ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

FAKULTA BIOMEDICÍNSKÉHO INŽENÝRSTVÍ

Katedra biomedicínské techniky

Návrh konstrukce "inteligentní" ortézy

Design of construction of intelligent orthosis

MASTER'S THESIS

Study of program: Biomedical and Clinical Technology

Field of study: Biomedical Engineering

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Kladno 2017

Czech Technical University in Prague, Faculty of Biomedical Engineering

Department of Biomedical Technology Academic year: 2016/2017

Diploma thesis assignment
(Master project thesis assignment)

Student: **Ana Carolina DAngeles Mendes de Brito**

Study branch: Biomedical Engineering (CEMACUBE)

Title: **Design of construction of intelligent orthosis**

Title in Czech: Návrh konstrukce "inteligentní" ortézy

Instructions for processing:

Create construction design and select sensors of subsystems of "intelligent" orthosis. Create the design of elements and kinematics properties of orthosis in SolidWorks software. Subsystems of orthosis will be used for measurement of kinematic, kinetic and other physical data of the upper limbs and ambient environment. The "intelligent" orthosis will be designed to enable the measurement of upper limb of patients during the rehabilitation process. Validate and verify the strength of elements, the entire construction and kinematics of construction in the SolidWorks software by finite element analysis and motion analysis.

References:

[1] MANTO Mario; ROCON Eduardo; PONS Jose; BELDA Juan Manuel; CAMUT Stephane, Evaluation of a wearable orthosis and an associated algorithm for tremor suppression, Physiological Measurement, ročník 28, 2007, 415-425 s.

[2] BAKLOUTI Malek, GUYOT Pierre-Arnaud, MONACELLI Eric, COUVET Serge, Force Controlled Upper-Limb Powered Exoskeleton for Rehabilitation, Intelligent Robots and Systems, 2008

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Validity of assignment until date: 20.08.2018

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In Kladno, 20.02.2017

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Acknowledgements

I would like to express great gratitude towards my supervisor, doc. Dr.-Ing. Patrik Kutílek, Ph.D., he was a great guide and support during this whole process. I learned a lot from him.

ABSTRAKT

Jednou z nejběžnějších forem léčby svalových onemocnění je fyzická léčba. Aby se zabránilo svalové atrofii a paralýze, musí zraněná osoba pokračovat v cvičení těla, i když nemá svalovou sílu a podmínky. Při řešení těchto případů musí vyškolený odborník přesunout pacienty pomocí řady pohybových cviků, aby se podnítila regenerace. To však může vyčerpat kliniku, který poškozuje cvičení. Řešením tohoto problému je použití inteligentní ortézy, která s pomocí mechanických pohonů přesune vybrané tělesné končetiny řadou pohybů a díky použití snímačů bude dosaženo opakovatelnosti a přesnosti. Tato studie představuje mechanický a elektronický návrh konstrukce inteligentní ortézy pro horní končetiny. Projekt byl zaměřen na navrhování orthotického zařízení s nízkou hmotností, v níž je pohyb končetin spouštěn bovdenskými kabely spojenými na jednom konci s končetinami a druhým na krokový motor umístěný u batohu neseného pacientem. Tento návrh rovněž zahrnuje výběr senzorů, které poskytnou potřebné informace pro přesun těla s přesností cesty a také pro kvantifikaci svalových sil, které usnadňují vyhodnocení fyzické kondice v průběhu času. Potřebné simulace jsme provedli, abychom potvrdili konstrukční mechanickou pevnost a kinematickou funkčnost.

Klíčová slova

Inteligentní ortéza, horní končetiny, svalové onemocnění, rehabilitace

Abstract

One most common treatment for muscular diseases is the physical therapy. To prevent muscle atrophy and paralysis an injured person must continue to exercise the body even if lacks muscle force and conditions. When dealing with these cases, the trained professional must move the patients through a series of motion exercises to spur the regeneration. This, however can exhaust the clinician impairing the exercise. A solution around this problem is the use of intelligent orthosis that, with the help of mechanical actuators will move the selected body limbs through a series of motions, and with the use of sensors will achieve repeatability and precision. This study presents a mechanical and electronic design for the construction an intelligent orthosis for the upper limbs. The project aimed in designing an orthotic device with light weight, in which the motion of the limbs is triggered by Bowden cables connected in one end to the limbs and the other to a stepper motor located at a backpack carried by the patient. This design also comprises a selection of sensors that will provide the necessary information to move the body with a precision of path, and also to quantify the muscle forces facilitating the physical condition evaluation through time. The necessary simulations we made to certify the design mechanical strength and kinematic functionality.

Keywords

Intelligent orthosis, upper limbs, muscle diseases, rehabilitation

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1 INTRODUCTION

Many people have severe problems with muscle degeneration and muscle atrophy. Muscular problems are a common consequence of many neural diseases and can drastically affect the daily life impairing normal activities such as eating, drinking, and brushing teeth [1]. This condition can result in paralysis and can also interfere in the metabolic rate increasing the risk of metabolic disorders [3][5]. To regain motor function and muscle power is necessary to treat these diseases with an intense physical therapy which demands a dedicated physical therapist. This treatment can be very expensive and also creates a distress to the physically impaired that needs to travel to the clinic in order to get treatment [5]. Another problem in the manual assistance rehabilitation is that the exercises are very repetitive and can easily exhaust the staff, thereby the treatment can be limited by the fatigue of the professional [7]. An option to around these problems is the motor assist robotic systems. Its development can assist the patient in the daily life motions or in the rehabilitation process [1].

Wearable robotics devices today are a substantial tool for the clinicians taken that, with electronic components, is possible to control the motion in exercises generating a repeatability path that humans can’t. In addition, it facilitates the evaluation of the patient condition through time. Those devices are able to quantify each component of the movement in a form of force, speed or motion range allowing the comparison of the body state [7]. There are 2 types of orthosis, hard and soft. The first is usually a rigid-framed high weighted device supporting the specific limbs with actuators attached directly to the frame in body (intelligent hard orthosis). The design is based in a traditional exoskeleton with rigid mechanical body supports. Although the present a very good option for limb sustainability and control, they have several disadvantages including bulkiness, mechanical constraints to host bodies, and safety issues [40]. The soft ones on the other hand, uses the rigid characteristic of the human bones to act on the body removing the need of rigid parts. The actuation is performed by mechanical tendons, air or other soft actuators. This option reduces the weight of the device due to its simple structure [13], but cannot offer the same level of support as a hard orthosis.

This study proposes a design of an intelligent orthosis for the upper limbs in order assist the physically weak patients in the rehabilitation process. The device is a junction of a hard orthosis with a soft orthosis to perform passive physical therapy exercises. The actuation is made by cables connected in one end to the limb and another to a stepper motor located at a backpack carried by the patient. The main point was to offer a reliable low weighted exoskeleton with selected sensors to move and control the upper limbs covering 6 motions: shoulder adduction and abduction, shoulder flexion and extension and elbow flexion and extension. This device has a very low weight due to the fact that the motor is not attached directly on the impaired limb, and also promotes a high muscle reinforcement due to the existence of rigid arm supports that sustain the arm at the correct position.

2 ANALYTICAL PART

This section will describe the muscle atrophy in a physiological point of view, its causes and the means of the rehabilitation process. It will show methods chosen to establish the upper limbs dimension according to age, sex and level of muscle injury. The orthosis takes into consideration the mass and weight of the upper limbs as well as the points of mass of each segment. Taken that, this part will demonstrate the techniques used to obtain these points which allowed the calculation of muscle strength in a dynamic and static point of view. The torques and forces created by the arm joints in the abduction and adduction, flexion and extension movements of the shoulder and the flexion and extension movements of the elbow were primordial for the definition of the material and the actuators used on the design.

2.1 Muscle Diseases

Muscle diseases, or myopathies, are disorders of skeletal muscle structure or function and can be divided in inherited muscle diseases or muscular dystrophies. The muscle dystrophies are a pathologic description of muscle fiber degeneration and abnormal muscle regeneration. This condition can be associated with an increase in fat and fibrous connective tissue. Both can cause a impair of movement and thus muscle atrophy [4].

Atrophy can be described as a decrease in cell size which is determined by a balance between new protein accumulation and existing protein degradation. In a cell, this size loss is caused by a loss of organelles, cytoplasm and proteins. Following the same description, muscle atrophy is defined by a loss of muscle mass. The muscle growth or loss is controlled by the balance of the new myofibrils production and the degradation of existing proteins. Mechanical stress, physical activity, nutrients availability are direct factors in this process [1]. The reduction in the muscle size can cause a decreased metabolic rate which, if combined with an inadequate energy intake, can cause an increase in fat storage and metabolic disorders [3].

The muscle behavior is directly related with neurological conditions. The motor unit which is the basic unit of motor function is defined by the anterior horn cell body, its axon, the neuromuscular junction, and all the skeletal muscle fibers innervated by the one axon. Thus, a serious of neural diseases has muscle impairment as consequence. Usually, when considering neural problems, is easily noticeable the differences in muscle tone (flaccid, spastic, or rigid), muscle size (atrophy or hypertrophy), and muscle strength [4]. Specifics genetic condition can also result in muscle damage and in an abnormal muscle movement. These can be also related with the neural system. Genetic modifications that interfere with embryonic and postnatal growth result in smaller muscles in adults [2]. The same behavior can be also noticed when dealing with an acquired muscle disease. This can be related to an inflammatory myopathy, endocrine myopathy drug induced / toxic myopathy[2].

2.1.1 Spasticity

Spasticity, or muscle stiffness is described as an abnormal increase in muscle tone cause by a non-physiological process of transportation of information by the nervous system. [22][23]. When dealing with a damage of the central nervous system spasticity is one of the main symptoms and, because of the random timing of occurrence, must be taken in consideration in any mechanical design for the body [21]. The muscle spasms are a consequence of a pathological muscle contraction and relaxation during a movement [22][23]. The spasm can cause discomfort, pain and also can limit the body function. Usually neural abnormalities are the cause of spasticity including spinal injury, multiple sclerosis, cerebrovascular accident, brain injuries and cerebral palsy [22], and strokes [21]. The magnitude of the spasms forces are being measured over the years, being the Ashworth scale the most popular method used. This scale can distinguish the resistivity levels of muscles during a passive motion in join [21].

The spasticity of men and women from ages of 50-70, with hemiparesis, from the after-stroke, was measured. The values of torque (M) in the elbow joint under isostatic conditions for the extensors and flexors during maximal voluntary isometric contraction is shown on the Table 1. The spasticity varied within the group from 1 to 3 on the Ashworth scale. [21]

Table 1: The moments of force in the elbow joint according to angle [21]

Joint	Limb	Group of muscles	Angle [deg]	Moment of force [N.m]
Elbow	Non-spatic	Flexors	90	53,64
			60	39,69
			15	36,64
Elbow	Spatic		90	13,81
			60	11,99
			15	3,97

The spasticity was also measured discerning women from men (**Table 2** and

Table 3). The data showed that the values of the torque for flexors and extensors of spastic and non-spastic limbs were almost twice as high for men as those for women [21].

Table 2: The values of torque for elbow flexors and extensors woman [21]

WOMEN				
Joint	**Limb**	**Group of muscles**	**Angle [deg]**	**Moment of force [N.m]**
Elbow	Non-spatic	Extensor	90	19,79
		Flexors		12,89
Elbow	Spatic	Extensor		16,78
		Flexors		18,61

Table 3: The values of torque for elbow flexors and extensors Men [21]

MEN				
Joint	**Limb**	**Group of muscles**	**Angle [deg]**	**Moment of force [N.m]**
Elbow	Non-spatic	Extensor	90	36,78
		Flexors		30,19
Elbow	Spatic	Extensor		27,18
		Flexors		29,37

2.2 Rehabilitation

Most of the muscular diseases has as principal treatment intense physical therapy [4], which is designed with repetitive exercises that can be divided in passive or active. The exercises in which the professional or robot actively assist the patient moving the segment being treated repetitively is denominated a passive exercise. The active exercise takes place when the main effort comes from the patients themselves without any physical assistant [8].

A passive rehabilitation method requires an intense attention of the physical therapist, and in case of severe muscle impairment such as atrophy or dystrophy conditions, the trained professional must move the patients through a series of motion exercises to spur the regeneration of their neurophysiology and muscle control [5]. Also it has been recorded some success of increasing bone mass with a number of interventions including standing, electrically stimulated cycling or resistance training, and walking exercises [3].

2.2.1 Upper Limbs motion

The upper limbs are responsible for 8 basic body motions: shoulder vertical flexion/extension, shoulder horizontal flexion/extension, shoulder adduction/abduction, also shoulder internal/external rotation, elbow flexion/extension, forearm supination/pronation, wrist flexion/extension, and wrist ulnar/radial deviation. Each different movement will activate a different set of muscles in the upper limbs. Those movements are possible due to de several degrees of freedom (DOF) from each joint. 3 DOF on the shoulder, 2 DOF on the elbow and 2 DOF on the wrist [24]. The **Table 4** shows each muscle responsible to a certain type of motion.

Table 4: Activated muscles for each motion [24]

Motion	*Activated Muscles*
Shoulder vertical flexion (SVF)	Coracobrachialis, Deltoid (anterior), Pectoralis major
Shoulder vertical extension (SVE)	Deltoid (posterior), Teres major, Latissimus dorsi
Shoulder horizontal flexion (SHF)	Pectoralis major (calvicular part)
Shoulder horizontal extension (SHE)	Deltoid (posterior)
Shoulder adduction (SAD)	Coracobrachialis, Latissimus dorsi, Teres major, Pectoralis major
Shoulder abduction (SAB)	Deltoid, Supraspinatus
Shoulder internal rotation (SIR)	Deltoid (anterior), Subscapularis, Latissimus dorsi, Teres major
Shoulder external rotation (SER)	Deltoid (posterior), Infraspinatus, Teres minor
Elbow flexion (EF)	Biceps brachii, Brachioradialis, Brachialis
Elbow extension (EE)	Anconeus, Triceps brachii
Forearm supination (FS)	Supinator, Biceps brachii (long head)
Forearm pronation (FP)	Pronator quadratus, Pronator teres
Wrist flexion (WF)	Flexor carpi radialis, Flexor carpi ulnaris, Palmaris longus
Wrist extension (WE)	Extensor carpi radialis longus, Extensor carpi radialis brevis, Extensor carpi ulnaris
Wrist ulnar deviation (WUD)	Flexor carpi ulnaris, Extensor carpi ulnaris
Wrist radial deviation (WRD)	Extensor carpi radialis longus, Extensor carpi radialis brevis, Flexor carpi radialis

Even though the Table 4 shows activity in several muscles for certain movements, the discrepancy of each movement can be done with only one or two muscles. Is possible to identify the occurrence of an external rotation movement when the infraspinatus and/or deltoid (posterior) are activated. The deltoid muscle anterior and posterior can be used to identify the shoulder abduction motion. The muscles of teres major and pectoralis major, when activated simultaneously defines the shoulder adduction motion without shoulder internal rotation. And when the angle of the shoulder horizontal flexion are between 0 and 90 degrees, pectoralis major (clavicular part) is used. And a shoulder horizontal flexion can differ from the others with the activation of deltoild (anterior) and pectoralis major [24].

2.2.2 Upper-limb segment dimensions

A good approach to acquire the arm length is with the sum of the principal bones length of the upper limbs. A procedure was carried out with two embalmed human female cadaver upper extremities obtained from anatomical donations. Musculoskeletal data was collected using the 2 bodies that had the ages and weights at time of death of 28 years, 65.9 kg and 91 years, 63.6 kg, and both specimens were 1.65 m in height [15]. The **Table 5** shows the values obtained for humerus and upper arm length.

Table 5: Humerus length and upper arm circumference in cm [15]

	28 years old - 65Kg	91 years old - 63,9Kg
Humerus Leght (palpable)	27.6	2.8
Upper Arm Circunference	26	31.8

Another procedure was carried out with 43 men divided in 3 groups according to age: Group I with 20 men (mean age 23), Group II with 10 (mean age 77) and group III with 13(mean age 86) [16]. The **Table 6** shows the values acquired for the humerus and radius length in cm.

Table 6: Humerus and radius length in cm [16]

Bone size Male (cm)			
Age	23	77	83
Humerus Length	32.7+-1,6	35.1-18	33.2+-26
Radius	23.9+-16	23.8+-12	23.9+-12

This study also provided information regarding the upper limbs cross sectional area (CSA), **Table 7**. The cross-sectional area was calculated using the % of fat in each segment [16],

$$Fat\% = \frac{CSA\ Fat}{Whole\ Arm\ CSA} \times 100$$

$$Whole\ Arm\ CSA = \frac{CSA\ Fat}{Fat\%} \times 100$$

Table 7: Cross sectional area upper arm [16]

Muscle and Subcutaneous Fat Cross-Sectional Area			
Age	23	77	83
Subcutaneous fat (cm2)	19.8 +- 6.4	27.4 + - 8.7	23.4 + - 6.2
Subcutaneous fat (%)	28.9 +- 6.7	38.7 + - 8,4	39.1 + - 7.4
Arm Muscles (cm2)	52.0 + - 5.7	43.4 + - 5.4	35.5 + - 5.3
Whole arm muscle (cm2)	68.12	70.8	54.84
Forearm muscles (cm2)	39.4 + - 5	35.7 + - 1.7	31.0 + - 2.8
Whole forearm (cm2)	50.78	49.26	42

Another study measured the left side of five upper limb dimensions and the stature of each subject in centimeters to the nearest millimeter. The measurements were taken with 200 normal healthy Sudanese Arab volunteers, 100 males and 100 females, between 25 am 30 years old, an age that ensures bone and body maturity. The mean age of the males was 27.64 - 1.7, and the mean of females was 27.8 - 1.69 [17]. The Table 8 shows the results useful for this study.

Table 8: Upper arm, Ulnar and wrist length [15]

(cm)	Male (27.64 Yo)	Female (27.8 Yo)
Hight	175.11	160.25

Upper arm Length	31.65	28.9
Ulnar Length	9.26	26.07
Wrist Breadth	5.59	4.92

Henry Dreyfuss studied the human anthropometry for years and achieved a very complete work regarding the size of each body segment [18][19]. Its research is from the 60s however is still applied today [19]. This study contains a detailed description of female and male children from the ages of 4 to 17 years old. The **Table 9** and **Table 10** shows the segments sizes in inches, each segment detail is indicated in the **Figure 1**.

