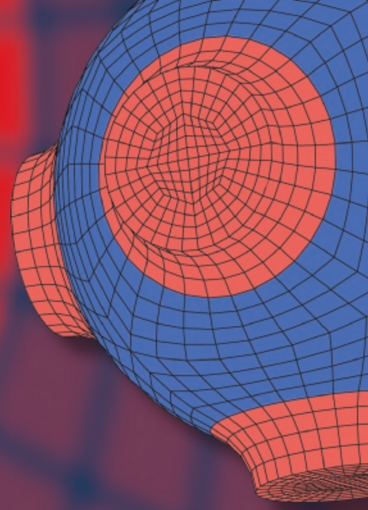
Advanced Structured Materials



Andreas Öchsner
Holm Altenbach *Editors*

Engineering Design Applications III

Structures, Materials and Processes

Springer

Advanced Structured Materials

Volume 124

Common engineering materials reach in many applications their limits and new developments are required to fulfil increasing demands on engineering materials. The performance of materials can be increased by combining different materials to achieve better properties than a single constituent or by shaping the material or constituents in a specific structure. The interaction between material and structure may arise on different length scales, such as micro-, meso- or macroscale, and offers possible applications in quite diverse fields.

This book series addresses the fundamental relationship between materials and their structure on the overall properties (e.g. mechanical, thermal, chemical or magnetic etc) and applications.

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Editors

Engineering Design Applications III

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Preface

Different engineering disciplines such as mechanical, materials, computer and process engineering provide the foundation for the design and development of improved structures, materials and processes. The modern design cycle is characterized by an interaction of different disciplines and a strong shift to computer-based approaches where only a few experiments are performed for verification purposes. A major driver for this development is the increased demand for cost reduction, which is also connected to environmental demands. In the transportation industry (e.g. automotive or aerospace), this is connected with the demand for higher fuel efficiency, which is related to the operational costs and the lower harm for the environment. A possible way to fulfil such requirements is lighter structures and/or improved processes for energy conversion. Another emerging area is the interaction of classical engineering with the health and medical sector. This further volume in this series gives an update on recent developments in the mentioned areas of modern engineering design application.

We would like to express our sincere appreciation to the representatives of Springer, who made this volume possible.

Esslingen, Baden-Württemberg, Germany — Prof. Andreas Öchsner
Magdeburg, Sachsen-Anhalt, Germany — Prof. Holm Altenbach

Contents

Geometrical Characterization of a Lumbar Spine

Daniel Villaseñor-Chávez, Luis Héctor Hernández-Gómez, Juan Alfonso Beltrán-Fernández, Juan Carlos Hermida-Ochoa and Juan Luis Cuevas-Andrade

Abstract The design and development of a system, which is used in the geometrical characterization of a healthy or pathological curvature of the human spine, are discussed. The main objective is to avoid the application of invasive techniques that involve the application of radiation, such as X-rays or computerized tomography. For this purpose, a compact design has been proposed. It was manufactured with 3D-printed components and common electronic devices such as Arduino or NANO©. The anthropometric characteristics of Mexican individuals have been taken into consideration. This device can be used with young and adult patients. Preliminary results have been discussed.

Keywords Ultrasonic sensor · Spine · Lordosis · Printed circuit

Abbreviations

PCB	Printer circuit board
PWM	Pulse-width modulation
USB	Universal Serial Bus

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1 Introduction

The spine plays a fundamental role in the human musculoskeletal system. Its mechanical design allows an adequate performance for many years. However, alterations occur, such as lordosis that causes pain. The costs associated with this pathology are high [1].

The most used method for the evaluation of curvature of the spine in standing position is the radiological that can cause harmful effects on the individual due to the excessive use of X-rays. Other alternatives are photographic analysis, goniometry, electro-goniometry and flexible ruler [2, 3]. One of the main applications of such methods is for the evaluation of the deviation of kyphosis and lordosis diseases (Fig. 1).

Lordosis is a sagittal curvature of the anterior convex rachis. The column has four physiological curvatures, two of them are outwards in the thoracic spine (at the level of the ribs) and in the sacral spine [4]. On the other hand, the hyperlordosis (increased curvature) may be caused by an anterior rotation of the pelvis, the upper part of the sacrum that takes an anteroinferior inclination through the hips. It causes an abnormal increase in the lumbar curvature. Regarding the kyphosis, it is the most frequent deformation of the spine [5]. It is generated by a posterior convexity of one or several segments of the spine and some alterations of the vertebrae that adopt a typical wedge shape [6, 7].

