the software simulation was analysed and validated, the circuit was physically integrated through Arduino (Gehlot *et al*., 2018).

Stage 6. Assembly of mechanical and electronic components. Once the parts that make up the mechanism were printed, the orthosis was assembled based on the design in Figure 2. The placement of the servomotors coincided with the distribution of the fingers and the length of the phalanges of the test subject's hand. To attach the rings to the servomotors, PLA cylinders were used, whose function is to make a linking connection to the phalanges of the hand, and thus to transmit the movement from the servomotor to the fingers. To join the lower and upper fasteners, "Velcro" was used as an adhesive material, recommended by Fitzgerald *et al*. (2004), as well as being economically viable and easy to remove (Figure 7).

Figure 3 Manufacture of individual parts in PLA material with AXIOM printer. ®

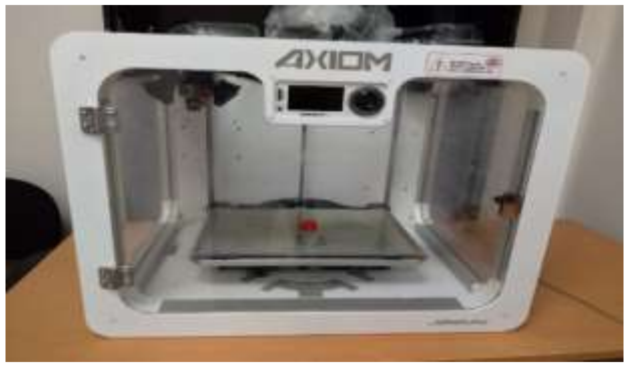

Figure 4 3D printing of the upper bra at AXIOM

Figure 5 Manufacture of individual parts in PLA material with AXIOM printer

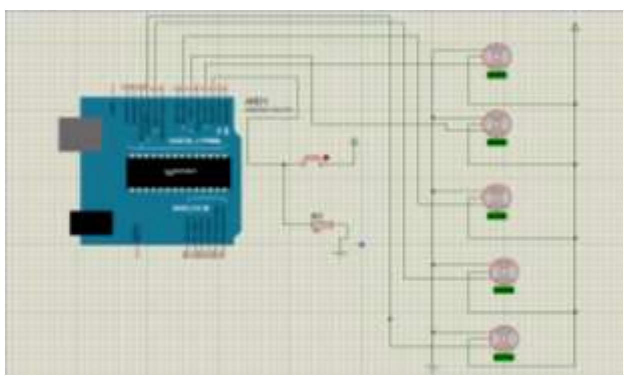

Figure 6 Simulation of rotational speed in servomotors with Proteus Design Suite, with Arduino Nano controller

Figure 7 Upper and lower fastener connections with "velcro"

Results

Based on the literature on the functional biomechanics of the hand, a prototype of a dynamic orthosis with one degree of freedom in the phalanges of the fingers was fabricated. The degree of freedom corresponds to the flexion/extension movement of the fingers. This movement is realised by means of a simple linkage mechanism, consisting of rigid fasteners (links), anchored to the servomotor shaft, and directly connected to the rings for the transmission of movement to the fingers. The 180° circular motion of the servomotors generates a linear motion in the rigid fasteners, allowing flexion/extension motion in the fingers.

The prototype was used by the test subject to perform some measurements, which involved measuring the angles formed by the fingers when the fingers are extended (open hand). In this situation the measurements were as follows: separation between thumb axis and index finger = 44°, index finger and middle finger = 22°, angle formed by the third and fourth finger = 19°, and, finally, angle formed by the fourth and fifth finger = 21°, all values agreeing with (Smith-Agreda, Ferres and Montesinos, 1992), with a margin of error of less than 5%. In the flexion measurements (closed hand), it was observed that the mechanism performs an inclination in the fingers of almost 90° in the index finger, with an increase in the lateral fingers as it approaches the little finger, coinciding with the information analysed in (Viladot and Ruano, 2001).

Qualitatively, it was observed that the movement made by the rigid links between the rings and the servomotor axes generate a movement very similar to that of the biomechanics of the hand, however, this alters as the speed of the motor increases. The prototype is shown in Figure 8.

Figure 8 Prototype dynamic orthosis

Conclusions

A dynamic hand orthosis helps the recovery of the hand when it suffers an accident that compromises the correct functionality of bones, muscles, ligaments and/or tendons. To help more people with physical disabilities, the manufacture of assistive devices based on simple and inexpensive technology is essential for the field of rehabilitation, especially in developing countries such as Mexico.

In this study, a prototype of a dynamic hand orthosis made from 3D printing was presented. The innovation of this prototype consisted in the movement of flexion and extension in an assisted manner, that is, automatically by means of a mechanism controlled by servomotors with limited rotation, for those cases where the user has no movement in the phalanges and thus prevents the muscles from atrophying. The contribution of this research is the development of an economical device that can partially or completely replace the physiological therapies of a patient with upper limb (hand) problems.

With the help of a physiotherapist, important decisions can be made to decide the type of therapy that can be performed with this orthosis system and thus make the required modifications to the prototype; selection of materials, programming, sizing and actuators, to name a few, all to meet the needs of the patient.

It is important to note that the prototype is currently programmed for the fingers to move simultaneously, however, the code is flexible and the servomotors could be programmed to move one at a time, two at a time or any combination required, as each case is different, and therefore with different needs. These configurations can be added through a selector (a button or knob, for example) to suit the user's needs. Although the long-term usability of the prototype has not been evaluated, it is hoped that future optimisations with the help of professionals in the field can benefit users with injuries to other body parts and its possible application in clinics and hospitals. This research is still at an early stage, however, the prototype dynamic orthosis developed from 3D printing and electronic actuation devices appears to be cost-effective and promising for use as an alternative to conventional rehabilitation technologies and techniques.

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