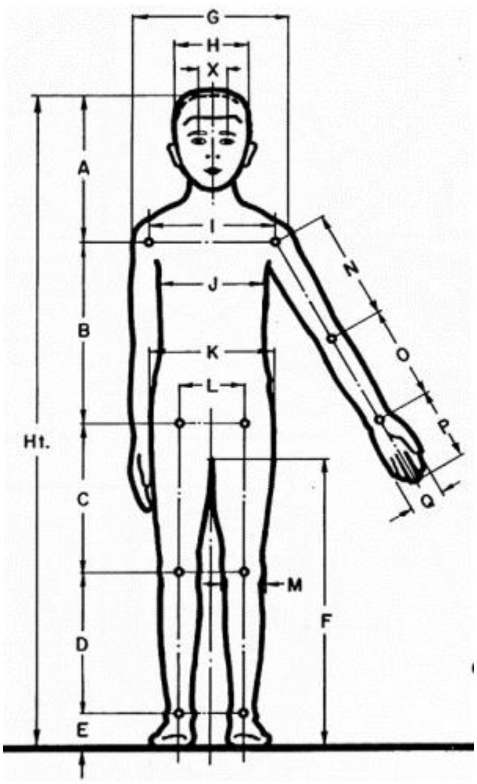


Figure 1: Indication of body segments [18][19]

Table 9: Body segments sizes male children in inches. [18][19]

MALE CHILDREN (in)				
AGE	**G**	**I**	**N**	**O**
17	15.7		12.3	10
16	15.2		12.2	9.9
15	14.7		11.9	9.1
14	14.1	11	11.4	9.7
13	13.5		10.7	9.3
12	13		10.3	8.8
11	12.6		9.9	8.1
10	12.3	10,5	9.5	7.8
9	11.8		9.1	7.4
8	11.4		8.7	7.1
7	10.9	9,2	8.2	6.8
6	10.4		7.6	6.1
5	10.1	8,5	7	6
4	9.7		6.4	5.6

Table 10: Body segments sizes female children in inches. [18][19]

FEMALE CHILDREN (in)				
AGE	**G**	**I**	**N**	**O**
17	14.4		11.5	9.1
16	14.3		11.7	9.1
15	14.2		11.5	9
14	14	11	11.4	9
13	13.6		11	8.8
12	13		10.6	8.5
11	12.4		10	8.1
10	12	10,5	9.5	7.7
9	11.5		9.1	7.3

8	11.1		8.7	6.9
7	10.7	9,2	8.2	6.6
6	10.8		7.6	6.2
5	9.8	8,5	7	5.9
4	9.4		6.4	5.4

2.2.3 Upper limbs center of mass

Another specification that is also important to understand the body and muscles behavior is the center of mass of each segment. De Leva presented a study based on calculating the centers of mass (CM) of the human body using gamma-ray scanning techniques. The study reports the CM values according to the percent longitudinal distances of the main joint centers (**Table 12**). It considered the mass of an average female and male to calculate the mass percentage of each body segment according to the body total mass (

Table 13). The body mass used as reference in this study was 61,9 Kg for female woman with a body stature of 173.5 cm, and a mass of 73 Kg for males with a stature of 174 cm. [20]

There is a relationship between the mass of each segment and the total mass of the body for male and female. The **Table 11** shows results considering a female body mass of 61.9 Kg with a stature of 173.5 cm and a male body mass of 73 Kg with a stature of 174 cm.

Table 11: Arm segments mass percentage according to total body mass

	Female		Male	
	Mass (kg)	Mass (%)	Mass (kg)	Mass (%)
Upper Arm (SJC - EJC)	1.86	2.55	1.98	2.71
Forearm (EJC-WJC)	1.01	1.38	1.19	1.63
Hand (WJC - DAC3)	0.41	0.56	0.45	0.61

Table 12: Upper limbs size (cm) and Center of mass location in male and female [20]

	Female		Female		Male		Male	
	Size (cm)	Size (%)	CM (cm)	CM (%)	CM (cm)	CM (%)	Size (cm)	Size (%)
Upper Arm (SJC - EJC)	27.51	14.8	15.83	57.54	16.57	57.72	28.71	15.8
Forearm (EJC-WJC)	26.43	9.4	1.,05	45.59	12.31	45.79	26.89	12.8
Hand (WJC - DAC3)	17.01	15.4	5.83	34.27	6.81	36.24	18.79	18.4

Table 13: Upper limbs segments mass and mass percentages with the human body [20]

	Female		Male	
	Mass (kg)	Mass (%)	Mass (kg)	Mass (%)
Upper Arm (SJC - EJC)	1.86	2.55	1.98	2.71
Forearm (EJC-WJC)	1.01	1.38	1.19	1.63
Hand (WJC - DAC3)	0.41	0.56	0.45	0.61

- CM = Center of Mass
- SJC = Shoulder joint center
- EJC = Elbow joint center
- WJC = Wrist joint center
- DAC3 = Dactylion the tip of 3th

2.2.4 Use of orthosis in rehabilitation

The orthosis is a very positive scientific approach when dealing with human rehabilitation. Exoskeletons are designed to provide support for human movement. The support that is provided orthotic devices can not only be use in human neuromuscular rehabilitation, but can also be exploited to augment the strength of healthy people [10]. Many companies work with non-robotic orthosis. This device are used seeking the protection of the limb Figure 2.

Figure 2: Non-robotic orthosis

The use of robotics comprehends many areas from high production industries to automobilist, however the implementation of robots is not only comprised in high industries corporations. Over the years there was a big development of robotics applied to human medicine aiming the increase of life quality and health. This progress is easily seen in the field of orthopedics in which the incorporation of the robot to human body can generate better rehabilitation. In case of a neurological injure, or muscle disease the use of robotics in a form of orthosis or exoskeletons can facilitate the restoration of muscle movements and task performance. These devices can generate a precise and reproducible path in comparison with the manual assistance, and can quantify the muscle recovery obtaining better image of the patient health [7]. Many exoskeletons for the upper body used today are rigid and hard to manipulate. A soft orthosis takes advantage of natural anatomic structure such as bones and joints for the device structure. The conventional rigid robots frame can be disregard and its function is performed by the user bones, and the actuation is performed by mechanical tendons or other soft actuators that will apply shear forces to its attachment points in the body [13].

Literature shows development of orthosis to assist a set of for upper limbs movement, the shoulder vertical and horizontal flexion-extension movement and the elbow flexion-extension. For the first set was used 2 dc motors located in an apparatus behind the patient shoulder, and elbow flexion-extension motion was made using a pulley and another DC motor. This design had the assumption that many physically weak patients uses wheel chair to assist in body dislocation, allowing the attachment of all heavy parts such as the 3 DC motors at the chair. The motors move the arm using driving wires connected to tension sensors which measures the driving force. The shoulder angle was measures by potentiometers. The whole system was controlled by EMG sensors [11].

Another wearable orthosis was used to treat bilateral postural tremors involving upper limbs. The device allowed not only not only the assessment of the essential tumor with various viscosity conditions, but also provided its direct cancellation and suppression. 3 rotatory flat DC motors with a harmonic pancake were used to apply forces on 3 respective upper-limbs movements: elbow flexion–extension, forearm pronation–supination and wrist flexion–extension. Strain gauges were used for the force measurement between the patient and the orthosis, kinematics and kinetic sensors were essential for the monitoring and suppression of the tremors, as well as gyroscope were used to measure the rate of rotation and the angular position and acceleration were obtained with the computation of the sensors data. A metallic bar was displaced in parallel with the forearm controlling the pronation-supination movements [6].

In order to help disabled people that suffers with myopathy and muscle degeneration an exoskeleton was designed. A bracelet containing 4 pressure sensors placed on the forearm and upper arm measured the forces made by the patient in any attempt of movement. The sensor bracelet input also indicated the moment of a movement activating a set of motors placed on the orthosis joints complementing the muscle force [12].

Another option for rehabilitation is the use of soft orthosis. A glove was developed using the soft orthosis ideal inducing flexion and extension movement through the transmission of the tension of mechanical tendons to the body such as a human hand. The glove has 2 mechanical tendons for each finger and thumb and several straps joined together forming a pulley simulating the muscle origin. The fingers movement and trajectory is made by changing the length and position of the fabric straps (mechanical tendons). Bowden cables fixed one end in the actuators and the other at finger the strap is essential to the control (Figure 3). A bend sensor detecting the wrist motion was the main tool to obtain the inputs necessary for the control system.

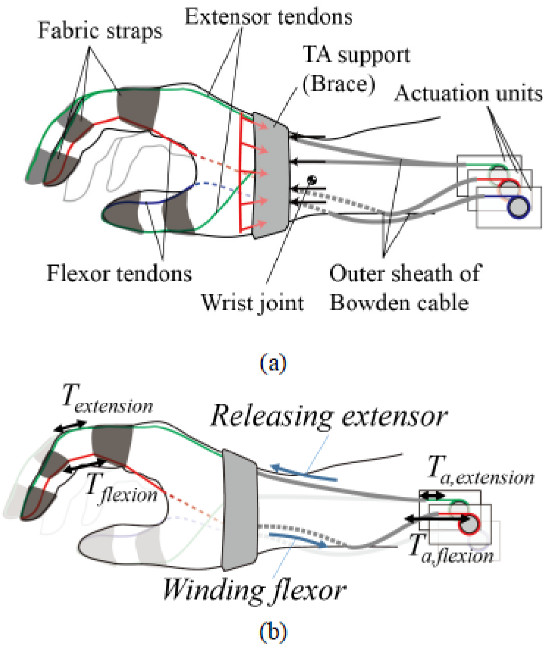
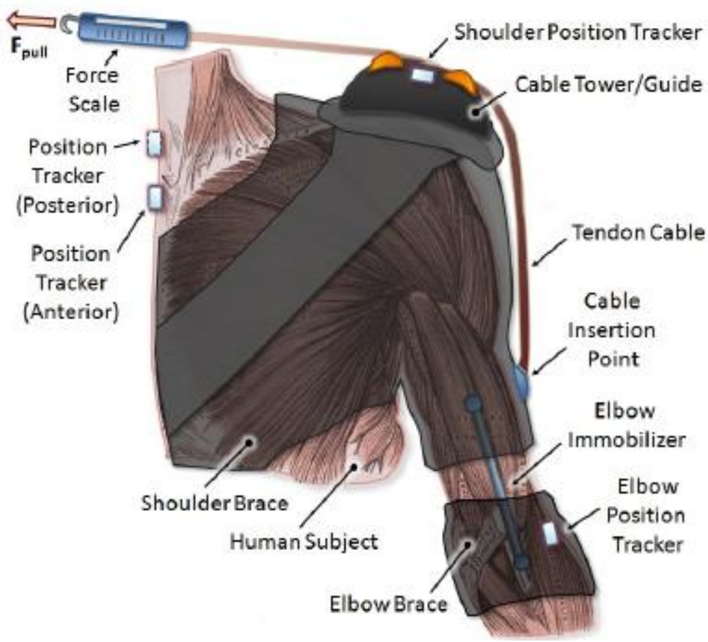


Figure 3:Glove assembly mechanism [13]

A soft orthotic system for the shoulder rehabilitation if port stroke patients was designed to mimic some physical therapy exercises moving the patient is a passive type exercise (**Figure 4**). The system showed the advantages of a soft orthosis such as light weight, adaptation capability to misalignment and anatomical variation through sensing and control the range of motion obtained were sufficient to achieve rehabilitation. Bowden cables were connected to the arm and to the actuator (motor unit 20 N.m for a 300 g arm mass). Each brace is part of a redundant antagonist pair to match the degrees of freedom of each joint. This antagonist pairs provide a “push” “pull” functionality. The force control and feedback was performed using the inputs provided by a series elastic actuator. This technique uses elastic elements is series to actuators which allows the measurement of the forces made by the device.

Figure 4: Shoulder soft orthosis [14]



2.3 Sensors of clever orthosis and prosthesis

This part will describe the sensors and electronic components available in the market that suits the design being proposed.

2.3.1 Load Cells

A load cell is a transducer that produces an electric outlet according to the force being applied. There is a grand variety of load cells being the strain gauge the most used one. The first sensor to measure force was invented by the physicist Charles Wheatstone. He developed a circuit in bridge that was able to measure changes in the resistance values.

The hydraulic load cells as well as the pneumatic ones are advantageous because there is no necessity of an energy source, thus they are considered more hygienic and safe. The hydraulic ones measure the weight with the pressure change in their internal filling fluid. The load acting force is transferred to a piston that will compress a fluid confined within an elastomeric diaphragm chamber. This compression will induce a change of fluid pressure. The measure obtained is linear, but those devices are usually used in industries that security as main concern. It requires a bigger amount of time to obtain a result [25].

The strain gauge is a sensor that varies its electrical resistance according to the variation of forces, weights or pressure applied. Mainly, it converts the load acting in an electrical signal. This changes in the electric current can be converted in weight units finishing the measurement. From all electric measurement tools, the strain gauge is classified as one of the most important ones, taken that, allows the measurement of compression and traction providing the results in negative or positives values. The quantification of the deformation level is important to define the resistance of a structure [25].

The first strain gauge consisted in a network of aluminum wires resulting in a resistance of 0.025 mm. Its surface would change shape with the application of an external force and would also cause a change on the resistance. The latter would translate the shape deformation in electrical terms. Usually the strain gauge is composed by 4 sensors creating a Wheatstone bridge. The output voltage is measured I millivolts per volts on the inlet voltage.

2.3.2 Inertial Measurement Units

The inertial measurement unit (IMU) is a system that will have as an output will the integrating quantities of angular velocity and acceleration of a body. This system will measures linear and angular motion using, usually, three gyroscopes and three accelerometers [28]. The accelerometers are mounted orthogonally to each other and are responsible for measuring the directional specific force, which is also the total acceleration of an object subtracted to the gravitational force [1].

In case of the gyroscopes, those sensors are also mounted orthogonally and its main point is to measure the rotational motion which is achieved with the principle of conservation of angular momentum [1].

2.3.2.1 Accelerometers

Microelectromechanical systems (MEMS) is the combination of a mechanical and electrical components in a micrometer scale. When these systems are used as sensors is possible to measure linear acceleration (accelerometers) or angular motion (gyroscopes). The accelerometers sensors will use a positioning interface circuit to measure the displacement of a certain mass. The measurement can be digitally processed later with an A/D converter. These values can be a very resourceful input when dealing with a control system [23].

The acceleration of a body is dependent on 2 variables: the net force acting on the body and the body's mass. The change of velocity will be directly proportional and in the same direction of the net force acting on the body and inversely proportional to its mass. (Newton's Second Law). The accelerometer has a force-detection mechanism that is able to measure the force created by an acceleration. The acceleration values are obtained indirectly by the sensor, taken that it will directly measure the force applied on its axes. The sensing technique of this MEMS is made by change in the capacitance of a moving mass, **Figure 5**, [26].

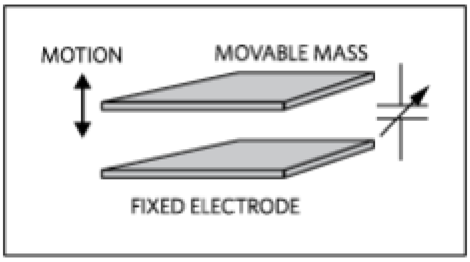


Figure 5: Sensing accelerometer mechanism: moving mass and capacitance [26]

2.3.2.2 Angle Sensor

The detection of linear or rotatory position can be done using anisotropic magnetoresistive technology (AMR). For rotatory measurements, there is a pole ring creating a magnetic field that will be sense by the AMR sensor, **Figure 6**. The colored regions shows the magnetic field orientation [27].

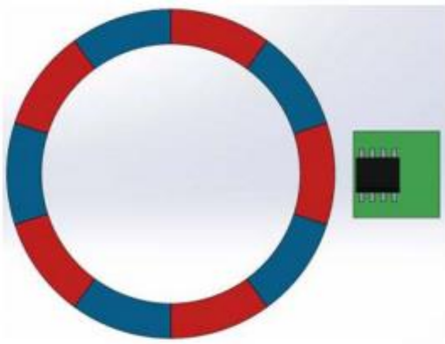


Figure 6: Off shaft Magnetic configuration [27]

Each color represents a pole, thus the ring in Figure 6 shows the sensor magnetic poles. The sensor will be able to measure with precision 36° at a time. With more poles this angle decreases. In the device there is a rotating shaft with a dipole magnet located at the end. The sensor is located underneath the rotating shaft and magnet. The magnetic field rotate with the magnetic shaft and the north and south poles of the diametric magnet form a uniform field above the center of the magnet [27].

An optical angle sensor is a combination of emitter and detector modules that translate a rotatory motion of a selected shaft into a digital output using a codewheel. Basically, the modules contain a light source: light emitting diode (LED), a polycarbonate lens, and an integrated detector circuit, **Figure 7**. The light emitted by the LED is collimated into a parallel beam (polycarbonate lens) which is located over the LED. The detector circuit is on the opposite site and consists of multiple sets of photodetectors and the signal processing circuitry necessary to produce the digital waveforms. When the codewheel rotates between the emitter and detector the light beam will be interrupted according to the pattern of spaces on this codewheel. This interruption will also be detected by the photodiodes and thus 2 different signals will be generated and sent to comparators that will interpret this lights interruption into angle velocity [29].