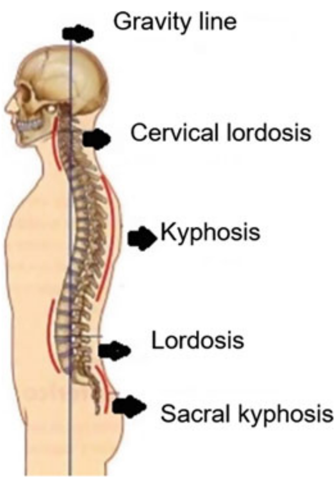

Fig. 1 Schematic representation of the kyphosis and lordosis pathologies

2 Statement of the Problem

Currently, low back pain affects 84% of the population of the world in developed countries. This generates a disability associated with low back pain. There are 10 million of disabilities in the USA every year [8].

In Mexico, it was the seventh cause of work absenteeism in 2015 and it was placed second in this year. It is in accordance with the data of the Mexican Institute of Social Security, which is one of the main institutions of the National Health Service in our country. Thirteen percentage of the population goes to consultation for this condition. It can be multifactorial given the aetiology of pain [9].

In 2017, the Mexican Institute of Social Security reported 30,105 accidents associated with the vertebral column. Consequently, 2507 invalidation opinions were given for dorsopathies [10, 11]. In private hospitals in Mexico, 1827 patients were admitted due to dorsopathies during the period 2012–2014. The National Institute of Rehabilitation, which is a specialized hospital in these diseases in Mexico, reported 2,121 cases treated for dorsopathies in 2011. Their classification is presented in Table 1.

Based on the aforementioned, an ultrasound sensing system has been proposed. It is related with the evaluation of lordosis and kyphosis diseases. Actually, these cases

Table 1 Dorsopathies reported by the National Rehabilitation Institute 2014 [10]

Dorsopathies	Frequency	Percentage	Global percentage
Dorsalgias	–	–	–
Lumbago	567	26.70%	2.61%
Radiculopathy	411	19.40%	1.89%
Lumbar disc disorders	164	7.70%	0.76%
Cervical	100	4.70%	0.46%
Cervical disc disorders	94	4.40%	0.43%
Lumbago with sciatica	77	3.60%	0.35%
Sciatica	44	2.10%	0.20%
Other dorsalgias	23	1.10%	0.11%
Deforming dorsopathies	–	–	–
Other deforming dorsopathies	307	14.47%	1.41%
Scoliosis	178	8.39%	0.82%
Other unclassified dorsopathies	8	0.38%	0.04%
Lordosis	2	0.09%	0.01%
Kyphosis	2	0.09%	0.01%
Spondylopathies	–	–	–
Spondylosis	124	5.85%	0.57%
Other spondylopathies	20	0.94%	0.09%
Total	**2121**	**100%**	**9.77%**

are evaluated with invasive methods. However, they can affect the individuals in the long term. This is the case of radiography [12].

3 Materials and Methods

The block diagram of the proposed system is illustrated in Fig. 2. Figure 3 shows the methodology, which was followed in the development of the sensing system, as well as the data acquisition system, the creation of the algorithm and the design of the printed circuit.

The Nano V3 board was selected. This is a more specific product than the Arduino® one and Arduino® mega cards. It is compact and suitable for more synthetic applications. Despite its small size, it is ideal for the sensing system. It is made up of 14 digital input/output connectors, and six of them are used as PWM and 8

