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FACULTAD DE INGENIERÍA

Escuela Académico Profesional de Ingeniería Mecatrónica

Tesis

Design of a 3DoF Passive Hip Exoskeleton for Rehabilitation

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Para optar el Título Profesional de
Ingeniero Mecatrónico

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Design of a 3DoF Passive Hip Exoskeleton for Rehabilitation

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Abstract— **In recent years, many mechanisms have been developed to help people with reduced mobility, especially for people with injuries that impede the mobility of the lower part with respect to the hip. That is why this work presents the design of a passive hip-based exoskeleton of a standard size so that it can be used in the rehabilitation area. Most hip exoskeletons make a strong call on walking assistance rather than on the stability of the user, so the design is adjusted to the stability, the objective of this work is to design a self-balancing exoskeleton with control by sensors that detect the hip rotation and send a signal to the microcontroller which assists the movement of the hip, allowing the servos to move according to the degrees detected by the sensor. In addition, the exoskeleton has been designed using CAD software, using aluminum elements to provide lightness and robustness to the exoskeleton and, at the same time, an external PLA plastic shell is made, in order to provide lightness, flexibility and limited volume, when performing a stress test shows optimal results that allows us to know the durability and comfort of the exoskeleton.**

Keywords— ***Exoskeleton, rehabilitation, microcontroller, CAD software, sensor.***

I. INTRODUCTION

Nowadays, the increase in accidents is causing bone damage, locomotor disorders, and the natural deterioration of the resistance of human joints [1]. For this reason, it has promoted innovation in various technologies that help improve the quality of life of people, obtaining a benefit which is the development of exoskeletons focused on the hip joint that help the rehabilitation process and allow to perform the functions of a real hip as close as possible [2].

The exoskeleton is an electromechanical structure worn by the user that adapts to the shape and functions of the human body to assist in daily tasks, rehabilitation, and strengthening [3-4]. In addition, the exoskeleton can improve the extension of the human limb and treat fragile muscles, joints, or parts of the skeleton. Its classification is related to the function of the human body and can be acted passively and/or actively [5].

Babič et al. [5] addressed low back pain as one of the most frequent health problems in modern society, for which the electromechanical design of a passive exoskeleton with ON/OFF control for its operation was developed. In addition, in the research "Design of a lower limb exoskeleton" [6] the proposed in the title is realized, within the lower extremities are included the hip, knee, and ankle, this exoskeleton has a communication system composed of the Arduino one development board, a DC controller and a DC motor, it should be noted that it was designed to help people who have limitations in their mobility.

Zhang et al. [7] developed an exoskeleton that involves the user in motion control, unlike our design, in which the exoskeleton is powered by a microcontroller in addition to acceleration and movement sensors. Naghavi et al. [8] presented an article in which a controller was proposed that assists according to the user's ability to perform the assigned task, such assistance is given by an impedance controller, in addition, the adaptive torque controller uses a generalized fuzzy logic, for the design of this research it is planned to use an ON/OFF control for the operation of the system.

Seireg y Grundman [9] from the University of Wisconsin designed and implemented an exoskeleton to facilitate walking, sitting, standing, and climbing stairs. This exoskeleton is also hydraulic. It also has active hip joints. and knee support flexion/extension. The remaining degrees of freedom are passive, or spring controlled.

This article details the design of a passive exoskeleton for hip rehabilitation and assistance based on the anatomy of the human body. The work begins with the determination of the anatomical factors of the human skeleton involving the hip. Subsequently, 3D modeling is performed with the Inventor program, describing the mechanical parts of the exoskeleton. Once the mechanism is ready, the next step is the design of the electronic control. Finally, the designed exoskeleton is tested in a laboratory environment.

II. MATERIALS AND METHODS

For the design of the exoskeleton, the VDI 2221 methodology is used, which was developed by "The Association of German Engineers" (Verein Deutscher Ingenieure, VDI), which begins with the search for a solution to a problem or need, among the most important steps we have the development of a diagram of functions and most importantly a morphological matrix where all the functions that must fulfill the desire and for each function of all mechanisms are found, then the electrical and mechanical design is performed to obtain the optimal solution for the design [10], as shown in Fig. 1.