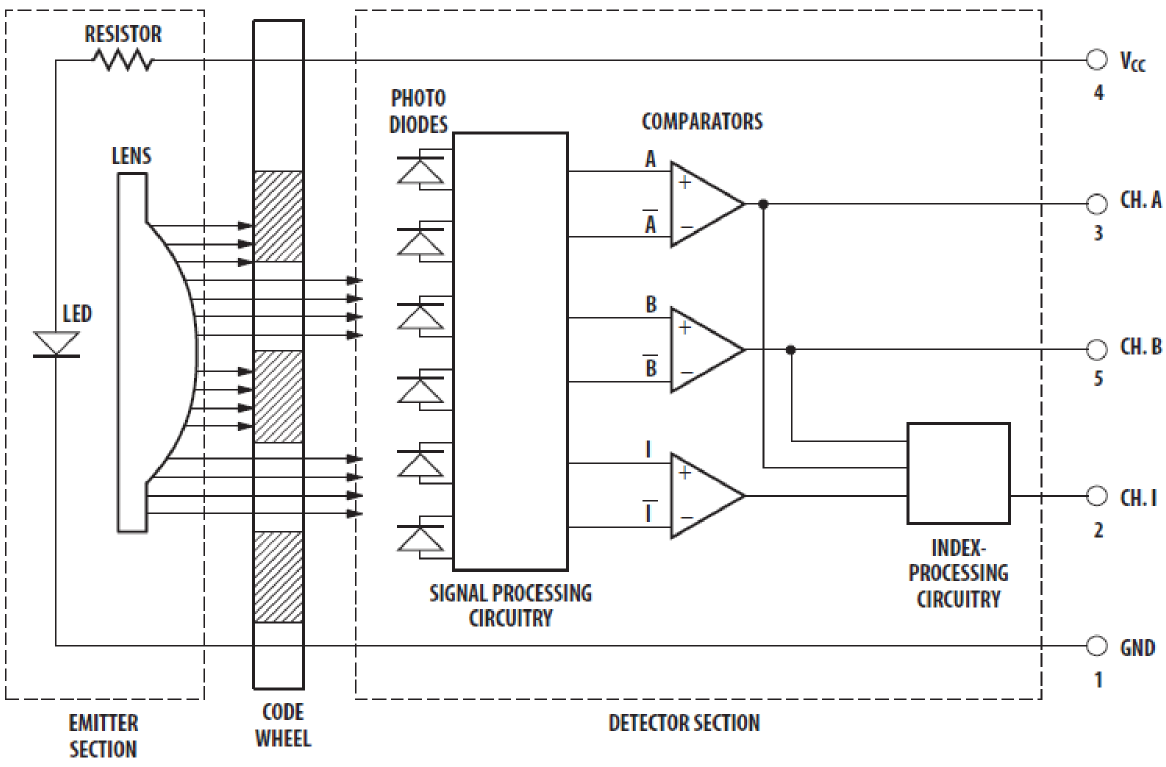


Figure 7: Block diagram optical angle sensor [29]

2.3.3 Thermometer and cooling system

This section will approach all types of sensors that can be used in orthosis and prosthesis.

2.3.3.1 Cooling system

Is known since the 19th century will exist a flow of electrical current if there is a temperature gradient across the junctions of two dissimilar conductors. And a heat can be emitted or absorbed at the junction of the materials of two dissimilar electrical conductors with a creation of an electrical current [31].

A Peltier module is a unique cooling device in which the electron gas serves as the working fluid. It is noiseless, inherently reliable and environmentally friendly [30]. A general thermoelectric module is formed by pellets of semiconductors forming an array of Bismuth Telluride, in which one type of charger carrier will carry the majority of current that is flowing, can be positive or negative. The pellets are connected thermally in parallel unlike the electrical connection that is in series. The positive and the negative charge carriers will absorb energy in a form of heat from one substrate, and will release heat from the other substrate when there is a DC voltage actuating on the material. With that, one surface will become cold while the other will become hot [31].

2.3.3.2 Thermostat

A thermostat is a sensor that measures temperature and converts the data into digital form. The conversion is possible due to an I^2C (Inter-Integrated Circuit) interface [33]. Usually the sensor measures the voltage at 2 currents on a chip transistor. The ratio of these currents will give a temperature value. The temperature is measured from a semiconductor material block (die) which is mounted on a metal lead frame (thermal input) [34].

2.3.4 EMG sensors

The EMG is a primary tool to study the muscle function. Its signal includes information about the muscle activity. It can be used as diagnostic device or with biomechanics purposes in which the signal input carries a valuable information that can estimates forces in muscles or even motor control [32]. The information taken from the EMG signal allows the understanding of the user motion, this can be used to assist many human-robotic systems [24].

An action potential is an electric impulse issued by cells that can initiate a voluntary contraction of a muscle. This contraction will emanate a biopotential waveform signal that can be read by the EMG electrodes. One of the EMG electrodes are the surface electrodes, these are able to detect electrical signal on the skin surface when positioned according to each specific muscle. Taken that those electrodes are placed at the body surface, deep muscles cannot be detected by the sensor. The surface electrodes can be dry or gelled. The dry ones have a system with a preamplifier that can convert the high skin impedance to low impedance output. The gelled electrodes use an electrolytic gel that will reduce the skin impedance improving the signal quality. Another type of EMG electrodes are the needle electrodes. These are inserted directly in the muscle of interest and has to be carefully positioned to obtain the correct signal [32].

2.3.5 Oximeter and heart rate sensor

The pulse oximeter is a device that will measure the amount of oxygen dissolved in the blood (oxygen saturation - SpO_2) using a non-invasive method. The method is based on the detection of the hemoglobin (Hb) and deoxyhemoglobin (HbO_2) using two different wavelengths to detect the difference in the absorption spectra in both proteins. The wavelength of 660 nm (red light spectra) will be better absorbed by the HbO_2 and the wavelength of 940 nm (infrared spectra) will be better absorbed by the Hb. A photo-detector will detect the non-absorbed light from the LEDs after passing through the blood and will emit a signal that after being inverted will represent the absorbed light. This signal will have 2 components: a DC (direct current) component and a AC (alternating current) component. The DC will represent the non-pulsating blood, thereby the venous blood, the AC represents the pulsating blood, thus the arterial blood.

2.3.6 Controller Electronics Systems

A microcontroller is a complete operational system with a central processing unit (CPU), storage memory, clock system and input and output signals (I/O). Is also possible to find in many controllers analog/digital conversers (A/D converser) and timing modules. The CPU is instructed by a program (software) and is able to read the inputs and the memory information writing these information on the outputs. The memory represents the addresses where the information will be stored. Each address has a fixed value that will change according to the microcontroller specification. A system with n addresses lines has 2^n memory positions [36].

The CPU processes the external information by the input digital signals: 0 volts correspond to the logic level 0 and the logic level 1 will vary according to the energy source of the system. The process accomplished by the CPU will be presented to the external mean using the outputs systems [36].

2.3.6.1 Programable Automation Controllers (PACs)

Programmable automation controllers (PAC) are open digital control systems for a user with a modular construction and with a easy user interface [37]. PAC can be described as a blended system of a PLC and a PC. It integrates the process control advantage of the PLC system with the flexible configuration and enterprise integration strengths of a PC-based system [38].

3 DESIGN

This part will describe the mechanical design developed for this orthosis. The project was based on the literature review and is presented in 4 different sections. The first will describe each mechanical component designed for this prototype, as well as its materials, dimensions and specifications. The second will describe the actuation system operation added to the selection and dimensioning of the actuators. The third contains a detailed description of each sensor proposed and the sensors selected to measure the exoskeleton. The latter will explain the controls mechanisms and the electrical actuation designed.

3.1 Construction of the mechanical parts of the orthosis

The orthosis is formed mainly by 3 main parts, the upper-arm support, the forearm support and the shoulder support. It also contains 2 for Peltier modules, 2 body temperature sensors, 2 accelerometers, 2 encoders, 2 strain gauges, one pulse oximeter probe, and one disk fixating the forearm to the upper arm. All limbs are driven by Bowden cables being manipulated by a motor and 2 sets of gears located in a backpack carried by the patient.

3.1.1 Upper-arm support

The upper-arm support is formed by a 2mm thickness aluminum alloy 7050- T7350 covering the upper-arm from the shoulder to elbow joint and a thick (8mm) cylinder placed at the circular ending of this part. The cylinder is necessary to support the rotational movement of the elbow. The choice of the material was due to its light weight and mechanical strength. The size of the upper arm taken in consideration was 28.71 cm (Table 12) from the shoulder joint center to the elbow joint center. Mainly, the support is formed by a rectangular part covering the upper-arm length followed by a circular part covering the elbow joint.

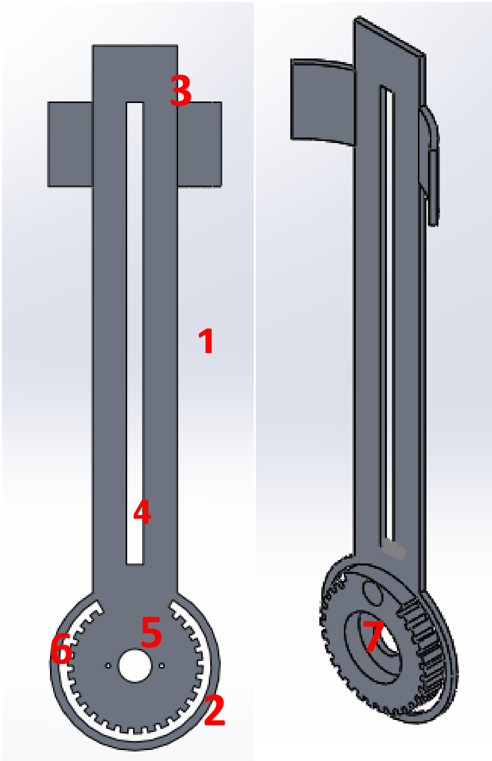


Figure 8: Upper-arm support

1- Upper-arm holder, 2- Elbow joint section, 3- Upper-arm fixation, 4- Peltier module section, 5- Encoder fixation, 6- Motion restriction pin orifice, 7- Motion range cylinder

The main function of this part is to support the upper-arm. To fix the exoskeleton to the body was necessary to design an arm holder (Figure 8 – 3), and for this part measurements was considered a limb with a cross sectional area of 68.12 cm^2 (Table 7), thus with radius around 4.6 cm. This part will involve a percentage of the arm circumference and the whole section (upper-arm holder + upper-arm) is wrapped with the shoulder support part (Figure 10). The rectangular orifice in the middle (Figure 8 – 4) was designed to place the Peltier module and to allow the sensor movement through the limb. The patient will be able to place the sensor in the desired place around the orthosis according to his needs.

There is an encoder attached on the upper-limb placed in the 3 orifices in the middle (Figure 8 – 5); The orifice number on the cylinder (Figure 8 - 6) is for setting the movement range. Many patients after an injure can't move the arm freely. To avoid that the doctor will be able to place 2 pins locking or limiting the movements of the arm. The cylinder was designed to support those forces maintaining the limb in place.

3.1.2 Forearm support

The forearm support is formed by a 1.5 mm thickness aluminum alloy 7050 - T7350 covering the forearm from the elbow joint to the wrist joint. The choice of the material was due to its light weight and mechanical strength. The size of the upper arm taken in consideration was 26.89 cm (Table 12) from the elbow joint center to the wrist joint center. Mainly the support is formed by a rectangular part covering the forearm length followed circular part covering the elbow joint.

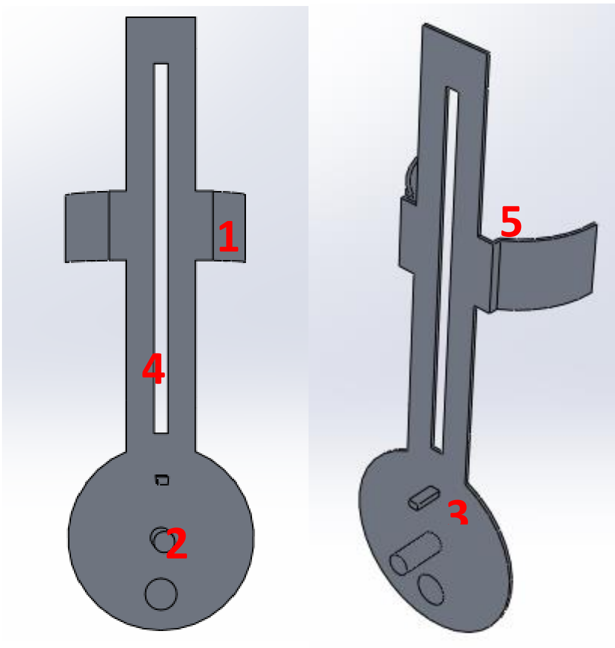


Figure 9: Forearm support

1- Forearm holder, 2- Rotational shaft, 3- Motion range pin, 4- Peltier module section, 5- Peltier module pass way.

As well as the upper-arm support was necessary to design an arm holder (Figure 9- 1) to fix the exoskeleton to the body, and for this design measurements was considered a limb with a cross sectional area of 50.78.84 cm^2 (Table 7), thus with radius around 4 cm. The shoulder support does nor cover the forearm, thus to fix the forearm support to the body is necessary the use of Velcro strips involving the limb from the forearm holder up and down. The shaft (Figure 9 – 2) is connected to the upper-arm support by a 9x26x8 bearing allowing the elbow flexion and extension movement.

The motion range pin (Figure 9 – 3) will move inside the motion range set orifice (Figure 8 - 6) and its motion limits will be set by 2 pins (Figure 13). As well as the upper-arm support the rectangular orifice in the middle (Figure 9 – 4) was designed to place the Peltier module in such a way that allows the sensor movement through the limb. Due to the upper-arm radius was necessary to modify the forearm holder to allow the passage of the Peltier module (Figure 9 – 5).

3.1.3 Shoulder support

The shoulder support was designed mainly to fix the upper-arm support to the body and organize the sensors wires though the arm. This device will be used in physical therapy exercises, thereby it cannot have any wore or cables lose. This part resembles a shirt and among the fabric will have orifices for the wire fixation and has to ne made according to the patient measure. The fabric chosen is neoprene and is already used in many arms immobilizers.

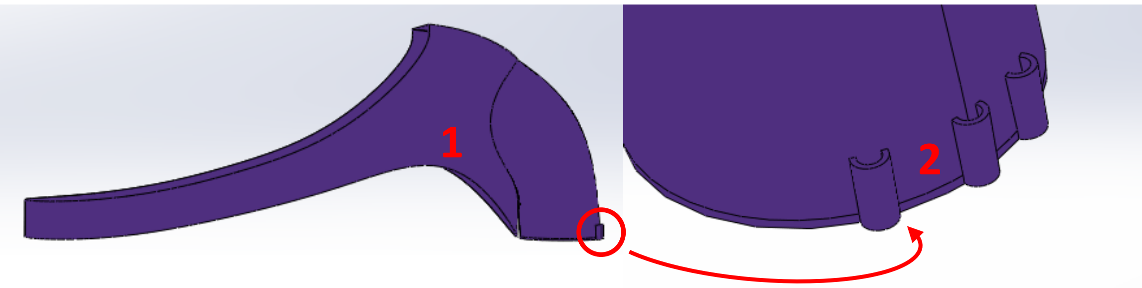


Figure 10: Shoulder support with cables fixation

3.1.4 Shoulder Pad

The shoulder pad was designed only to increase the torque for the movement of shoulder abduction and adduction. Increasing the distance between the cable and the arm lower the force needed from the motor. The pads have orifices allowing the passage of the Bowden cables. On cable at the right extremity for the shoulder abduction and adduction motion (Figure 11 - 1) and 2 cables positioned linearly from each other close to the upper-arm support for the other movements (Figure 11 – 1 and 2)

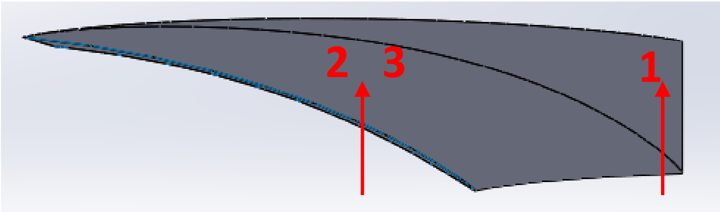


Figure 11: Shoulder pad

3.1.5 Bowden cable disk

This disk is fixed to the forearm support moving in the same manner as the limb. It was designed to fix the cables to the forearm support. Its radius was specified in order to increase the torque decreasing the force needed from the motor. The disk is fixed to the forearm and has 2 gaps on the side, the first if for the placement and fixation of the Bowden cables (

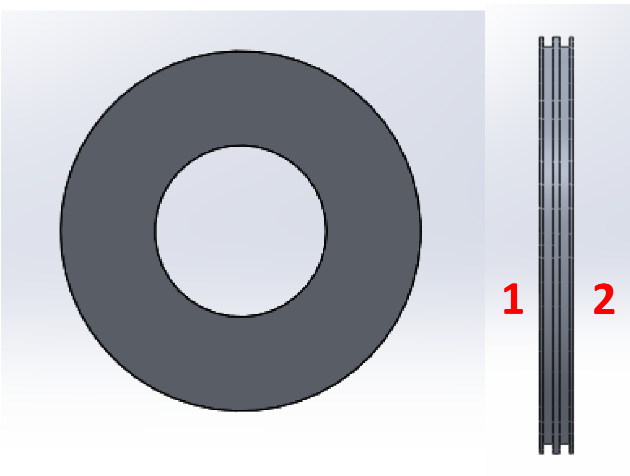
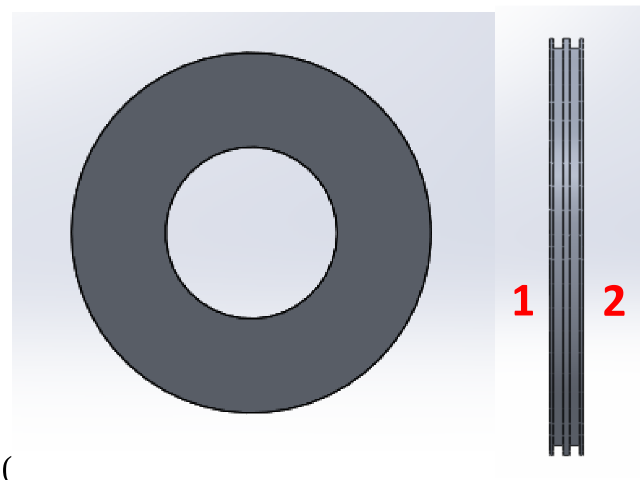


Figure 12 – 1), the second is for the placement and connection of the motion restriction



pin (

Figure 12 – 2). The material chosen for the disk was an aluminum alloy 7050- T7350 due to the material light weight and mechanical resistance.

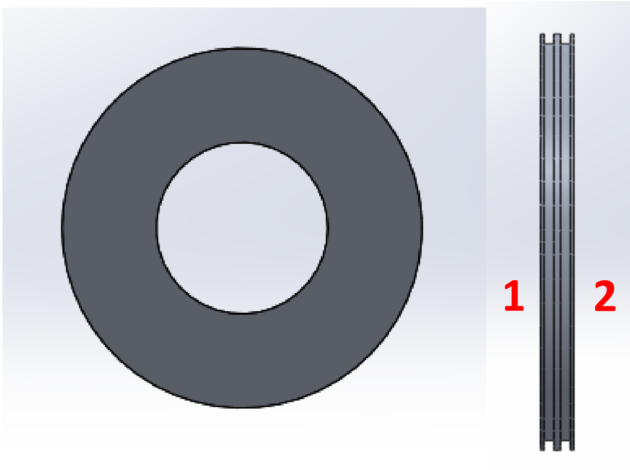


Figure 12: Bowden cable disk

1- Bowden cable gap, 2- Motion restriction pin gap,

3.1.6 Motion range limiting pin

To set the limits of the free movement of the upper-limb two pins had to be placed over the upper-limb support crossing the Bowden disk (Figure 13). The 2 pins will set the max angle of the motion. This is a mechanical safety maneuver to preventing the patient to reach an arm position that can damage the body.