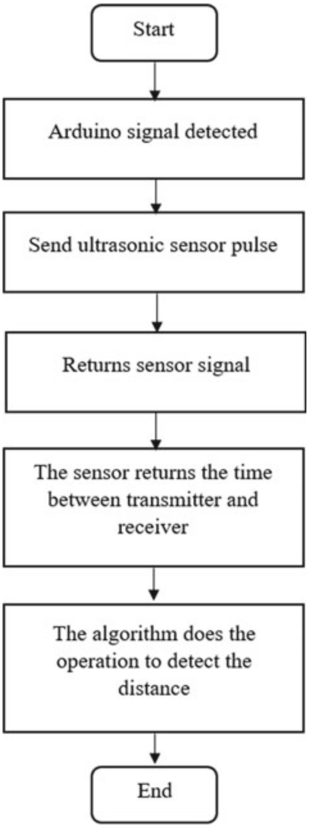

Fig. 2 Block diagram of the sensing system

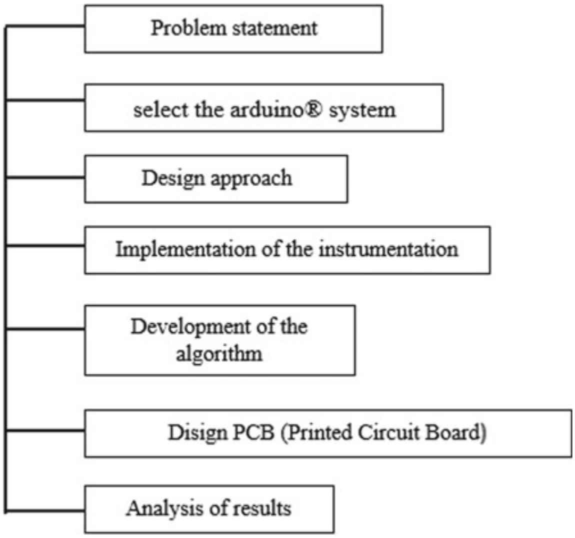

Fig. 3 Methodology followed in the development of the sensing system

analog input connectors. In addition, a mini-USB connection is used, instead of a classic USB port and a reset button (Fig. 4) [13].

In the following step, a comparison was made of the different distance sensors that are available. The specifications required by the system were taken into account. This is the case of compatibility, range, cost, size and power among others.

Table 2 compares some of the proposed devices. The HC-SR04 ultrasonic sensor was selected as it meets the ideal characteristics for data acquisition [14–16].

The circuit design was performed in a computer program (Proteus©), in accordance with the circuit shown in Fig. 5. Once the system was designed, the simulation

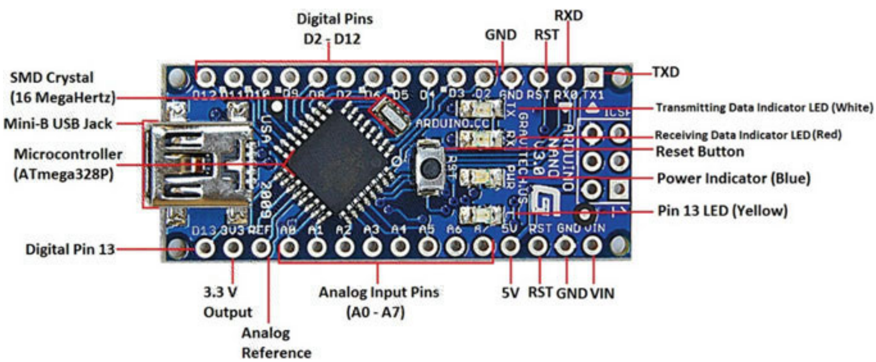

Fig. 4 Schematic arrangement of the Arduino Nano V3 card

Table 2 Sensor comparison [13, 14]

Model	Voltage (v)	Distance (cm)
GP2Y0A41SK0F	5	4–30
GP2Y0A21YK	3.1–0.04	10–80
GP2Y0A02YK	5	20–150
GP2Y0A710K0F	5	100–500
HY-SRF05	5	3–3000
HC-SR04	5	1–4000
LV-EZ0	5	40–600
IS471F	5	1–15
QRD1114	5	0–3

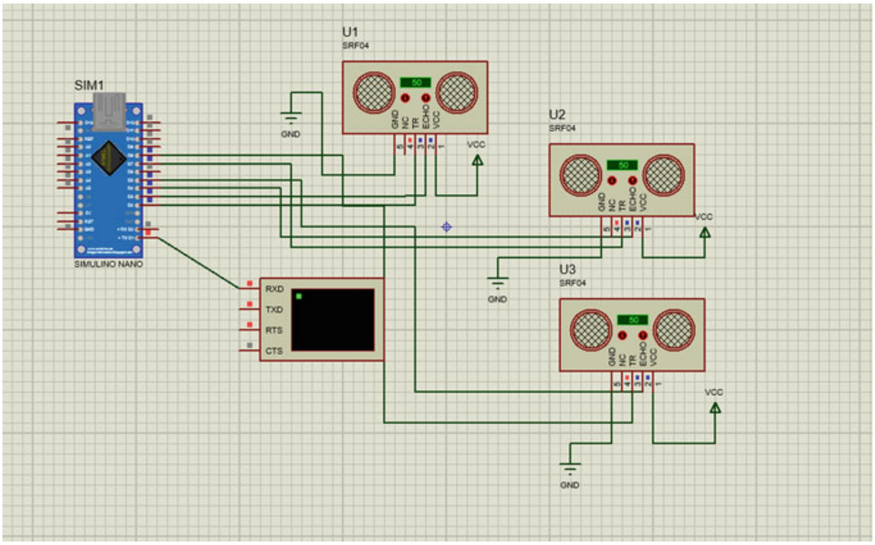

Fig. 5 Design of the sensing system

was carried out. The operation of the sensors in an ideal environment was observed, and its performance was evaluated in a virtual terminal.

In the next step, the physical connections necessary for each component were implemented in a test plate. The physical functioning of the system was observed. The digital pins, which were required, were taken into account, since these will be used for the development of the algorithm. Figure 6 shows the connection of the components of the sensing system in a preliminary prototype.