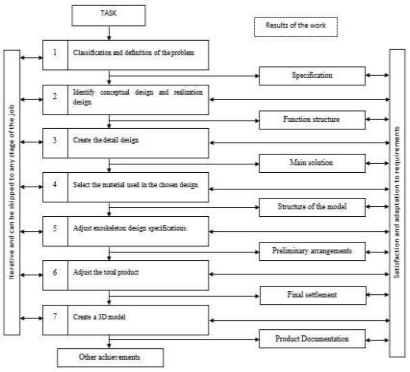

Fig. 1. VDI 2221 Methodology

A. Morphological matrix

Several matrix-based tools and techniques have been developed. They support the design process. Matrices are commonly used to map and visualize the relationships between product attributes and/or activities in the design process [11]. The generating tool is a detailed description of the generic morphological matrix basket, where each characteristic is presented in a separate table showing, the sub-characteristic and the data source [12].

Likewise, the morphological matrix is derived from the concept of n-dimensional morphological boxes (Zwicky and Wilson, 1967). The two-dimensional form of the "Zwicky box" is called the "morphological diagram", which consists of carefully defining and delineating all the important elements of the design and listing the possible solutions for each feature [13].

Thus, morphological science is a way of thinking introduced by physicist Zviki. One of the ideas of morphology is to systematically search for solutions to solve problems that can be combined in the matrix. That search that also reveals unusual combinations is one of the basic components of creativity, which also resembles the theory of invention to solve problems [14].

Therefore, a morphological matrix of components was proposed for possible solutions for the design of a passive hip rehabilitation exoskeleton for people with low back pain.

TABLE I. MORPHOLOGICAL MATRIX LEGEND

No	**Partial Functions**	**Function Carriers**		
		1	***2***	***3***
1	Development Board	Arduino UNO 🔴 🔵	Raspberry Pi pico 🟠	Arduino Mega 🟢
2	Sensors	MPU 6050 🔵	Encoder 🔴 🟢	Infrared 🟠
3	Shield	L298 🔴	Mini L293D 🟠	L293D 🟢
4	Programming language	C++ 🔴 🟢 🔵	MicroPhyton 🟠	
5	Material of Plastic	Plastic ABS 🔴 🟠	Plastic Pet 🟢	Plastic PLA 🔵
6	Material alloy	Aluminum 6061 – ahc 🔴 🔵	Chrome 🟠	Titanium 🟢
7	3D modeling software	Inventor 🔴 🔵	Solidworks 🟢	Solid Edge 🟠

From the combination results, 4 solution concepts were determined.

TABLE II. SOLUTION LEGEND BY COLOR

Color	Solution
🔴 Red	S1
🔵 Blue	S2
🟢 Green	S3
🟠 Orange	S4

a. S1: 1.1 – 2.2 – 3.1 – 4.1 – 5.1 – 6.1 – 7.1
b. S2: 1.1 – 2.1 – 4.1 – 5.3 – 6.1 – 7.1
c. S3: 1.3 – 2.2 – 3.3 – 4.1 – 5.2 – 6.3 – 7.2
d. S4: 1.2 – 2.3 – 3.2 – 4.2 – 5.1 – 6.2 – 7.3

Once the 4 solution concepts have been obtained, an economic analysis of the materials for the modeling will be carried out, which will help to select and validate the design.

B. Electronic design

The electronic design has a working part of the Arduino development board system, which will be responsible for receiving the signal sent by the MPU 6050, the sensors detect the hip rotation and send a signal to the Arduino board, which will assist the hip movement, causing the servos to move in the degrees indicated by the MPU 6050 sensors as shown in Fig. 2.