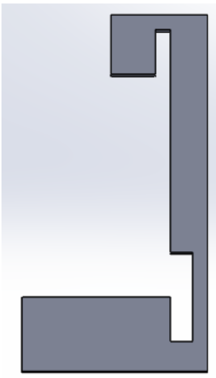


Figure 13: Motion range limiting pin

The pin is on a locked position on Figure 14, to choose the angle is necessary to move it on the direction demonstrated by 1 (Figure 14 - 1). After setting the angles is necessary to return the pin to the locked position which will cause an obstruction to the forearm pin (Figure 9 – 3) blocking any further motion.

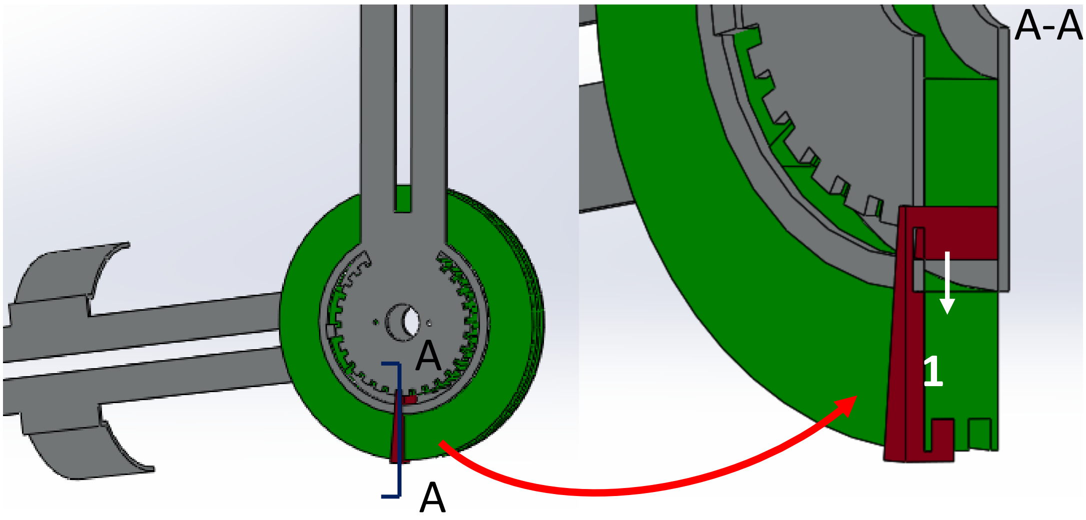


Figure 14: Pin place

3.1.7 Mechanical elements of sensors systems

This design is using 22 sensor in which 4 are fixed on the orthosis. The 10 EMG are placed on the skin and the wire is fixed by the shoulder support and connected at the microcontroller located at the backpack. The 2 strain gage has a duct tape face and is fixed directly at the orthosis plate, the pulse oximeter is connected to the patient index finger, one decoder is connected at the motor shaft and the other at the upper-arm (Figure 8 – 5). To attach the accelerometer and the cooler system to the orthosis was necessary to design an fixation part according the dimensions of the sensors.

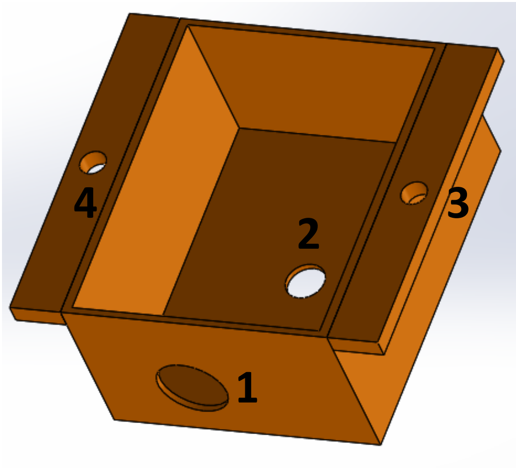


Figure 15: Accelerometer X Sens fix piece

1- Sensor cable, 2- Screw 6 mm, 3 and 4 – Screw 4 mm

The Figure 15 shows the accelerometer piece with the respective orifices for the cable sensor (Figure 15 – 1), for attach the sensor to the exoskeleton with a 6mm diameter screw and 6 mm diameter nut (Figure 15 – 2), and to attach the sensor to the piece with a 4 mm diameter screw and nut ((Figure 15 – 3 and 4).

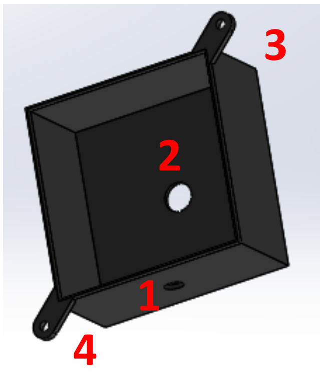


Figure 16: Cooler system

The Figure 16 shows the piece for the fixation of the cooler system, in which the middle orifice (Figure 16 – 2) is for the fixation of the sensor to the orthosis with a 6 mm diameter screw and nut, the orifice 1 (Figure 16) is for the cables, the orifices 3 and 4 (Figure 16) are for the fixation of the sensor to the part with a 1 mm pin or soldering.

While the accelerometer is tightly fixed at the orthosis the Peltier module screw can be loose to allow its movement through the muscles.

3.1.8 Installation device Box

The mechanic box was designed for the installation of the motor, gear sets, locking mechanism, the gear shift wheel mechanism and also the electronic board with the electric organization. The box is located inside a backpack carried by the patient. The ratchet is located at the shaft 1 (Figure 17 – 1) and is fixed to the pinion that is centralized in the motor shaft in 2 (Figure 17 – 2). The 2 gears are centralized at the shaft 3 (Figure 17 – 3) and the pawls for the locking system are located at the shaft 4 (Figure 17 – 4). The shaft 5 (Figure 17 – 5) has the pneumatic pin carrying the 2 gear shift wheels that are centralized at the motor shaft (Figure 19 -7, 8). The motor is placed on 6 (Figure 17 – 6) and is fixed by 2 screws inserted at the orifices in 7 (Figure 17 – 7). The electronic assembly is made on 8.

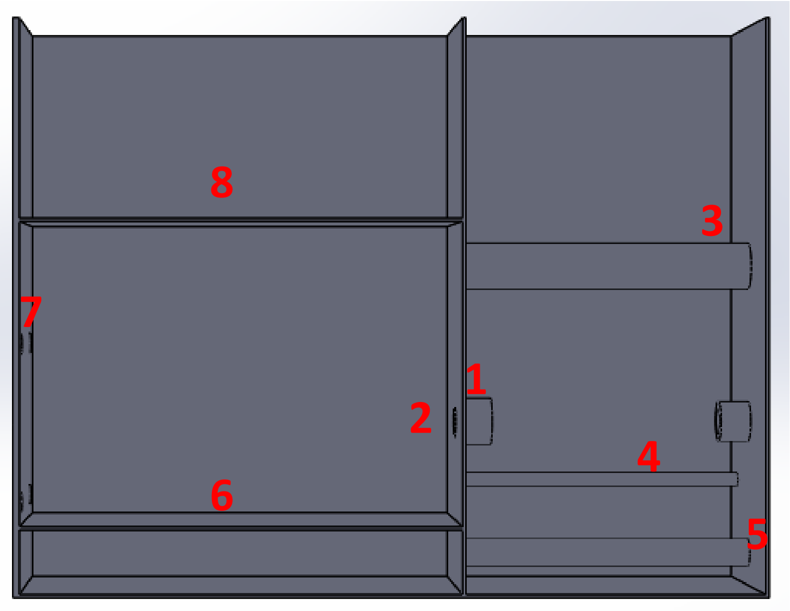


Figure 17: Installation device box

3.2 Actuation and control

This design will be able to assist the patient in 6 different upper-limb motions: shoulder flexion/extension, elbow flexion/extension, shoulder adduction/abduction. To be able to perform all those movements with only one motor was necessary to design a gear box with 2 separated main gears. Each gear is attached to a spool with a winding cable connected to some part of the orthosis (Figure 18). Each gear will activate a specific subpart of the exoskeleton that will perform a specific movement. A electromagnetic pin located in the motor shaft will select each mechanism according to the movement being made (Figure 19).

Gears set 1: Shoulder Flexion/extension motion, Elbow flexion/extension motion

Gears set 2: Shoulder Adduction/abduction motion

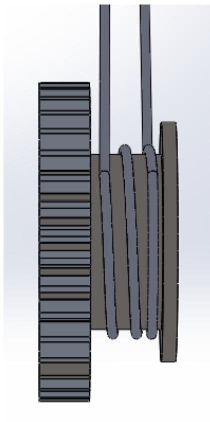


Figure 18: Gear with spool and cable

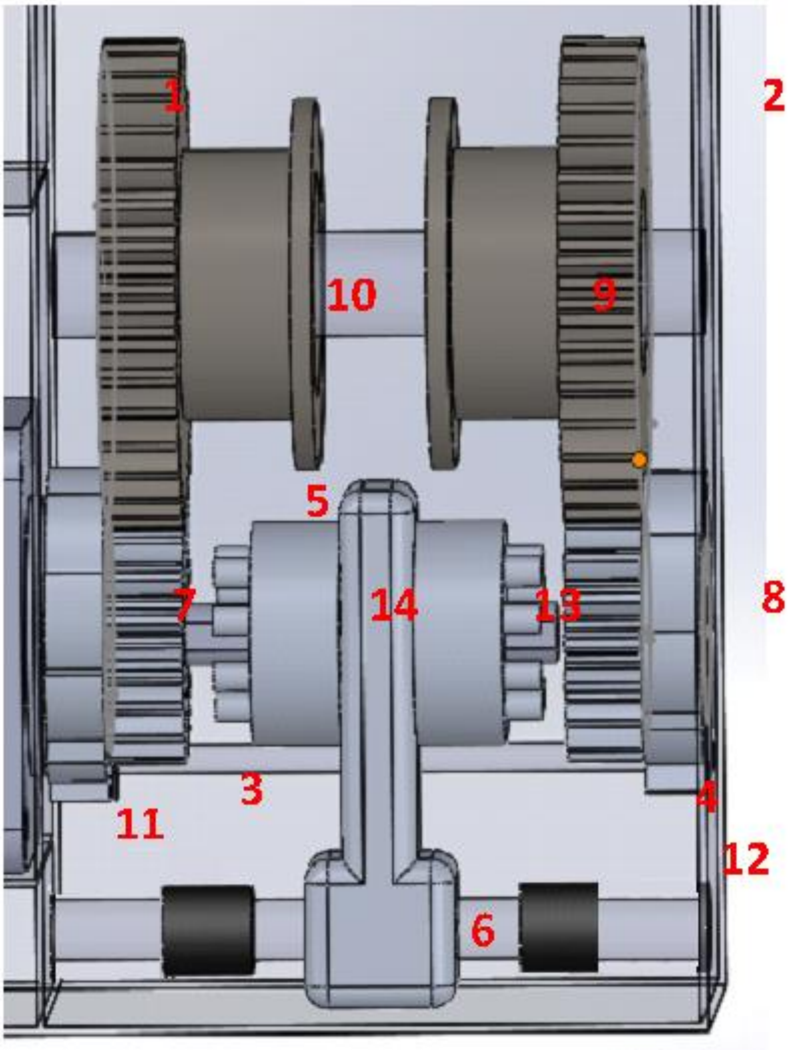


Figure 19: Gear Box

1- Gear set 1, 2- Gear set 2, 3- Pinion 1, 4- Pinion 2, 5- Motor Shaft, 6- Electromagnetic pin selector, 7- Ratchet 1, 8- Ratchet 2, 9- Spool 1, 10- Spool 2, 11- Magnet 1, 12- Magnet 2, 13- Gear shift wheel 1, 14- Gear shift wheel 2

For the movements shoulder flexion/extension, elbow flexion/extension the electromagnetic pin selector will be activated and attracted by the magnet 1. The gear shift wheel 1 (Figure 19 – 11) activates the pinion 1 (Figure 19 – 3) which will move the gear 1() and thus, the spool 1. For the movements shoulder adduction/abduction the electromagnetic pin will be activated and attracted by the magnet 2. The gear shift wheel 2 (Figure 19 – 1), in this instance, will fit the pinion 2 gear shift wheel 1 (Figure 19 – 4) moving the gear 2 and the spool 2. The mechanism described changes the length of the cable enrolled in the spools and moves the arm.

The Figure 20 shows the movement of the arm in the shoulder abduction/adduction motion. The shoulder pad was designed to increase the angle made by the cable with the upper-arm increasing the torque respectively. With that, the force needed to perform this movement decreases.

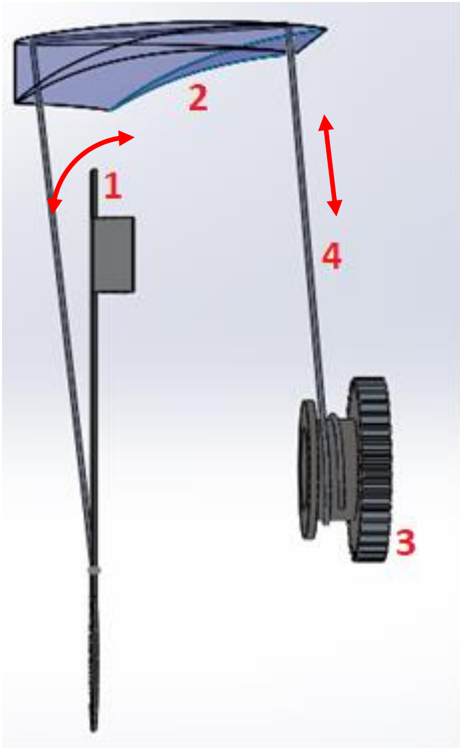


Figure 20: Mechanism shoulder adduction/abduction motion

1- Upper arm support, 2- Shoulder pad, 3- Gear 2, 4- Cable

To perform the flexion and extension movement of the elbow a disk was designed and fixated at the forearm support at the elbow end. The cables winded on the spool 1 were also placed around this disk in order to move the forearm with the activation of the gear 1 (Figure 21). The flexion/extension or adduction/abduction are opposite movements, therefore is possible to perform them by simply changing the direction of the motor.

The gear set 1 will trigger 2 different motions in 2 different joints (elbow and shoulder) separately. To achieve that without including another motor or set of gears another electromagnetic pin was placed at the elbow joint position of the orthosis. This position is exactly the union of the forearm orthosis part with the upper-arm orthosis part and the disk. When there is no energy passing through the pin the elbow joint is free to move enabling the elbow flexion/extension movement, Figure 21

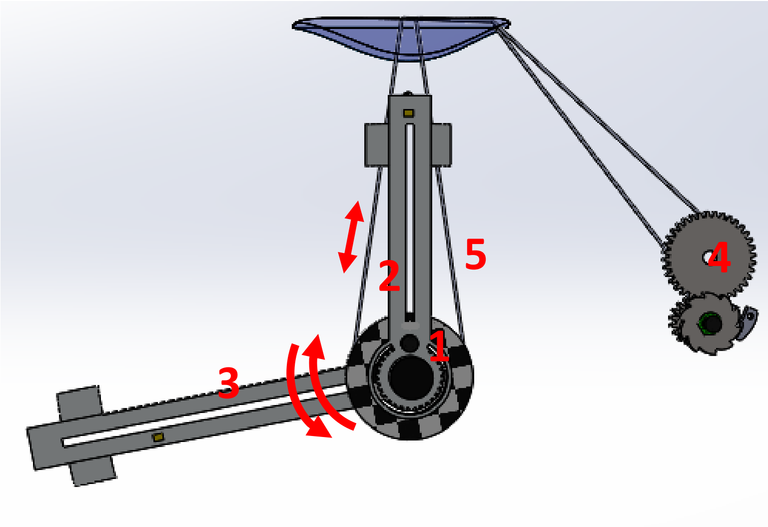


Figure 21: Magnetic pin locker deactivated: elbow flexion/extension motion enabled

1- Magnetic pin locker, 2- Upper-arm orthosis part, 3- Forearm orthosis part. 4- Gear 1, 5- Cable

When there is energy passing through the pin the magnetic lock will fix the upper-arm orthosis part to the forearm orthosis part making the whole system (upper-arm + forearm + disk) a rigid piece. In this condition, the whole structure will move together triggered by the gear 1. Taken that the only moving free articulation is the shoulder joint the motion of shoulder flexion/extension will happen,

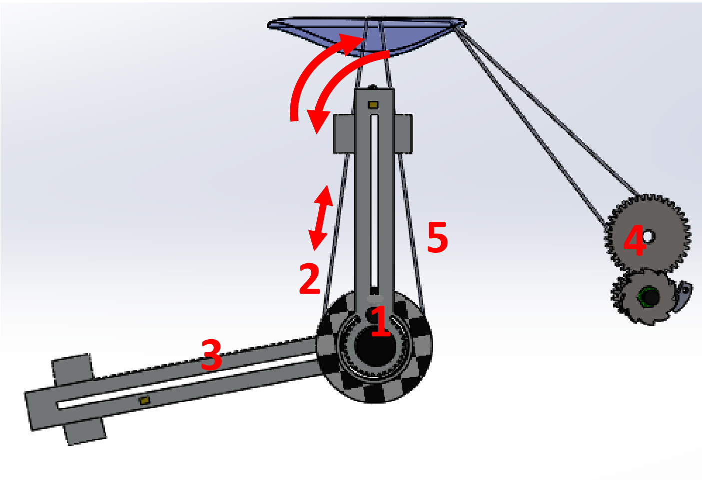


Figure 22.