Communication tests between the Arduino Nano V3 card and the computer were made. The objective was to transfer the programming of the sensing system and visualize the data. For this purpose, the algorithm that allows communication between the

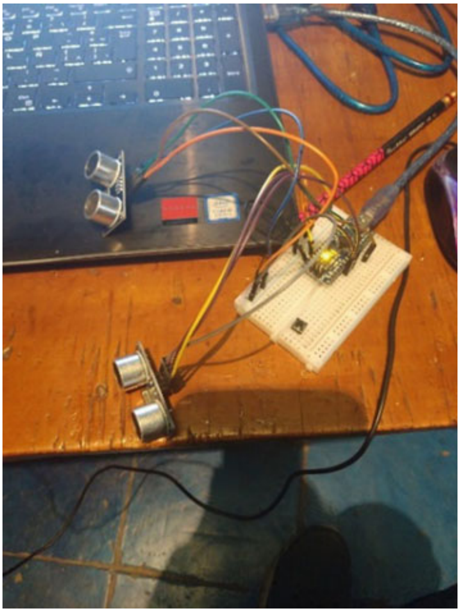

Fig. 6 Sensing system on a plate test

hardware and the software was developed. Then, it was loaded into the programming card and performed the communication tests. The characteristics of the card of the sensing system are shown in Fig. 7.

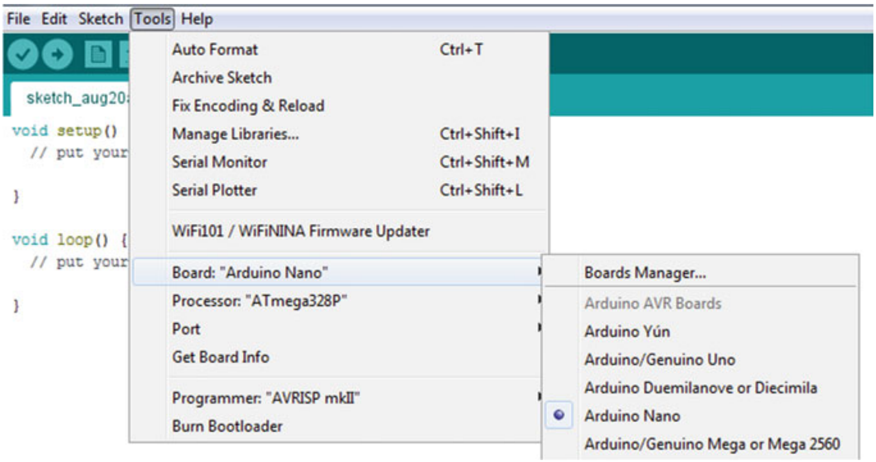

Fig. 7 Arduino Nano V3 communication card

4 Results

Figure 8 shows the electronic design of the sensing system and its instrumentation. Simulation tests were performed, and the results were observed in the virtual machine (Proteus©). Once the simulation tests were done, physical tests of the system were made on the test plate.

Figure 9 illustrates the design of the printed circuit with its optimum characteristics for a correct operation of the sensing system. This will allow the reduction of the voltage drops caused by the thickness and length of the ideal tracks.

In an initial test, the spine geometry of a male, who was 31 years old and apparently healthy, was evaluated (Fig. 10). Table 3 shows the coordinates evaluated. The geometry of the spine of the individual was obtained, for both lumbar lordosis and kyphosis.

Figure 10 shows the coordinates of the points recorded with the sensing system. They are compared with the geometry of the spine. Good convergence has been observed.

5 Conclusions

Engineering science allows the development of systems required in the area of biomechanics that are more complex and accurate for the pathological diagnosis of patients. As a result, a product with easy access and lower cost to society is offered. However, all criteria must be taken into account to obtain the desired result of these devices.