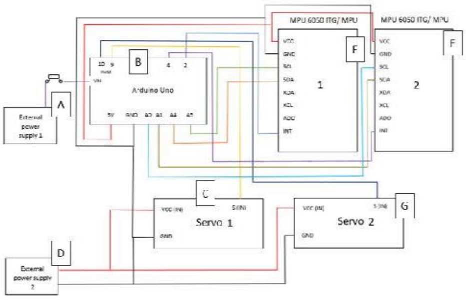

Fig. 2. Electronic design

TABLE III. LEGEND OF COMPONENTS

Letters	Components
A	External power supply (1)
B	Arduino Uno
C	Servo (1)
D	External power supply (2)
E	MPU 6050 (1)
F	MPU 6050 (2)
G	Servo (2)

A brief description of the components chosen for the electronic design of the passive hip exoskeleton was made:

TABLE IV. LEGEND OF COMPONENTS AND THEIR DESCRIPTION

Element	Features
External power supply (1 y 2)	5V power supplies.
Arduino Uno	The Arduino Uno development board will receive the signal from the MPU 6050 sensors and, according to the necessary parameters, will determine the operation of the servos.
Servo (1 Y 2)	They will assist in hip rotation and will be controlled by the signal coming out of Arduino pins 10 and 9.
MPU 6050 (1 Y 2)	It will oversee detecting the hip rotation and will send this signal to the Arduino, which in turn will turn on the servos according to the established parameters.

The free BioDigital software was used to generate a reference image of the hip (pelvis). In addition, for the representation of standard hip measurements, as shown in Fig. 3.

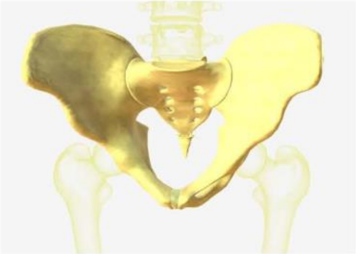

Fig. 3. Representation of the hip

People have a fixed degree of freedom and natural mobility in the human lower limb joints Fig. 4 [15]. The maximum turning angles at the maximum bending moment in walking and the maximum bending moment in running of the lower limb and hip [16]. The angles are obtained from the X, Y, and Z coordinate systems at each hip joint, as shown in Fig. 5. [17].

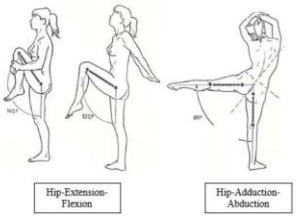

Fig. 4. Hip joint mobility

Fig. 5. Hip angles

Literature studies have shown that the hip joint also plays an important role in providing high mechanical power, up to 45%, during human gait [18]. The hip comprises standard measurements for the development of a 3 DoF hip exoskeleton.

TABLE V. HIP MEASUREMENT LEGEND

Description of the hip	Measure
Anteroposterior diameter: between the promontory and the upper edge of the pubic symphysis.	12 cm
Oblique diameter of the upper strait: between the sacroiliac joint and the pectineal eminence of the opposite side.	12.5 cm
Transverse diameter of the upper strait: between the deepest zones of the innominate lines.	13 cm
Between the deepest zones of the unnamed lines	13.5 cm
The promontory-retropubic diameter, between the promontory and the posterior aspect of the pubic symphysis.	11.5 cm
Anteroposterior diameter, between the coccyx and the lower edge of the pubic symphysis	10 cm
Transverse or bisciatic diameter	11 cm

C. Mechanical design

The key to designing a lower limb exoskeleton is to choose the overall leg and hip structure. Many different joint and limb designs can be combined to create a functional hip [19]. Important criteria for mechanical design are limitation of motion, safety, ease of use, and adaptability [20]. Shown in Fig.6 is the exoskeleton support consisting of hip support and an exact position for the use of the electronic box, also presented are spine supports with the implementation of hydraulic suspensions that allow to keep the individual upright and reduce lumbar pain, pivoting mechanism.