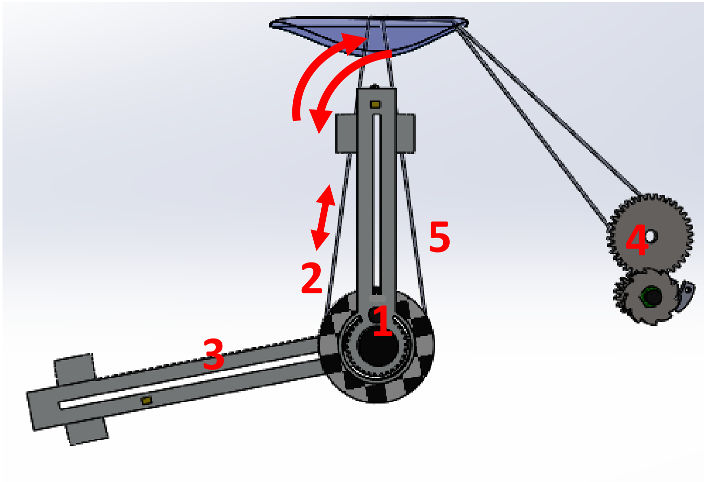


Figure 22: Magnetic pin locker activated: shoulder flexion/extension motion enabled

Magnetic pin locker, 2- Upper-arm orthosis part, 3- Forearm orthosis part. 4- Gear 1, 5- Cable

3.2.1 Gear selection system

The system designed to select between the 2 gear sets is comprised by 1 magnetic pin, 2 gear shift wheels, and 2 magnets (Figure 23). The forms were designed to perfectly fit the pinion. The magnetic pin is located inside the selector (Figure 23 – 1) and 2 bearing (14x25x6 Bearing Stainless Steel ABEC-3) are acting to lower the friction between the 2 gear shift wheels and the selector (Figure 23 – 6 and 7). The 2 magnets are positioned in opposite to each other (Figure 19 – 11 and 12) and will trigger the movement of the selector in direction of the selected gear set. The only contact with the motor shaft is made by the gear shift wheel that transfers that motor dynamics to the rest of the system.

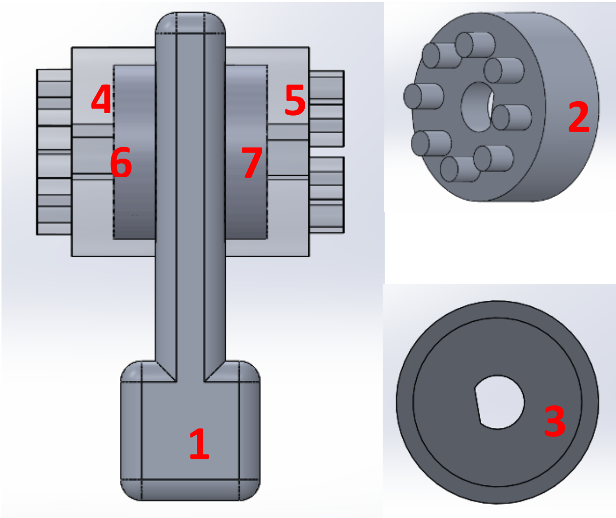


Figure 23: Gear selection system

1- Electromagnetic pin, 2- Gear shift wheel isometric view, 3- Motor shaft orifice, 4- Gear shift wheel 1, 5- Gear shift wheel 2, 6- Bearing 14x25x6, 7- Bearing 14x25x6.

3.2.2 Upper limbs static analysis

To decide the gears specifications, at first, was necessary the calculation of the force needed to move the arm. Static computations where made considering the positions of the upper limbs that demand higher forces from the motor in the 6 motions allowed by the orthosis. The limbs size considered was according to Table 12:

- Upper-arm length (UA): 28.71 cm
- Upper-arm center of mass (UA_{CM}): 16.57 cm
- Forearm length (FA): 26.89 cm
- Forearm center of mass (FA_{CM}): 12.31 cm
- Hand length (H): 18.79 cm
- Hand center of mass (H_{CM}): 6.81 cm
- Total arm: 74.39

The center of mass distance is in relationship with each anterior joint. The upper arm is related to the shoulder joint, the forearm is related to the elbow joint and the hand to the wrist joint.

The weight considered of the limbs was according to the Table 11 and was considered a person with 73 Kg in total:

- Upper-arm mass: 1.98 Kg
- Upper-arm weight (W_{UA}): 19.4 N
- Forearm mass: 1.19 Kg
- Forearm weight (W_{FA}): 11.6 N
- Hand mass: 0.45 Kg
- Hand weight (W_H): 4.4N

On this study is necessary to consider the weight of the orthosis as well. The whole system at the arms has a mass of 390g, thus a weight (W_O) of 3.82 N and its center of mass (O_{CM}) is located at 51 cm from the wrist joint center.

The analysis main point was to find the lowest force that will be required from the motor to sustain the arm. For this calculation was considered 6 positions of the arm during the range of movements covered by the orthosis. All the analysis considers the arm at the threshold of any movement.

Figure 24 is the static diagram for the arm in the threshold shoulder flexion-extension motion with arms completely extended in front of the body. W_{UA}, W_{FA} and W_H represents the weight of the upper-arm, forearm and hand respectively, located at each center of mass position. FM represents the force exerted by the Bowden cable. The cable is positioned inside the Bowden cable disk gap with a 6 cm radius located at the elbow joint. $UA_{CM}, FA_{CM}, and\ H_{CM}$ are the distances of the center of mass of the upper-arm, forearm and hand respectively.

d (Bowden cable position) = 6 cm

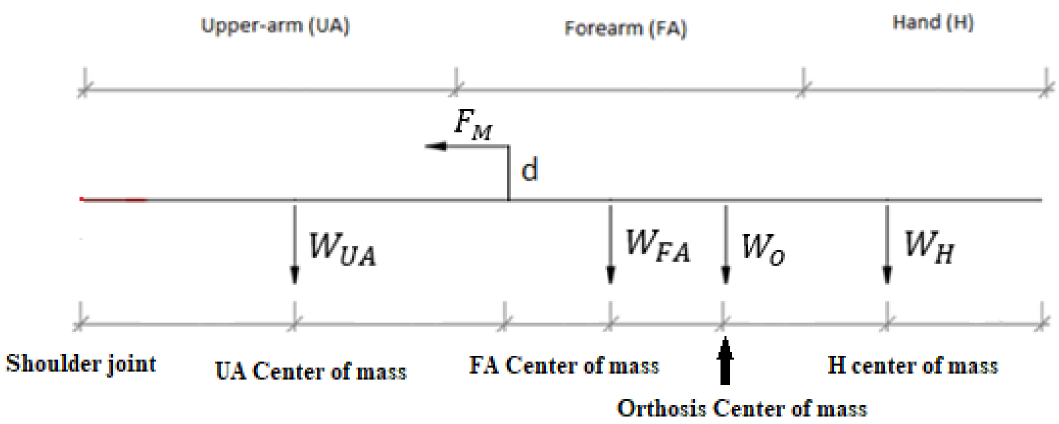


Figure 24: Static diagram shoulder flexion-extension extended arm in front of the body

The force FM is balancing against all limbs weight maintaining the arm in equilibrium, therefore the minimum torque (T) necessary is calculated by equation (1) and the equation (2) is formed considering the sum of moments are equal to 0 on the shoulder joint.

$$T = F_M * d \tag{1}$$

$$\sum M = 0$$

$$W_{UA} \times UA_{CM} + W_O \times O_{CM} + W_{FA} \times \ (FA_{CM} + UA) + W_H \times (H_{CM} + UA + H) - T = 0 \tag{2}$$

According to the equations the cable must do a force of 193 N in order to maintain the arm extended in front of the body at the threshold of any motion.

Figure 25 is the static diagram used to analyze shoulder flexion-extension motion when the arm is static but on the threshold of motion. Here is being considered the arm at an extended relaxed position parallel to the body. The cable also is positioned inside the Bowden cable disk gap which is 6 cm from the elbow joint at the forearm. In this situation, the arm is supporting itself meaning that without the motor the shoulder joint is balancing the forces and maintaining the whole limb in equilibrium. The orthosis is symmetric, its point of mass in this situation is aligned with the limbs center of mass.

To put the arm at the threshold of motion the cable force must be equal to the arm weight, thus, FM equals 35.4 N. And the moment (M) being made in this situation is calculated by equation (3).

$$M = FM * d \tag{3}$$

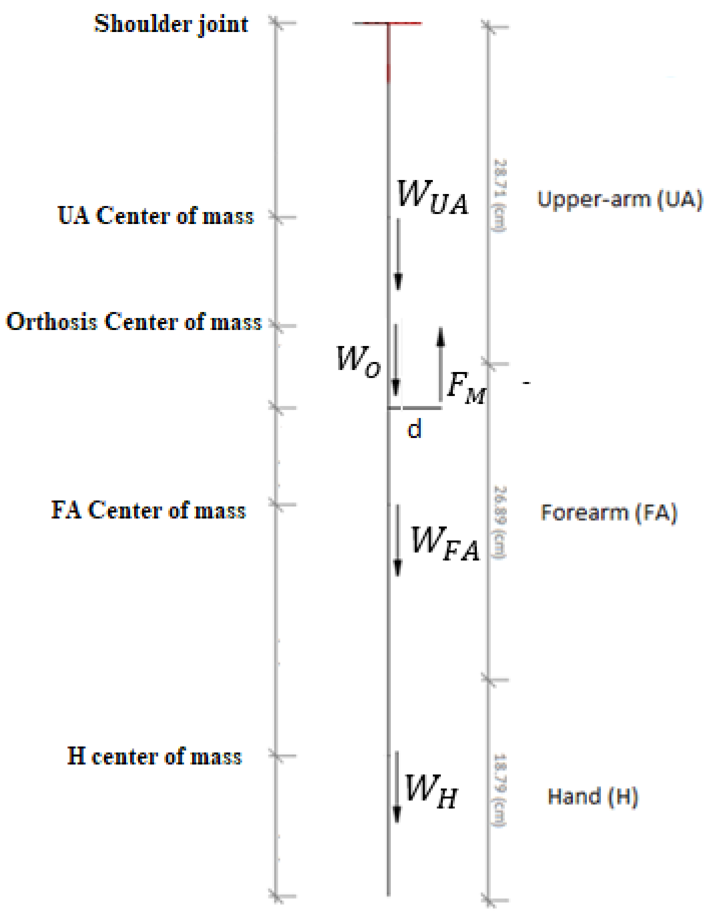


Figure 25: Static diagram shoulder flexion-extension arm parallel to the body

On the movement of shoulder flexion and extension the highest force exerted by the cable is when the arm is extended in front of the body forming a 90º angle with the body trunk.

The Figure 26 is the static diagram used to analyze shoulder adduction/abduction motion when the arm is static but on the threshold of motion. In this situation with the arm is extended on the side forming a 90º angle with the body trunk. The cable in this condition is attached at the upper-arm support at 3.6 cm of the elbow joint. Taken that the center of mass of the arm is located at the joint axis, in this scenario is necessary to consider the arm radius, 4.6 cm (Table 7) and also the distance of the orthosis to the body (cooler system + plate thickness). This distance (upper-arm radius + distance of the orthosis) is represented by the letter d and has the value of 7.6 cm. The cable has an angle of 10º with the orthosis due to the shoulder cap.

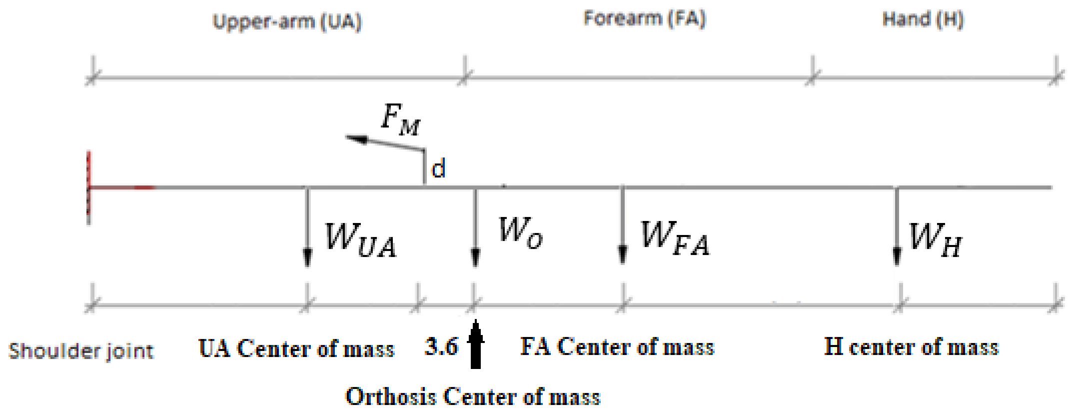


Figure 26: Static diagram shoulder adduction/abduction extended arm on the side of the body

The force FM is balancing against all limbs weight maintaining the arm in equilibrium, therefore the minimum torque (T) necessary is calculated by equation (4) and the equation (5) is formed considering the sum of moments (M) are equal to 0 on the shoulder joint.

$$T = F_M \times \cos(10) \times d + F_M \times \sin(10) \times (UA - 3.6) \tag{4}$$

$$\sum M = 0$$

$$W_{UA} \times UA_{CM} + W_O \times O_{CM} + W_{FA} \times (FA_{CM} + UA) + W_H \times (H_{CM} + UA + H) = T \tag{5}$$

According to the equations the cable must do a force of approximately 99 N in order to maintain the arm extended on the side of the body at the threshold of any motion.

Figure 27 is the static diagram used to analyze shoulder adduction/abduction motion when the arm is static but on the threshold of movement. In this case the arm is at an extended relaxed position parallel to the body. The cable, as well as the anterior situation, is attached at the upper-arm support at 3.6 cm of the elbow joint.

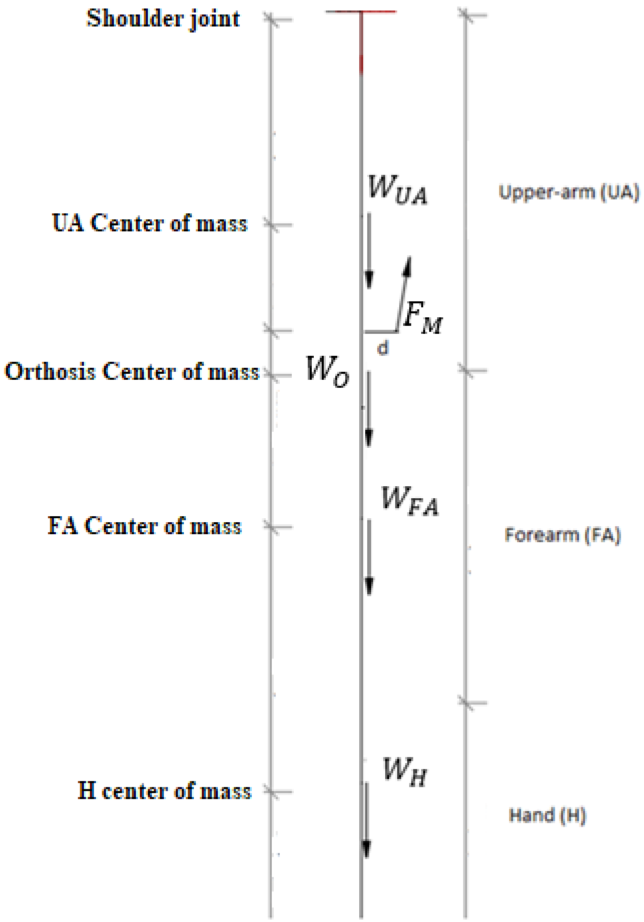


Figure 27: Static diagram shoulder adduction/abduction arm relaxed parallel to the body

In this situation, without the motor, the shoulder joint is supporting all the forces and maintaining the whole limb in equilibrium. To put the arm at the threshold of motion the cable force must be equal to the arm weight, 35.4 N. And the moment (M) being made in this situation is calculated by equation (6).

$$T = FM(cos10) \times d + FM(sen10) \times (UA - 3.6) \qquad (6)$$

As well as in the shoulder flexion/extension motion the highest force required by the cable to support the arm is when the limb forms 90º to the body trunk. However due to the shoulder cap existence and the distance of the skin to the joint axis the forcer needed to perform the adduction/abduction motion is way lower.

For the movement of elbow flexion/extension only the forearm and hand weight are considered and the cable is located inside the gap on the Bowden cable disk. Thereby, they are located at 6 cm from the shoulder joint at the forearm section. These 2 motions only take in consideration the forearm and the hand weight considering that the upper-arm does not move. The forearm support has a very low weight that can be disregard in this section.

The Figure 28 is the static diagram used to analyze the flexion/extension motion of the elbow when the arm on the threshold of movement. In this case the elbow joint is forming 90º between the forearm and upper-arm.

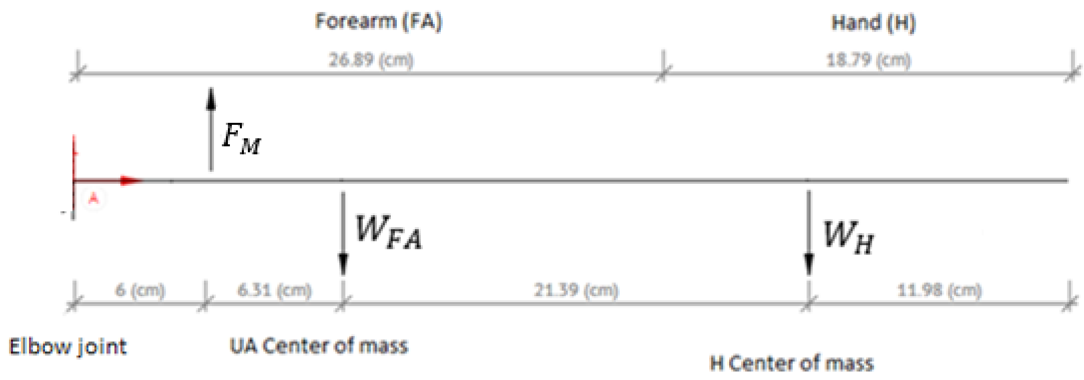


Figure 28: Static diagram elbow flexion/extension elbow joint angle = 90º

The force FM is balancing against all limbs weight maintaining the arm in equilibrium, therefore the minimum torque (T) necessary is calculated by equation (7) and the equation (8) is formed considering the sum of moments (M) are equal to 0 on the elbow joint.

$$T = FM \times 6 \quad (7)$$

$$\sum M = 0$$

$$W_{FA} \times UA + W_H \times (UA + H) = T \quad (8)$$

In this position is the cables are applying a force of approximately 48.5 N.

The Figure 29 is the static diagram used to analyze the flexion/extension motion of the elbow when the arm is on threshold of movement. In this case the elbow joint is extended and the arm is parallel to the body.