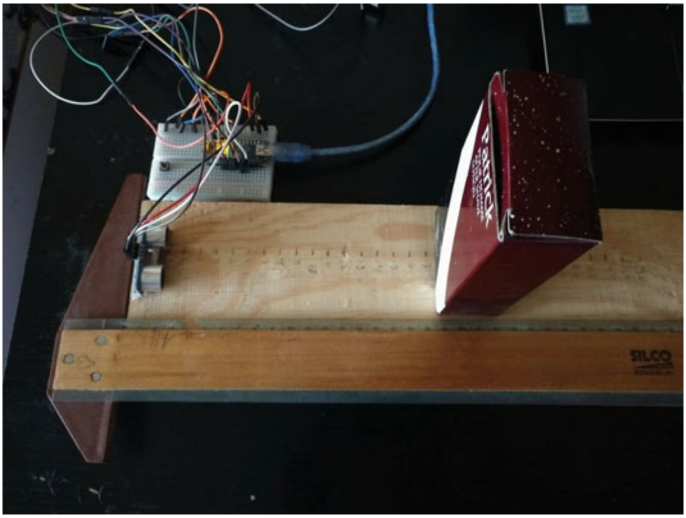

Fig. 8 Tests of the sensing system

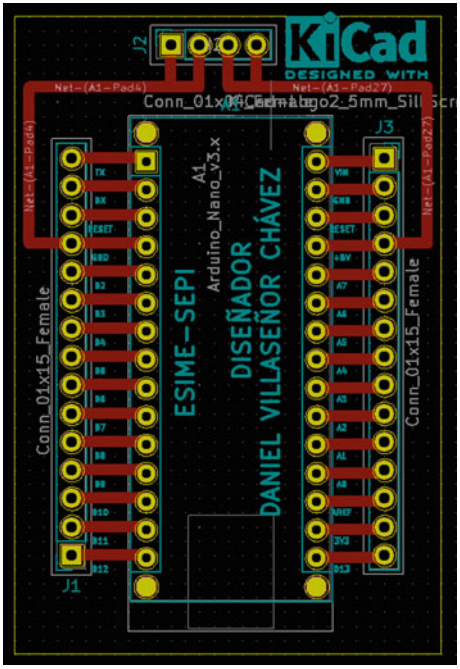

Fig. 9 Design of the printed circuit

Regarding the initial results of the design of the ultrasonic sensor, its disadvantages were evaluated. Such is the case of the multiple bounces of the emitter, environmental temperature and the black zone of the sensor that affects the measurement. The sensor signal in this area is not detected.

The geometry of the spine was characterized with the proposed assembly. The results were summarized graphically. A convergence with real geometry was observed. These results are encouraging. Consequently, an optimization has been proposed in order to evaluate the deviation of the lordotic pathology.

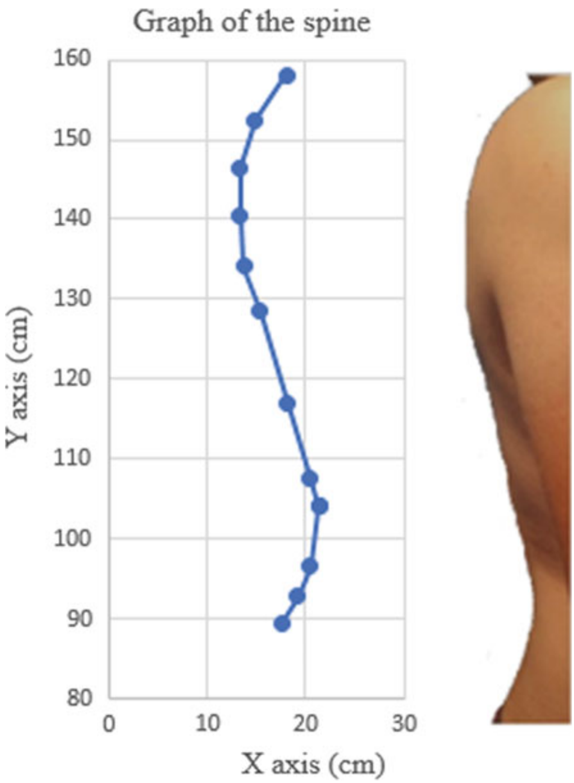

Fig. 10 Graphical representation of the spine of the individual

Table 3 Data recorded by the sensing system

X-coordinates (cm)	Y-coordinates (cm)
17.52	89.44
19.18	92.86
20.5	96.51
21.39	104.02
21.28	104.02
20.5	107.55
18.18	116.83
15.31	128.43
13.65	134.18
13.32	140.47
13.34	146.55
14.87	152.4
18.07	158.04

Acknowledgements The authors kindly acknowledge the grant awarded by the National Polytechnic Institute and the National Council of Science and Technology.

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Antigravity Device for Intravertebral Rehabilitation

Itzia Calalpa-Torres, Christopher René Torres-SanMiguel, Guillermo Urriolagoitia-Sosa, Alejandro Cuautle-Estrada, Beatriz Romero-Angeles and Guillermo Manuel Urriolagoitia-Calderón

Abstract Low back pain is a serious health problem that affects a lot of people in productive age (López-Hernández in Análisis del Puesto de Trabajo de Policía para Investigar la Posible Etiología Laboral del Síndrome Doloroso Lumbar, Propuesta de Control. Universidad Instituto Politécnico Nacional, p. 13, 2010 [1]). In this research is presented an antigravity rehabilitation device, which is designed to allow the intervertebral decompression and the antigravity muscles rehabilitation of the lumbar area. In addition, the main components of the equipment such as the base, the frame and the iron where the patient lays down, is studied through a computational program (finite element method) that is used for developing a static-structural analysis. Finally, the automation of the equipment is shown since the execution times and movements used to decompression of the intervertebral discs and/or the rehabilitation of the spine (Asghar-Norasteh in Low Back Pain. InTech, pp. 33–34, 2012 [2]).