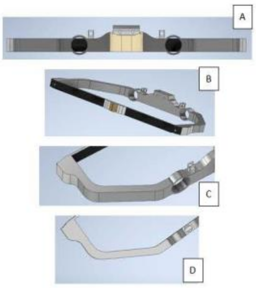

Fig. 6. Hip support and scarp

Consequently, the box for the electronic components was also designed, resulting in the connection of the power supply for the correct operation of the chosen components, has an average of 2x2 mm, resulting in the column support with secure fixings by the bolts with a measure of 1.5 mm radius with a depth of 1 mm, as shown in Fig. 7.

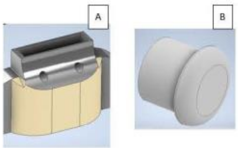

Fig. 7. Electronic enclosure and secure fastening bolt

Likewise, we found the design of the column support to reduce the weights or inadequate stooping in the person, with a measure of 7 mm long and width of 3 mm with a thickness of 1 mm with their respective fasteners for an exact fixation in the human body with two hydraulic suspensions of 7 mm long with a radius of 0.9 mm in the lower part and with a radius of 0.8 mm in the upper part to support the structure of the column with its respective assembly as in Fig. 8.

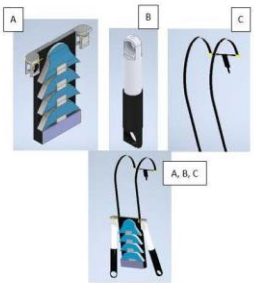

Fig. 8. Column support with hydraulics and scarps

Finally, this exoskeleton has a portable power supply, but it only assists the leg and hip muscles of the person; it cannot support weight or not support its weight [21]. Therefore, we found the design of the leg supports measure 15 mm in length and 4 mm in width, with a rotation on the XZ axis, with a rotation of 90° at the hip, and a lock on the legs with a radius of 10 mm as seen in Fig. 9.

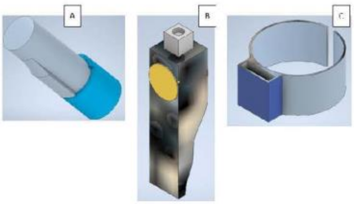

Fig. 9. Leg support and thigh brace

Finally, functional designs are structures designed to perform certain functions, such as gear structures, and joint structures [22]. Therefore, in the assembly of designed parts, any change in the product design will modify the assembly task. On the other hand, digitizing the design and 3D rendering [23] for efficient assembly, as shown in Fig. 10.

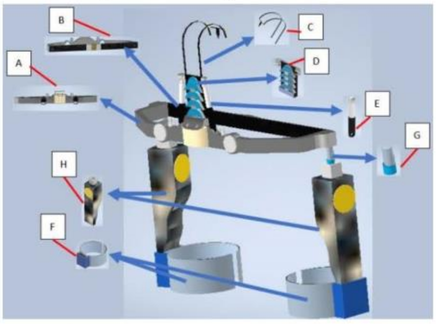

Fig. 10. Mechanical design of the exoskeleton

TABLE VI. LEGEND OF COMPONENTS AND THEIR DESCRIPTION

Letter	Parts	Description
A	Hip support	Hip support, coupled with the electronic box and with the exact position of the sensors.
B	Scrap for hip	precision fit at the hip
C	Shoulder support	Scrap fastening between the shoulder and hip gives a start in the design of the spine support.
D	Column support	Spine support, with the implementation of hydraulic suspensions for spine and hip support.
E	Hydraulic suspension	Hydraulic suspension for effective and efficient support of the spine and keep it straight to reduce low back pain.

F	Leg support	Leg support, two pieces of the same size are used to securely support the legs.
G	Rotating torques	Mechanism design that promotes hip rotation at 90° restricting all other rotation angles.
H	Leg support	Leg support, which is connected to the pivoting mechanism, supports the load bearing actuated at the hips and the support of the exoskeleton.