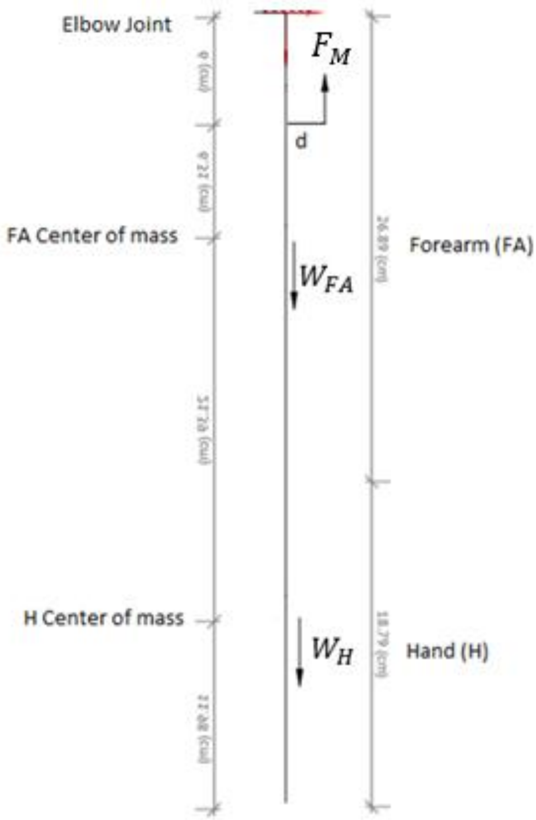


Figure 29: Static diagram elbow flexion/extension arm parallel to the body

The cable force necessary to put the limbs almost in movement is exactly the sum of the weights of the hand added the upper-arm (16 N). and moment applied can be calculated by the equation (3).

3.2.3 Gears design

The main goal of the gears in this design is to provide an adequate fixation for the spools. It was considered to trigger the spools directly by the motor and the electromagnetic pin without the use of the gears. However, this piece would need a large radius to allow the connection of the spool to the gear shift wheel, which would decrease the tangential force supplied by the motors at the cables. A The solution to avoid this problem was to design a set of gear in which the radius of the pinion can be lower than the spool. A spool dimensioned with a diameter as small as the pinion did not had the enough mechanical strength and the material limits were reached when applying full motor torque.

To dimension the 2 sets of gears was taken into consideration the weight of the system, the size of the gears and the force needed on the system. All the calculation were made in order to fit the DIN 862 and DIN 867 standards.

The definitions for the pinion:

- Pinion reference diameter (D_{o1}): 31.5 mm - DIN 780
- Number of teeth (Z_1): 18
- Pressure angle (α): 20º
- Gear ration: 2
- Thickness: 10 mm

After defining those characteristics was possible to calculate the specifications if the pinion and the gear (Table 14).

Table 14: Pinion and gear specifications DIN 862 and DIN 867 standards

	PINION	**GEAR**
Reference diameter [mm]	31.50	63.00
Outside diameter [mm]	35.00	66.50
Root Diameter [mm]	27.30	58.80
Clearance circle [mm]	29.60	59.20
Module [mm]	1.75	1.75
Number of teeth	18.00	36.00
Circular pitch [mm]	5.50	5.50
Pitch angle [deg]	20º	10º
Circular tooth thinkness [mm]	2.75	2.75
Working depth [mm]	3.50	3.50
Whole depth tooth [mm]	3.85	3.85
Adendun [mm]	1.75	1.75
Dedendun [mm]	2.10	2.10
Width of space [mm]	2.75	2.75

Pressure angle [deg]	20º	20º
Clearance operating	0.35	0.35
Gear ration	2.00	2.00
Centre Distances [mm]	47.25	47.25

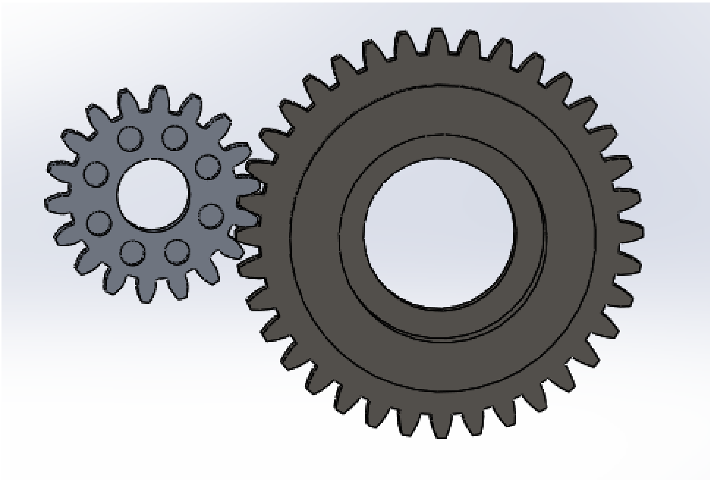


Figure 30: Pinion and Gear (set of gears)

The Figure 30 shows the pinion and the gear design after calculating the specifications. The pinion center orifice was projected to receive the gear shift wheel. The gear has a 55 cm diameter spool attached and will receive the Bowden cable (Figure 18). Each gear set is formed by the pinion and a gear and this design will use 2 sets.

The material selected for the pieces was aluminum alloy 6061-T4 SS. This material has a very light weight and also presents mechanical resistance that fits our project specifications.

3.2.4 Actuator

The main requirement for the motor was an output torque that will allow the limb movement in all conditions proposed. The highest force calculated considering the threshold of motion was 196 N when evaluating the shoulder flexion/extension with arms extended in front of the body in a 90º angle. This is the force that the cable must exert in the arm, thereby is the tangential force exerted by gear at the spool location. The spool is connected centralize with the gear and has 20 cm radius. The force made by the system then, can be lower, taken that the force value is inverse to the distance value when considering the same torque.

To achieve a force of 193N at the 20cm radius, the gear must have a moment of 3.86 N.m. With that, the tangential force at the reference diameter of the gear has a value of 122.5 N, and the torque at the pinion and the motor has a value of 1.89 N. If a motor is able to supply a value higher than the one calculated, the arm will be able to move in any of the motions allowed by this orthosis. The size and weight of the motor has also to be taken in consideration taken that the patient will be carrying it in a backpack.

Table 15: List of motors options

STEPPER MOTORS					
Company	**MODEL**	**SIZE (NEMA)**	**WEIGHT (g)**	**HOLDING TORQUE (N.m)**	**PRICE**
CNC4you	60BYG401-03	23	1600	4N.m	£34,00
Stepperonline	24HS39-3008D	24	1600	4N.m	$ 29,71
Stepperonline	24HS34-3008D	24	1400	3N.m	$ 26,41
Sparkfun	ROB-12472	-	133	4,3N.m	$ 24,95

The Table 15 shows the available motors that satisfies the specifications of the design. The motor model 60BYG401-03 has a higher price but presents a small size considering the given torque. The model ROB-12472 is a very small DC gearmotor with a very low weight. This device, however, only achieves 6 RPM. Taken that the orthosis proposed does not need high speed motor, this option can be also considered. Practical tests will define if the interior gears inside the motor cage are strong enough.

3.2.5 Locking system

The design proposed in this study only use 1 motor alternating between 2 set of gears. Therefore, the motor can hold only one arm position at once. A locking system had to be developed to avoid the uncontrolled spin of the gears once the electromagnetic pin selector releases the pinion. After achieving a determined arm position the mechanism must be able to maintain the arm in place.

The locking system is composed by a ratchet gear, a pawl and a spring, Figure 31. There are 2 gears set, thus also 2 locking systems. The ratchet is fixed at the pinion and locks the mechanism when the counterweight of the loose arm pushes it against the pawl. The spring maintains the pawl in the correct position preventing it to turn backwards. To release the mechanism an electromagnetic pin pushes the pawl back and the gear can rotate free in the other direction.

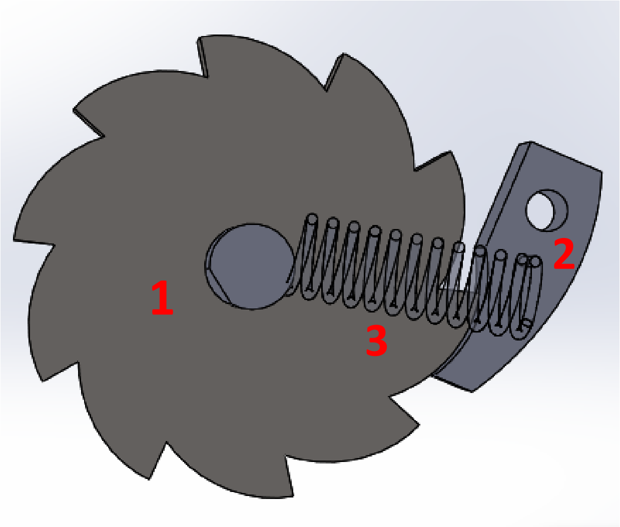


Figure 31: Locking system\

1- Ratchet, 2- Pawl, 3- Spring

The ratchet and the pawl have 10 mm thickness and are made of aluminum alloy 6061 (T4) SS.

3.3 Sensors

This proposed design uses many different sensors. This section will address the main requirements of sensors selection and their specifications.

In this design is proposed the use of:

- 2 accelerometers
- 2 encoders (optical angle sensor)
- 2 electromagnetic pins
- 2 thermostats (body temperature sensor)
- 2 peltier modules
- 1 pulse oximeter
- 1 motor
- 1 Li-ion battery

- 5 programmable automation controllers (PAC)
- 10 EMG sensors

3.3.1 Accelerometer

The accelerometer chosen is from the brand XSens. The device is able to provide real-time computation the position, velocity and is also an integrated GPS and MEMS Inertial Measurement Unit with a Navigation and Attitude and Heading Reference System processor.

The choice of this accelerometer was due to its accuracy and many features, but mainly because the laboratory already has 2 available to use at the project.

3.3.2 Peltier module

The Peltier module are usually very cheap components. But to achieve better thermodynamic operation is necessary to dissipate the heat using coolers and heat sinks. Since the Peltier module will be used to maintain the temperature of the muscle won't be necessary achieving very low values of temperature. The laboratory already has available a Peltier module connected to a heat sink and to a cooler. The system can achieve temperature around 10º Celsius which fit the project specification.

3.3.3 Strain Gauge

In this prototype won't be necessary the measurement of extreme high forces. The strain gauges are placed at the orthosis to inform and measure if there is any force being made by the patient. This information is very important to track the development of the muscle health. An increase of muscle force can indicate an improvement of the body condition, in the same way that a decrease can indicate a failure in the rehabilitation procedure. The force quantification is an important tool to verify if the healing methodology chosen is adequate to the patient. A limb can exert a force of 53.64 (Table 1), therefore the sensor must be able to measure up to this value with accuracy and repeatability. The Table 16 show the list of strain gauges that fit the project specifications.

Table 16: List of strain gauge options

Brand	Part number	Price
OMEGA	SGK-L3A-K350U-PC11-E	$39,00 (Pack of 6)
Micro Measurements	MMF307449	$20,00
OMEGA	SGT-3F/350-TY11	$35,00 (Pack of 5)

3.3.4 Pulse oximeter probe

The pulse oximeter probe will allow measurements of the patient heart beat and blood oxygenation. This sensor will be located at the patient finger being connected at the electronic board placed at the installation device box. This sensor is mainly for the patient monitoring and its information does not control any mechanical process. This sensor must have a repeatability, the probe must be reusable (washable) and capable to measure the blood oxygenation and heart beat in children and adults. The Table 17 show the devices available in the market that fit this project specifications.

Table 17: Pulse oximeter options

Brand	Part number	Price
Nihon Kohden	TL-101S	$32,00
Masimo	MAS-1863-1864	$129,00
NONIN	8000 J	$ 99,00

3.3.5 Body temperature sensor

The body temperature sensor will measure the temperature of the muscle. This information is really valuable in health treatment, taken that high temperature is an excellent indicator of inflammation and infections. This sensor must be small and easy to attach to the body, small, and should provide measurements with linearity, repeatability and accuracy. The Table 18 shows the available sensors in the market.

Table 18: Body temperature sensors options

Brand	Part number	Price
eHealth	Pro (My signals)	$60,00
Maxim	MAX30205	$11,95
JIANYUAN	JY-18b2020151210-24	$5,95

3.3.6 Decoder

This design uses 2 decoders, one fixed at the upper-arm support measuring the angle made in the elbow and the other at the motor shaft measuring the angular velocity of the motor. One of the main requirement of this sensor is the installment of the device in the orthosis. The sensor must be compatible to the shafts of the orthosis and measure the angles with accuracy and repeatability. This project does not need a high-speed measuring sensor, thereby this device must support simply the shaft torque. The information provided by this, together with the 2 accelerometers will allow the system to record the arm position through time. The Table 19 shoes the sensor considered to this design.

Table 19: Decoder options

Brand	Part number	Price
Megatron	ETA25PS	
Avago Technologies	HEDS-9040/9140	$25,09

The decoder Avago has an easy assembly with several types of shafts and has a better price and availability in the market, thus was chosen for this project.

3.3.7 EMG sensors

The EMG sensors will be attached directly to the patient skin being connected to the controller at the installation box inside the backpack. This study proposes a use of 10 EMG sensors located at each specific muscle to define the movements being made (Figure 32). The cable length of the sensor must be taken into consideration taken that the sensor cable must reach the control installation. The connectors must be reusable, or allow the attachment of disposable electrodes.

Brand	Part number	Price
MyoWare™ Muscle Sensor	AT-04-001	$37,99
Grove - EMG Detector	SKU 101020058	$48,00
e-Health	EMG sensor	$48,00

3.4 Control systems

The orthosis being proposed will actively move the arm of the patient. For that, is necessary an actuator (motor) and a set of sensors and controllers to control and measure the movement.

The control proposed on this project is made using 6 different modules, each one controlled by a PAC (Figure 38). The EMG controller (DKE-IOPE-16), the cooler controller (DKE-IOPE-16), the oxi controller (DKE-IOPE-16), the motor controller (DKE-IOPE-16), the power controller (DKE-IOPE-16), and the main controller (DKE-PAC-AT90).

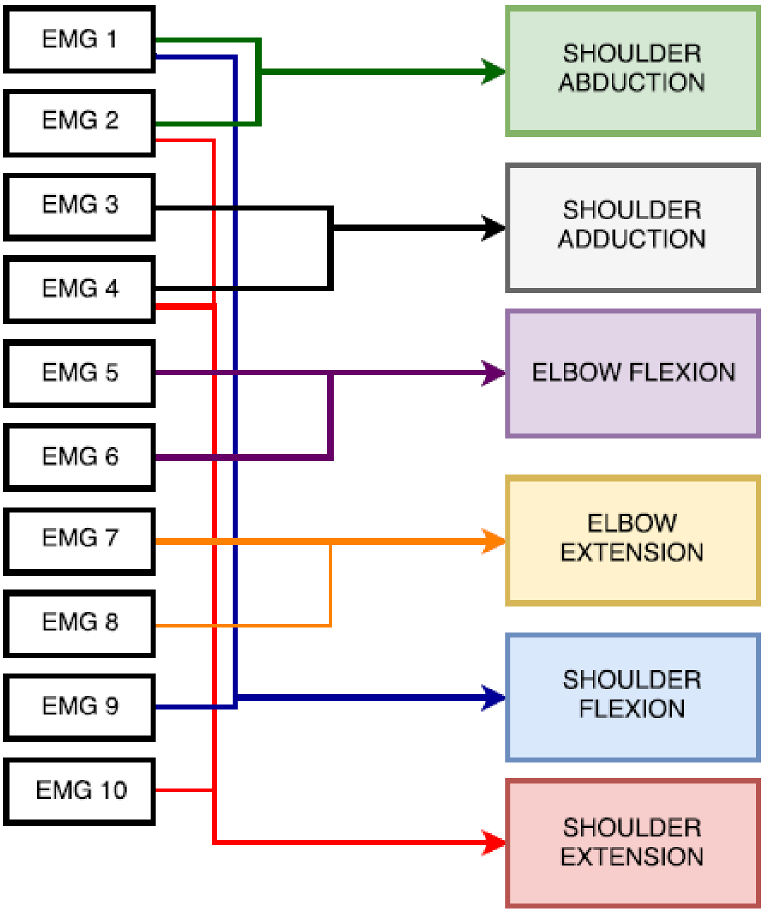
3.4.1 EMG Controller

The EMG sensor being used is a 3 leads MyoWare™ Muscle Sensor (AT-04-001) from Advanced Technologies. This sensor offers a lower price in comparison to others in the market and is already prepared for the communication with the microcontroller with an easy interface. This design will use a set of 10 EMG sensors that will be place on top of the following muscles:

- EMG 1: Deltoid anterior
- EMG 2: Deltoid posterior
- EMG 3: Pectoralis major
- EMG 4: Teres Major
- EMG 5: Biceps brachi
- EMG 6: Brachalis
- EMG 7: Anconeus
- EMG 8: Triceps brachii
- EMG 9: Pectoralis major
- EMG 10: - Latissimus dorsi

The Table 4 shows which set of muscles that will define each specific movement. The shoulder adduction will be activated by EMG 3 and 4, the shoulder abduction will be set by EMG 1 and 2, the shoulder flexion with EMG 1 and 9, the shoulder extension with EMG 2, 4, and 10 the elbow flexion with EMG 5 and 6 and the elbow extension is activated by EMG 8 and 7 (Figure 32).

Figure 32: EMG sensor body motion diagram



3.4.2 Cooler controller

The cooler controller is the module responsible for the control of 2 Peltier modules integrated with a cooler each and 2 body temperature sensors. The thermostat chosen is MAX30205 from Maxim Integrated, **Erro! Fonte de referência não encontrada.**. This sensor meets the clinical thermometry specification of the ASTM E1112 and has already integrated in its circuit an overtemperature alarm/interrupt/shutdown.

The main point of this module is to control the muscle temperature. There is 2 temperature sensors located one at the forearm and other at the upper-arm. During an exercise an increase of temperature detected by the sensor will activate the Peltier module cooling the muscle. The Peltier module is located in 2 movable pieces in the forearm and in the upper-am allowing the patient to apply cold at the desired are. The Figure 33 shows the simplified control diagram taking in consideration only one sensor and one cooler.