Keywords Low back pain · Vertebrae · Antigravity · Rehabilitation · Mechanism

1 Introduction

Low back pain is considered a public health problem in many parts of the world. This pain manifests itself between the lower limit of the ribs and the gluteal region (lumbar and sacral regions of the spine), whose intensity varies according to postures and physical activity of each person [2]. Most causes of low back pain are unknown; however, hypotheses have arisen that try to explain the mechanical alteration that generates pain. These include endurance of trunk extension, psychological stress, poor flexibility of the hip joint, poor muscle control of the trunk, inadequate posture and low body mass [3]. The main reason for this disorder is due to age, lifestyle,

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situations and the type of work performed, however, mechanically the force of gravity is responsible for generating efforts in the spine, generating the problem of low back pain, therefore, the force exerted by gravity on the human body must be balanced by the continuous effort of the muscles on the skeleton, in order to oppose this force and keep the body in an upright posture [4], the muscles in charge of this activity and of counteracting the effects of gravity are the postural or anti-gravity muscles, however, the sedentary life in modern society produces the overuse of the postural muscles, favouring the development of muscular rigidity. This work proposes the design of an equipment that makes possible the intervertebral decompression and the rehabilitation of the anti-gravitational muscles of the lumbar area.

2 Methodology

The main objective is to design an anti-gravitational column rehabilitation equipment to improve the quality of the patient, exercising the anti-gravitational muscles to help relieve the pain of the lumbar vertebrae. The steps used to perform the rehabilitation equipment of the anti-gravity type column are shown below.

- Equip design
  This section shows the main characteristics of the equipment and its operation.
- Numerical analysis of the mechanism
  The relevant numerical analysis of the equipment's pieces where most of the loads are concentrated at the moment of the use of this is presented.
- Engine and transmission
  The specific study for calculating the power and work of the engine is shown.
- Automation of the rehabilitation device
  Automation of the work sequence through a Functional Graph of Stages and Transitions Control.

3 Development

For the development of this rehabilitation mechanism, it is necessary to understand 2 concepts, the first concept is the antigravity that makes mention about the opposition to the gravity force of attraction that the earth exerts on the body [5]. The second concept includes the zero-gravity position or neutral body posture (NBP) that emerges from research conducted by NASA scientists who observed that the human body in zero gravity conditions takes this particular position (Fig. 1) with certain angles made by the joints which allowed the astronauts to be relieved of lower back pain and that the height of the intervertebral discs will increase. This information has allowed the development of new intervertebral disc decompression therapies that are used to

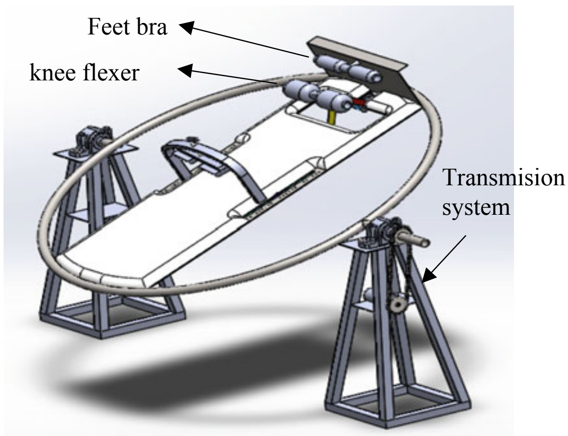
Fig. 1 Right, *zero*-gravity position, Left, position to decompress the vertebrae

treat various conditions such as disc bulging, herniation, degenerative disc disease, sciatica, spinal stenosis, spinal arthritis, among others in a safe manner [6–8].

The physical principle of zero-gravity position is planned to be used for rehabilitation therapy, however, for this principle to work, it is necessary for the human body to take a specific position in which, the bodyweight does not press the part of the lumbar and at the same time a separation of the lumbar vertebrae is generated. For this the Nachemson theory [9] is used, which shows the ideal position where the loads that comprise the weight of the human body have a deconcentration over the lumbar vertebrae, this position is subscribed as Supino, traction 500 N, which generates a null intradiscal pressure in an inclined position of 50° (Fig. 2). To corroborate this factor are considered data such as mass, normal and frictional force, which is defined as the tangential force acting between two bodies in contact that opposes or prevents movement, therefore, when two bodies they are at rest, there is a force of friction called static, for the particular case this force of friction is very useful because it prevents the body from sliding [10, 11].