III. RESULTS

This section presents the CAD prototype of the 3DoF passive hip exoskeleton developed in Autodesk Inventor software and designed with the described requirements and features. The design analysis covers the motion space of the exoskeleton, the validation by design, and the study of stresses and deformations by the Von Mises method of the selected materials.

1) Aluminum 6061-AHC

First, 6061-AHC aluminum material is used because it has a higher rate of film formation and thicker coating, high corrosion resistance, good wear resistance, and better mechanical properties [24]. Therefore, the use is made of this material to realize the design of the hip support and because of a more economical cost in obtaining the material.

2) Plastic Polylactic Acid (PLA)

Secondly, we find the material polylactic acid or also known as PLA. It is used because it has electrical insulation properties, is a hard resin, is resistant to traction (torsion), is not elastic, and is not toxic like other existing plastics [25].

Therefore, the stress simulation was applied to each piece of the hip exoskeleton. Thus, we have the first piece of the hip support with a pressing force of 1000 N with the Von Mises method, the displacement, and the safety coefficient. Obtaining a guaranteed result with a fixed support on the hip exoskeleton as shown in Fig. 11.

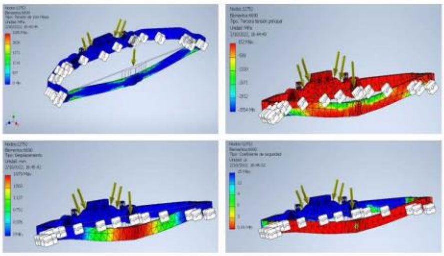

Fig. 11. Von Mises tension in the hip support.

Also, rotational stress of 1000 Nmm was applied on the leg support piece, resulting in a favorable Von Mises method and with the safety coefficient obtaining an acceptable deformation result for the 3DoF passive hip exoskeleton Fig. 12.

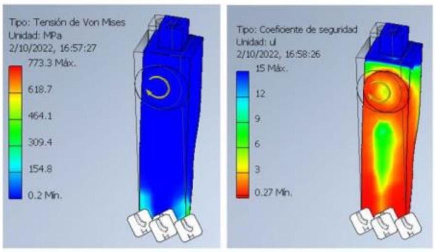

Fig. 12. Von Mises tension in the leg support.

The Von Mises method is of maximum distortion energy and static strength, applied on compact materials, as a result, can be seen in Fig. 13 with a maximum stress of 19622 Mpa, coated in blue color, stating that the designed structure does not contain problems of breakage or rupture in the materials.

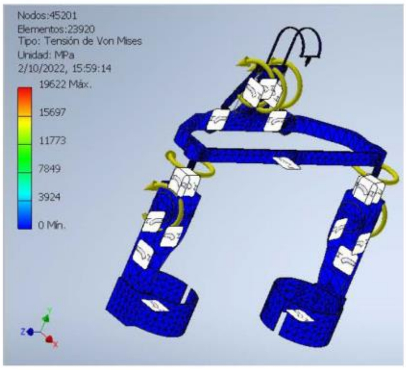

Fig. 13. Von Mises stress.

The objective of the research was to design a passive exoskeleton for rehabilitation in the hip of 3 DoF for people with low back pain, in the CAD software Autodesk Inventor as well as the electronic control design, which will allow us to control the IMU sensors, to collect data from the movements of the hip and the servomotors for the movement of the leg supports. Likewise, the spine support was designed to provide a complete exoskeleton for the rehabilitation of people with low back pain with standard hip measurements.

IV. CONCLUSION AND FUTURE WORKS

This article details the mechanical and electrical design process of a passive hip exoskeleton that meets the proposed features and mechanically the parts are easy to fabricate. The work with computer-aided design software to design a customized exoskeleton was satisfactory, taking into account the information obtained by Autodesk's inventor. The design has been validated through a stress test performed in the design software, demonstrating the advantages of the design such as comfort and durability.

Based on these formidable results, we will conduct an experimental evaluation with a functional prototype shortly. In addition, this prototype will have the ability to become an active hip exoskeleton, as well as the ability to lock individual joints to suit a user.

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