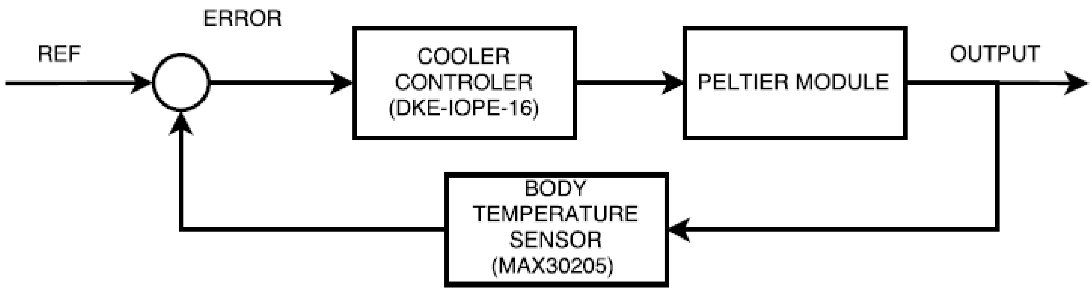
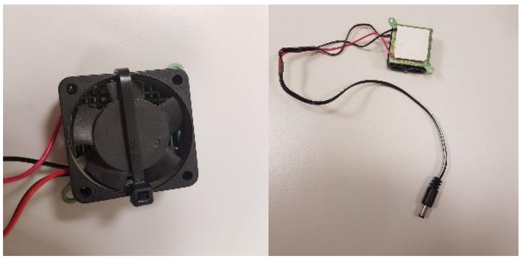


Figure 33: Simplified cooler control diagram

The lab has available 2 Peltier modules with an integrated cooler which will be used for this design (Figure 34).

Figure 34: Peltier integrated with cooler



3.4.3 Oximeter controller

This module has the purpose of monitor the patient oxygen saturation - SpO_2 during the exercises using the orthosis. The sensor here being proposed is an oximeter probe TL-101S from the company Nihon Kohden. This probe comes with a 2.7m cable and presents a better price than others available in the market. The cable can be directly connected with a 10 pin connector at the controller which will calculate the oxygen saturation showing the values in a display. Another advantage is that this probe is washable, reusable, and ideal for kids and adults.

3.4.4 Motor controller

This module is comprised by 2 magnetic pins, 2 encoders, one motor and the motor controller (DKE-IOPE-16), and has many functions. The first is the selection of gear set. This controller will define the direction of the current passing through the electromagnetic pin selector, and thus the polarity of its extremities. One direction will attract the pin in direction of the gear set 1 enabling the movement of shoulder flexion/extension motion or elbow flexion/extension motion. The other current direction will attract the pin in direction of the gear set 2 enabling the movement of shoulder adduction/abduction motion.

The second function of the Motor control module is the control the movement of shoulder flexion/extension or elbow flexion/extension by activating or deactivating the electromagnetic pin locker. When there is energy going through the pin the movement of shoulder flexion/extension happens, when there is no energy going through the pin the elbow flexion/extension happens.

The third function of this controller is to read the input signal of the encoder 1. This encoder is an optical angle sensor located the elbow joint (green arrow on Figure 35). The green nut on **Erro! Fonte de referência não encontrada.** fixates the sensor at the upper-arm support allowing the shaft to move together with the forearm. With that is possible to obtain the angle between the upper-arm and forearm through time. This information added by the values given by the accelerometers will define the arm position.

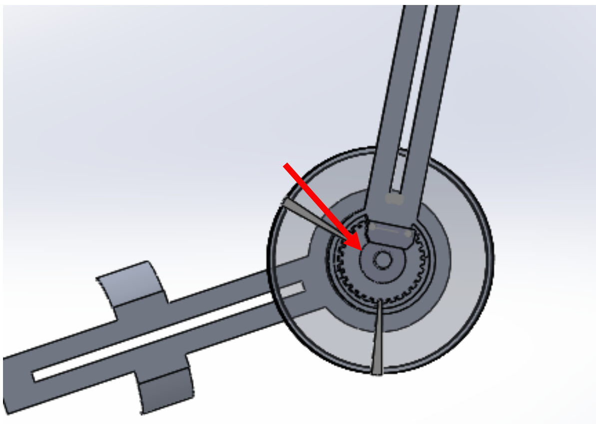


Figure 35: Encoder 1 location

To finish this module will control the motor actuator. It was proposed 2 different motors in this design, DC motor with an H bridge driver or Stepper motor with a stepper driver. In case of the DC motor this module will control which transistor to activate controlling the current direction and intensity and thus the changing the direction of the motor. In the stepper motor, the driver will control the direction according to the motor steps and phase. Another encoder

(Encoder_M1) is located at the motor shaft to give the information of the motor speed (RPM). This motor driver will use pulse modulation to lower the voltage from the battery.

The whole system is represented by Figure 36.

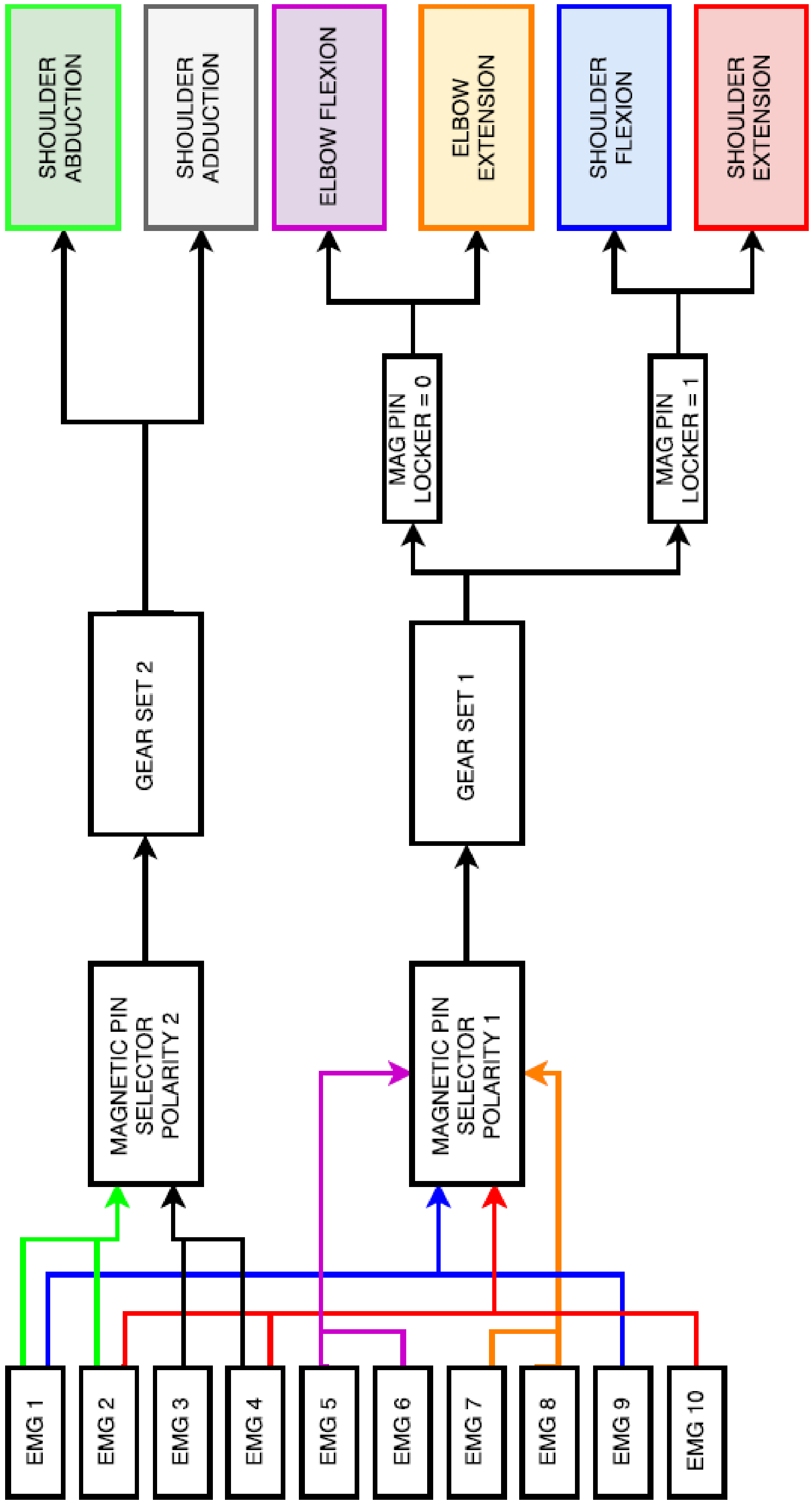


Figure 36: System block diagram

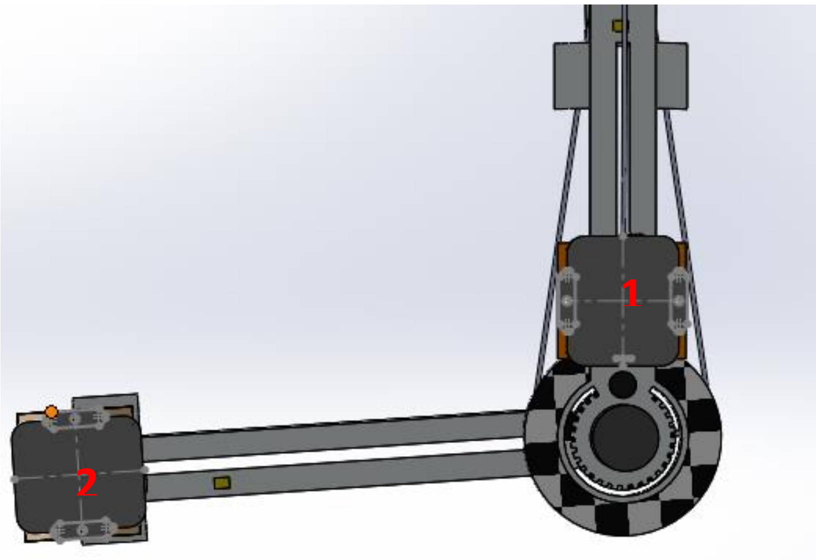
3.4.5 Power controller

This module is composed by the battery, the external power source and the PAC DKE-IOPE-16. The battery chosen is a Li-ion 11, Acer Aspire One A110/A150, D150/250, P531 series. It has 7800mAh and 87Wh. This battery may be more expensive, however will last longer considering all the electronics components that has to supply. The whole design together has power of 30 watts, thus this battery will be able to supply the system for almost 3 hours. After that is necessary a recharge

3.4.6 Main controller

All the modules presented will be controlled by a main controller PAC (DKE-PAC-AT90). In addition, this controller will read the information sent by the 2 accelerometers located one at the forearm, and the other at the upper arm (Figure 37). This information together with the encoder 1 will provide the arm positions. The accelerometers chosen are the X Sens MTi-G. Is an excellent quality device and also is available at the laboratory.

Figure 37: Accelerometers position



1- Accelerometer forearm, 2- Accelerometer upper-arm

This module will also set a machine machine interface (MMI) which will allow the communication with tablets, PC and smart phones. In this way will be also possible to obtain more detailed results from the movements realized with the orthosis.

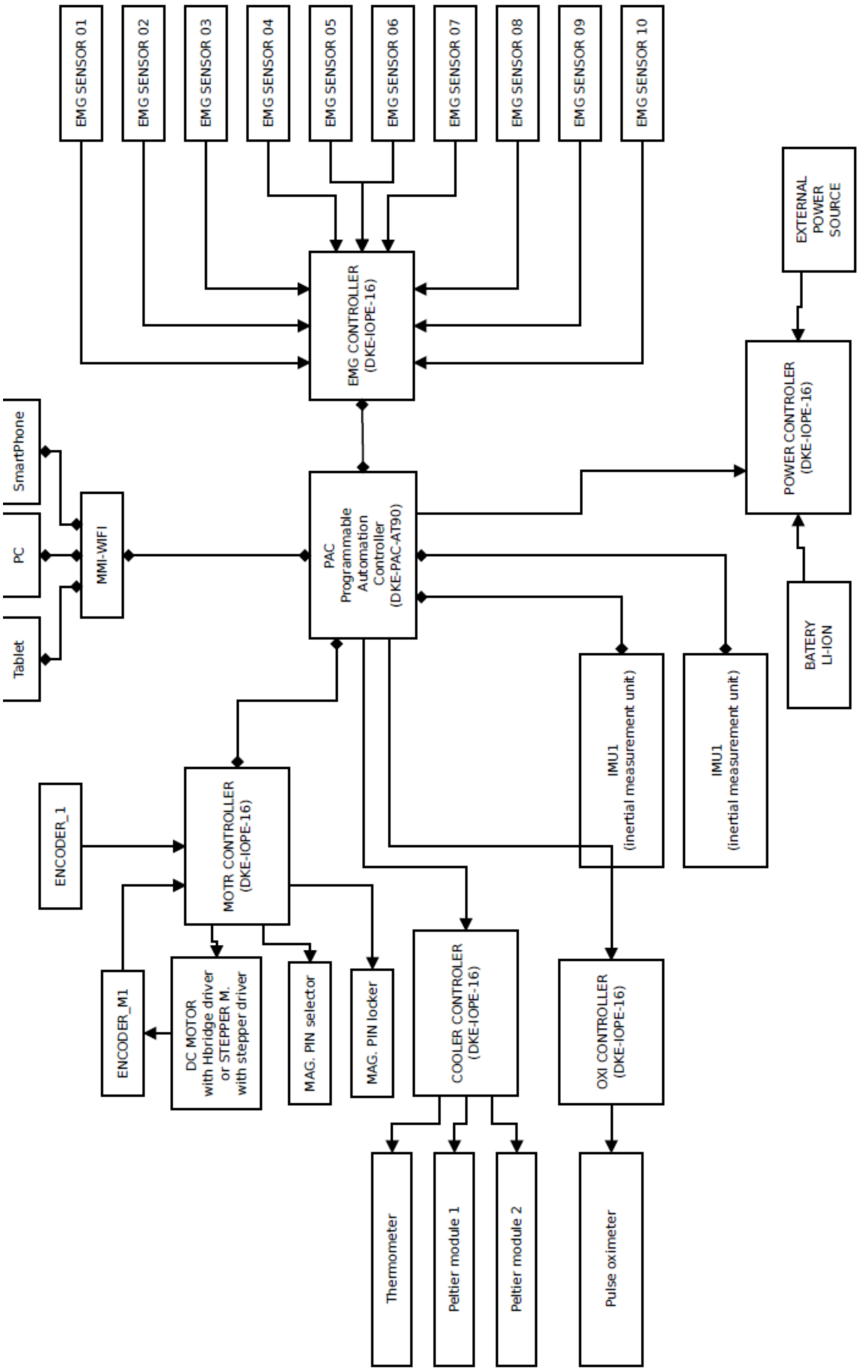


Figure 38: Electric diagram

4 TESTING OF ORTHOSIS KINEMATICS

To certify the mechanical functionality of the device was necessary to test the motion of the bodies in the orthosis and their movements among all the other parts. SolidWorks was the main tool used to validate the motion system taken that the software offers the motion study feature. Unfortunately, was not possible to analyze the system kinematics including all the parts at the same time. The program is not able to simulate the actuation of cables and thus couldn't predict the behavior of the proposed prototype. However, the test was possible if separating the exoskeleton in 2 different parts: the actuation system and the orthotic system. The first is comprised by the 2 gears sets, the locking system, the electromagnetic pin selector, the 2 gear shift wheels and all the fixating components. The second is comprised by the upper-arm support, forearm support, the Bowden disk, the motion range limiting pin and the fixating components.

This test will verify the geometry of the design in taking into consideration the dynamics, ensuring that the placement of all pieces together do not block any necessary movement.

4.1 Actuation system

This test aims to certify the gears and pinon relationship, as well as the torque transferred by the gear shift wheel to the gear sets. Also, must verify the assembly of all parts in its respective shafts and if occurs any blockage or obstruction of motion.

To ensure the operation of the simulation was necessary to align the teeth of the gear shift wheel with the teeth orifices on the pinion surface. The initial position of the system consists on the pinion already assembled to the gear shift wheel. All motors in stationary mode, all the gear also in stationary mode. The evaluation was carried with the application of different forces in selected components at different instances (

Table 20).

Table 20: Setting forces kinematic evaluation actuation system

TIME [SEC]	FORCE	COMPONENT
1 - 5	Torque	Gear shift wheel 1
5 - 10	Linear force	Electromagnetic pin selector
10 – 15	Torque	Gear shift wheel 2

At the beginning of the test the teeth of the gear shift wheel were already aligned with the pinion orifices. At the instance 1s to 5s a torque applied at the gear shift wheel caused the wheel to rotate around its shaft. The teeth of the wheel triggered the rotational motion of the pinion that triggered the rotational motion of the gear. At the moment 5s a linear force was applied at the pin selector (5 – 10) and the whole gear selection system (wheels + electromagnetic pin) dislocated in direction pf the pinion 2. Because there was no actuator acting on the gear set 1 the pair stopped rotating. At moment 10s the gear shift wheel was connected and aligned to the pinion 2 orifices. Another torque was applied to the wheel 2 which caused the gear set 2 to rotate until the end of the test (15s). The Figure 39 shows the behavior of the 2 gears through time

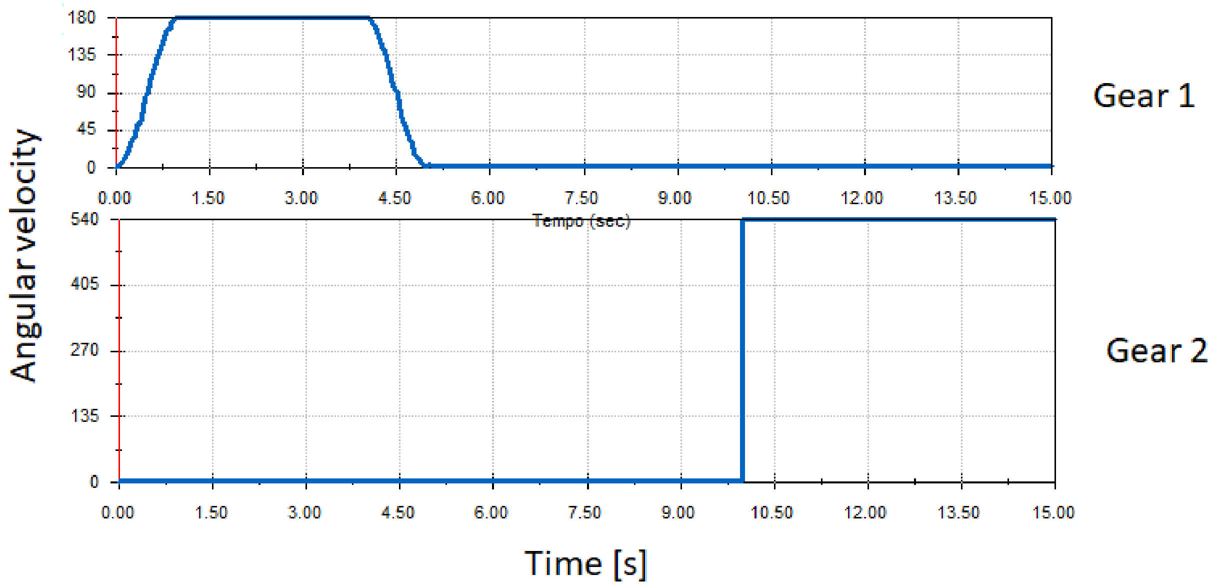


Figure 39 Gear 1 and 2 angular velocity x time

4.1.1 Orthotic system

The simulation of the orthotic system was simpler. The main point is to evaluate if the design contains any constrains of movement. After assembling all parts aligned with the forearm support shaft a oscillating torque was applied at the Bowden disk for 5 seconds. During this moment, the forearm support oscillated in a range of 50º.