In order to synthesize properly the rehabilitation of the lower back, it is necessary to separate the lumbar vertebrae and strengthen the lumbar muscles (psoas) that serve

Fig. 2 Equipment in vertebra decompression position



as support for the lumbar area. Therefore, the equipment presented in Fig. 2 will support the patient, realising their anti-gravitational muscles. The process consists of positioning the patient at different angles of inclination on the X-axis, with the purpose of concentric isotonic contractions in the muscles of the back with the support of the proprioceptive system.

The equipment has a transmission system which allows the bed to turn and be positioned at different angles, as required. It will also have a mechanism to flex the patient's knees and allow him to take the zero-gravity position (Fig. 2).

3.1 Numerical Analysis

In order to know if the structural materials are safety, the finite element method is used to carry out the static-structural study of the elements that are considered important for the safety and correct functioning of the equipment. Which are:

- Base.
- Plate.
- Frameworks.

For this analysis, two different materials are used, one for the axis and one for the plate and the frame, in Table 1 the mechanical properties of the materials are shown.

Table 2 shows the results of the numerical analysis of the structural elements of the device.

The numerical analysis shows stresses and elongations well below the elastic limit of the material, so it will no present problems the design, even it can be observed that values do not exceed yield limit.

Table 1 Mechanical properties of materials

Materials	Steel AISI 4140	Steel AISI 1020
Model type	Isotropic linear elastic	Isotropic linear elastic
Elastic limit	4.150×10^8 N/m^2	3.51571×10^8 N/m^2
Young's modulus	2.1×10^{11} N/m^2	2×10^{11} N/m^2
Poisson's number	0.3	0.29
Density	7850 kg/m^3	7900 kg/m^3
Shear modulus	8×10^{10} N/m^2	7.7×10^{10} N/m^2
Load applied to the base	1273.81 N	1273.81 N
Load applied to the plate	1584.22 N	
Load applied to the frame	2173 N	

Table 2 Numerical analysis results

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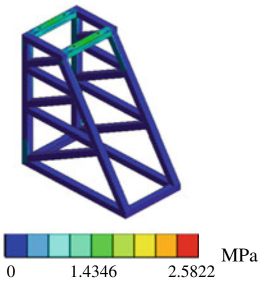
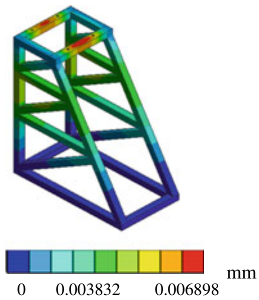
<tr><td>Base</td><td>
</td><td>
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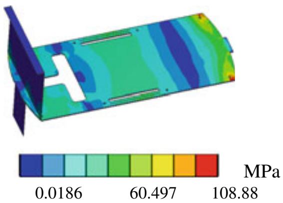
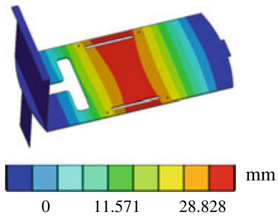
<tr><td>Plate</td><td>
</td><td>
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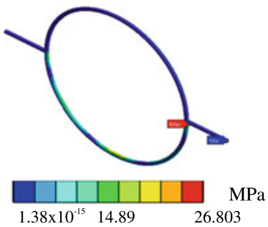
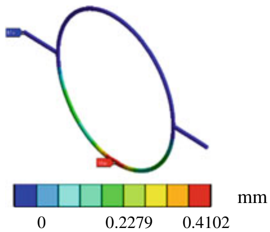
<tr><td>Frame</td><td>
</td><td>
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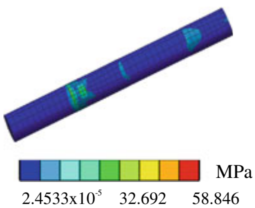
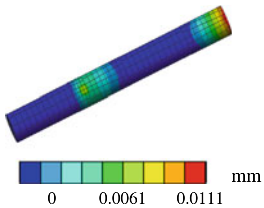
<tr><td>Axis</td><td>
</td><td>
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</table>

3.2 Engine Selection

The requirements of the transmission system are calculated. The torque required to move the total weight of the person and equipment is assessed. Having a payload of 2452.5 N the torque required is 82.011 Nm. In this way, the power engine is obtained. Table 3 shows the results of the necessary engine power calculation.

With these obtained values, the characteristic engine values are shown in Table 4.

Table 3 Data and results to obtain the power

Data	Results
$T = F \times d$ $F = 2452.5\,\text{N}$	$P = \frac{254.56\,\text{Nm}}{1\,\text{s}}$
$T = 2452.5 \times 0.1038 = 254.56\,\text{Nm}$	$P = 254.56$ W
Time The time proposed to develop the work is 10 s	hp = 0.3412

Table 4 Engine characteristics

Engine	
Engine power	370 W
Engine speed	1725 rpm
Service factor	1
Nominal torque	2 Nm

Table 5 Gear motor specifications

Gear motor	
Engine power	120 W
Engine output speed	1695 rpm
Engine-reducer ratio	537.49:3.2
Output speed gear motor	3.2 rpm
Torque output gear motor	225 Nm

The selected engine has the required power according to the previously realized calculations, however, the present project requires working at lower revolutions and higher nominal torque, for this reason, a gearbox with a ratio of 395.46 is chosen to decrease revolutions and increase torque: Table 5 shows the Gear motor characteristics.

3.3 Band and Pulley Selection

Once the engine data such as revolutions, power and torque were used to carry out the selection of the pulleys and the belt. First, information about the engine is gathered, such as the power in hp, the revolutions delivered by the engine unit and those required in the equipment (Table 6).

- Step two is to determine the design power in hp for which it is required to know the service factor that is 0.8 and multiply it by the power in hp.

$$\text{Design power} = 0.8 \times 0.160 = 0.128\,\text{hp}$$

Table 6 Gear motor data

Power	0.160 hp
Gear motor revolutions	3.2 rpm
Required revolutions	3 rpm

- Selecting a belt that is within the range of 3V, 3VX.
  A speed relation is established, and it is obtained by dividing the speed of the gear motor between the required revolutions:

$$\frac{3.2\,\text{rpm}}{3\,\text{rpm}} = 1.06$$

- Selecting of the driving pulley.
  The relationship between rpm and the diameter of the pulley determines the power that is needed to transmit the pulley. Therefore, the diameter will be 65 mm.

3.4 Programming of the Rehabilitation Sequence

Next, the sequence of the rehabilitation process is described, which begin when the start button is activated, and the rehabilitation option is selected. This process takes place in three stages (Fig. 3):

- First stage—When the start button is in state one. We proceed to introduce an angle of inclination and a time set giving the instruction that the engine is turned on.

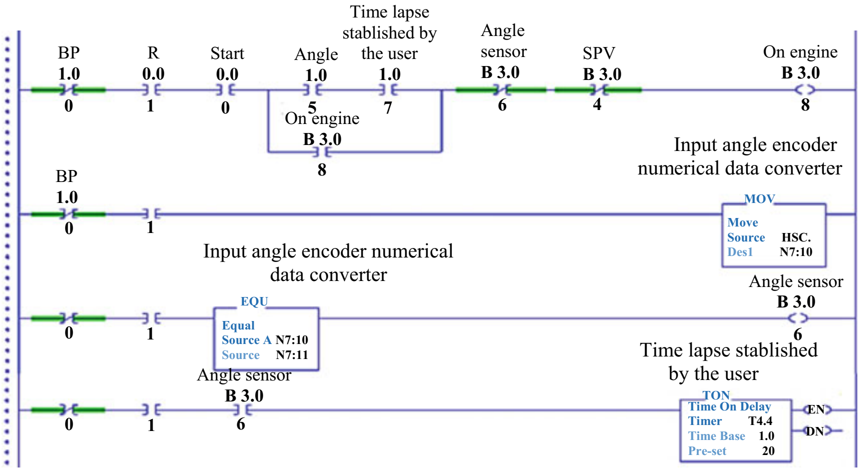

Fig. 3 Rehabilitation sequence

- Second stage—The patient reaches the set angle and the engine stops. When the timer complies with the time determined by the doctor, the engine is in the opposite direction.
- Third stage—The engine stops when it reaches the vertical position (vertical position sensor).

It is important to mention that, if you want to stop the treatment at some point of the routine, you can push the emergency stop button that detain the entire equipment.

4 Conclusions

The anti-gravitational rehabilitation mechanism shows a simple operation, it considers the zero-gravity position allowing rest and relaxation of the lumbar muscles while strengthening them, making a comprehensive rehabilitation, giving support to the psoas muscles and separating the vertebrae to relieve pain. Thanks to the design considerations and its simple way of functioning, its operation is easy and can be adapted to any size of the human body, being applicable for children and adults.

The materials proposed are appropriate for a useful life without problems of premature wear, seen in the numerical analyses made to structural elements, the yield limit is well above the factors obtained. While the engine and reducer selected are appropriate and their power is enough, which has a low cost for its development.

Thanks to its slow movement but controlled by means of encoders, this mechanism is comfortable and easy to handle, making it possible to consider a future market study if it is desired to market to perform rehabilitation therapies of the spine.

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