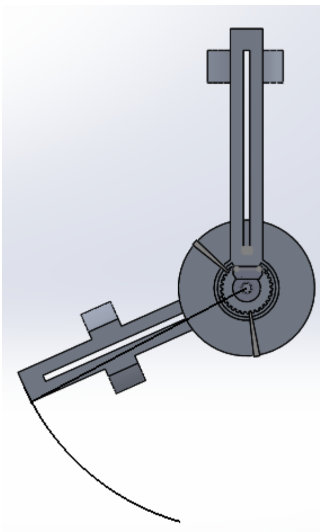


Figure 40: Oscillation path of the forearm edge

The Figure 40 shows the path made by the forearm edge during this simulation. In this first evaluation. This simulation was made to see the freedom of movement, of the part, thus the angle range limit pin was not being considered. When acknowledging the pin existence in the part the movement was block

4.2 System weight

One of the main focus of the study was the weight of the whole device. All the components and materials were chosen in order to offer a comfortable portable exoskeleton easy to carry.

Table 21:Weight of orthosis on the arm

Arm	Weight (g)
Upper-arm support	91.19
Forearm support	54.86
Bowden disk	241
Total:	387

The Table 21 shows the parts of the orthosis with a significant weight carried by the arm.

Backpack	Weight (g)
Motor	1600
Gear 1	93.1
Gear 2	93.1
Pinion 1	17.06
Pinion 2	17.06
Motor shaft	5.54
Ratchet 1	19.46
Ratchet 2	19.46
Gear shift wheel 1	16.30
Gear shift wheel 1	16.30
Eletromagneti gear selector	109
Installation box	376
TOTAL	2085

4.3 Results analysis

The test made with the actuation system indicated that the system behaves according to the expected. In a 3 sections interval of 5 seconds was is possible define and control the limits of the movement change with the position on the magnetic pin gear selector. The gear shift wheel was able to trigger each one of the pinions. Is noticeable in the graph different values of maximum angular velocity for each one of the gear. This is due to the fact that the torque applied on the gear 1 was set to stop the gear at the end of 5 seconds limiting its maximum value. When the software released the grip immediately gear started to spin uncontrolled until the friction force lowered its velocity. That means that in the construction of the device the motor must force the gear to stop moving before initiating any further motion.

The test made with the orthotic system showed that the joint between the pieces has good articulation. The forearm managed to move without obstacles and the geometry of the parts are adequate to the objective of this design.

Regarding the system weight, the heaviest components are located in the backpack which fulfils this study expectations. The heaviest of the components is the motor followed by the installation box. The total orthosis is around 2500 kg.

5 TESTING OF THE STRUCTURAL STRENGH OF ELEMENTS

This study also includes the structural analysis of the design functionality and the structural strength. SolidWorks software was the main tool used to validate the design with mechanical properties tests and finite element simulations. All the parts had to be tested considering the worst-case scenario to cover all the hypothesis of fracture and deformation. The situation that put the design at the highest level of stress is when the motor is actuating with the highest torque of 4 N.m and the tangential force produced by the gears was 258N and thus the force produced at the cables were 298N. The

Table 22, Table 23 and Table 24 shows the material properties of the material considered for this design.

Table 22:Material properties Aluminum 7050-T7350

PROPERTY	Aluminum 7075-T7350
Yield strength	$4.35 * 10^8$ Pa
Ultimate tensile strength	$4.95 * 10^8$ Pa
Young's modulus	$7.2 * 10^{10}$Pa
Shear modulus	$2.69 * 10^{10}$ Pa

Table 23: Material properties Aluminum 6061 – T4 SS

PROPERTY	Aluminum 6061- T4 SS
Yield strength	$2.4 * 10^8$ Pa
Ultimate tensile strength	$2.4 * 10^8$ Pa

Young's modulus	$6.9 * 10^{10}$Pa
Shear modulus	$2.6 * 10^{10}$ Pa

Table 24: Material properties polymer homopolymer

PROPERTY	Homopolymer
Yield strength	–
Ultimate tensile strength	$3.3 * 10^{7}$ Pa
Young's modulus	$1.79 * 10^{9}$Pa
Shear modulus	–

5.1 Upper-arm support

The upper-arm support was tested applying the highest force made by the motor at the Bowden cable (300 N). The support is articulated at the elbow joint location and is fixed on the other extremity at the upper-arm fixation. The material of this part is Aluminum 7050-T7350 (

Table 22). The Table 25 shows the results of the simulation.

Table 25: Upper-arm mechanical resistance analysis results

ANALYSIS RESULT	Upper-arm support
Maximum distress	$4.98 * 10^7$ Pa
Relative deformation	$4.51 * 10^{-4}$mm
Maximum Displacement	0.025 mm

5.2 Forearm support

The forearm support was tested applying the highest force made by the motor at the Bowden cable (300 N). The support is articulated at the elbow joint location and is fixed on the other extremity at the forearm fixation. The material of this part is Aluminum 7050-T7350 (

Table 22). The Table 26 shows the results of the simulation.

Table 26: Forearm mechanical resistance analysis results

ANALYSIS RESULT	**Forearm**
Maximum distress	$5.52 * 10^{7}$ Pa
Relative deformation	$5.47 * 10^{-4}$ mm
Displacement	0.095 mm

5.3 Bowden disk

The Bowden disk was tested applying the highest force made by the motor at the Bowden cable (300 N). The disk is fixed to the forearm support at the elbow joint location, however, in this test the disk was fixed in the middle to simulate the worst hypothesis on which can cause a deformation. The forces were applied in the region where the cable is fixed. The material considered for this simulation was the aluminum 7050-T7350 (

Table 22). The Table 27 shows the simulation results obtained with the software SolidWorks.

Table 27: Bowden disk mechanical resistant analysis results

ANALYSIS RESULT	Bowden Disk
Maximum distress	$5.52 * 10^{5}$ Pa
Relative deformation	$6.59 * 10^{-6}$mm
Displacement	$2.89 * 10^{-4}$mm

5.4 Gear

The gear was tested applying the highest force made by the motor. The higher stress in a gear is on the base of the teeth, thus, to simulate the worst hypothesis the force was applied on the teeth. The highest force received by the gear is at when the motor is working in full power: 258N. However, testing with 300N insures a safety window on the design. The material considered for this simulation was the aluminum 6061 – T4 SS (Table 23). The

Table 28 show the results of this simulation.

Table 28: Gear mechanical resistant analysis results

ANALYSIS RESULT	
Maximum distress	$3.13 * 10^{7}$ Pa

Relative deformation	$2.98 * 10^{-4}$mm
Displacement	$3.88 * 10^{-3}$mm

5.5 Pinion

The pinion was tested applying the highest force made by the motor. In the same manner as the gear, the higher stress in the pinion is on the base of the teeth, thus, to simulate the worst hypothesis the force was applied on the teeth and with the highest force delivered by the motor: 258N. However, testing with 300N insures a safety window on the design. The material considered for this simulation was the aluminum 6061 – T4 SS (Table 23). The Table 29 shows the results of this analysis.

Table 29: Pinion mechanical resistant analysis results

ANALYSIS RESULT	Pinion
Maximum distress	$9.80 * 10^{7}$ Pa
Relative deformation	$9.83 * 10^{-4}$mm
Displacement	$9.14 * 10^{-3}$mm

5.6 Ratchet

The ratchet was also tested considering the motor in its full power. Normally this part won't receive the total force of the motor. The forces apply in its surface is due to the arm sustainability, thus the arm weight. Also, there is the friction caused by the contact with the pawl when the pinion is on movement. Even with all these considerations, in the test analysis the force used on the test will be the highest force acting no the system to cover any eventuality or hypotheses of fracture and deformation. The material used was the 6061 – T4 SS (Table 23). The Table 30 shows the result of the tests made in this subsection

Table 30: Ratchet mechanical resistant analysis results

ANALYSIS RESULT	Ratchet
Maximum distress	$1.64 * 10^7$ Pa
Relative deformation	$2.12 * 10^{-4}$
Displacement	$5.91 * 10^{-3}$mm

5.7 Gear shift wheel

On the gear shift wheel the highest stress is at the teeth of the part. The fixation is made by the central orifice where there is contact to the motor shaft. The force considered here is also with the motor at its higher power, thus 300 N acting at the wheel's tooth. The material considered was the 6061 – T4 SS (Table 23). The Table 31 shows the result of the tests made in this subsection.

Table 31: Gear shift wheel mechanical resistant analysis results

ANALYSIS RESULT	
Maximum distress	$8.03 * 10^7$ Pa
Relative deformation	$8.70 * 10^{-4}$mm
Displacement	$1.59 * 10^{-2}$mm

5.8 Motion range limiting pin

The material chosen to the pin was a polymer type (homopolymer) which can be used to manufacture pieces in 3d printers. Due to its complicated design, the best way to machine this piece is printing, especially because the production of this piece will be in low scale. The material analysis simulated the pressure of the pin on the forearm support against the surface of this pin causing a bending moment. Again, the force used to calculate was 300 N.

ANALYSIS RESULT	
Maximum distress	$1.30 * 10^8$ Pa
Relative deformation	0.04
Displacement	0.2mm

5.9 Tests results analysis

The results showed that all the parts are correctly dimensioned and the mechanical limits were not reached. The arm orthosis sections such as the upper-limb support, forearm support and the Bowden disk suffered higher values of tension resulting in the need of changing the aluminum alloy to a higher strength alloy. The chosen material was the aluminum 7075-T7350 that presents a higher yield strength. The analysis on the motor range limiting pin does not covers the yield point. This is due to the polymer behavior under stress. The analysis of the mechanical configuration of this part under the orthosis tensions was made by observing the displacement of the pin. Even though the displacement was the highest among all components is still under the project configuration. Is expected that all components would deform under their elastic conditions without damaging the structure.

6 RESULTS

This study presents a design of a smart orthosis for the upper limb comprised of 43 components. Those components are divided between a backpack carried by the patient and the orthotic part located at the arm. The orthosis main goal is to assist in the rehabilitation process performing passive exercises in a patient with muscle impairment lowering the work load of the physician. The construction proposal has many mechanical features in order to perform 6 different movements of the upper-limbs (shoulder flexion/extension, shoulder adduction and abduction and elbow flexion/extension) using the lowest possible force from the actuators.

The orthotic section of this orthosis is in direct contact to the injured limb and is made by rigid materials in order to sustain the weak muscles. This part is comprised by the 2 arms supports, a disk fixed at the joint location, a shoulder pad, a shoulder support vest and the sensors. The upper-arm support is a 270 mm length metal plate with 2 mm thickness covering the arm from the end of the shoulder to the elbow joint. The material suggested was an aluminum alloy 7050- T7350. At the elbow position this part of the orthosis has a 10.5 mm thicker cylinder with an orifice contouring its center that serves as a connection to 2 pins that will set the limits of the patient active motion. The other support of this section is the forearm support. This part is also made with aluminum alloy 7050- T7350, it has 266 mm length and 1.5 mm thickness covering the forearm from the elbow joint to the wrist joint. At the location of the elbow joint there is a higher dimeter circle with a shaft that will fix the exoskeleton parts together and will also allow the joint freedom of movement. Between the two supports there is a disk with 126 mm of external diameter and 60mm of internal diameter. On the side of this disk there is 2 gaps, one is for the fixation of cables and the other is for the connection of the 2 pins to set the motion limit. In the orthosis, there is fixed 2 accelerometers, 2 Peltier modules with a cooler integrated, 2 body temperature sensors, 2 strain gauges, and a decoder. The whole part is fixed at the arm using the shoulder support vest and Velcro stripes.

The actuation section is comprised by a stepper motor (60BYG401-03) with a torque of 4N.m, 2 gears, 2 pinions, 2 ratchets, 2 pawls, a motor shaft, 2 gear shift wheels, 3 electromagnetic pins, in which, one of them are in the electromagnetic pin selector. The 2 gears, as well as the 2 pinions are made by an aluminum alloy 6061 – T4 SS, they have 10 mm thickness, and the gears gas a reference diameter of 63mm while the pinions have a 31.5mm reference diameter. The gear ration between the pinion and the gear is 2. The pinion has 8 circular orifices displaced around its surface that work as a male mold to the gear shift wheel. The connection between there 2 pieces triggers the rotation of the gears. The installation of all these components is made using a designed box made of aluminum 7050-T7350.

The mechanical designs here proposed were submitted to a material resistance evaluation. The highest tension calculated in this design was in the motion range limiting pin with the value of $1.30 * 10^8$ Pa. However, this value was obtained applying the highest force of the motor directly to the pin surface. In reality, this part will receive only stress made by the human body, thus this tension will be way lower. Even with the high stress, the pin did not presented deformations that would interfere with the orthosis functionality. The next component receiving high tension is the pinion. This is expected due to direct connection to the motor shaft. However, this high tension does not impair on the design in any way taken that the value is still under the yield strength.

The kinematics designs made by this study proved that the geometry does not interfere in the motion range of the exoskeleton, and the device will behave as expected.

7 CONCLUSION

The main goal of this work was to create a construction design on SolidWorks and select sensors of subsystems of an intelligent orthosis for the upper limbs of patients to assist on the process of rehabilitation. For the proper functioning of the device some project assumptions were made and had to be resolved:

1. The orthosis must allow a range of movements used at the rehabilitation exercises
2. The orthosis design should be able to measure the activity of the upper limbs during the physical therapy rehabilitation process.
3. The orthosis must be able to act directly at the patient limb performing passive rehabilitation exercises.

4. The orthosis must be comfortable and easy to use
5. The orthosis must be able to read the intention of movement of the patient and actuate in order to achieve the motion wanted.
6. The orthosis must be safe not endangering the patient health
7. The orthosis must be validated considering the strength of elements and kinematics performance.

7.1 Meeting the objectives of the thesis

This section will describe the main objectives of this thesis and the results of the work

7.1.1 The orthosis must allow a range of movements used at the rehabilitation exercises

The orthosis proposed on this study controls 2 joints; the shoulder and elbow joint. With that the device is able to perform 6 different motions: shoulder flexion, shoulder extension, shoulder adduction, shoulder abduction, elbow flexion and elbow extension. Two pairs of gears were designed achieve that using only one motor. The motor rotates the gear that is connected to a spool with a winded cable connected to the limbs in the other end. The movement of the motor can increase or decrease the cable length moving the arm.

The device is only able to perform one motion of the time creating the need to break the movement is several basic movements. However, physical therapy exercises are usually pretty basic in order to facilitates its execution. More complexes motions might present a certain difficult for patients with severe muscle weakness.

7.1.2 The orthosis design should be able to measure the activity of the upper limbs during the physical therapy rehabilitation process.

The device proposed on this thesis also comprise the implementation of a set of sensors that will send a signal carrying the information of the limb movement, position, temperature, strength, oxygenation and heartbeat. These information will be use to track the patient conditions and development through time.

The sensor being recommended are:

- Accelerometers
- Encoders (optical angle sensor)

- Thermostats (body temperature sensor)
- Peltier modules
- Pulse oximeter
- EMG
- Strain Gauge

The information sent by the 2 accelerometers added to the information of the encoder will provide the arm position through time. The body temperature sensor will provide a information in order to control the muscle condition, The pulse oximeter will provide the heart rate and oxygenation of the patient. The EMG will read the signals sent by the muscles and the strain gauges will provide the information about the patient muscle force.

7.1.3 The orthosis must be able to act directly at the patient limb performing passive rehabilitation exercises.

The orthosis actuation is made by the change of size of Bowden cables connected in one end to a motor and the other end to the orthosis. The cables will directly pull the limbs placing them into a correct position. The same movement can be repeated several times with accuracy and precision increasing the efficiency of the exercise. The motor will exert all the force needed to control the muscle increasing the possibility to regain the motor functions.

7.1.4 The orthosis must be comfortable and easy to use

The orthosis has a shoulder support aiming placing the rigid parts of the exoskeleton to the body. This shoulder support will also work putting the patient trunk in the correct place. This device also uses Velcro stripes for fixation. Another good quality of this project is the fact that the motor is not directly attached to the limbs. The motor is placed in a backpack carried by the patient. This make this device portable and practical. The weight carried by the arms decreased substantially increasing the comfort of the user.

7.1.5 The orthosis must be able to read the intention of movement of the patient and actuate in order to achieve the motion wanted.

This orthosis development has 10 EMG sensors placed at specific muscles in order to capture the body signals. This signal will indicate an intention of movement. The different combination of signals sent at the same time from different types muscles will determine which type of motion is being made. A signal then, is sent to the actuation system that will take the necessary measures to move the arm in the correct path.

7.1.6 The orthosis must be safe not endangering the patient health

This orthosis has several maneuvers to prevent any accident endangering the patient physical health. The decoders placed around the motor will read the angular velocity controlling the danger of excessive speed. Also pins placed along the elbow joint will mechanically control the angles made by the elbow flexion/extension movement. The installation box is safety action protecting the patient against the power of the motor and engines.

7.1.7 The orthosis must be validated considering the strength of elements and kinematics performance

The orthosis was tested using the simulations provided by the SolidWorks software. The design was validated according to the material properties and geometric connection of the mechanical parts. The results showed that the limits of the material were not reached and all the parts were working in their elastic parameters. Thereby, permanent deformations won't occur.

The kinematics analysis showed that the system will behave as expected. Forces were applied to specific system elements trying to imitate the real performance of the exoskeleton. The test was positive sowing that the geographic organization of the supports wont impaired any movement.

7.2 Perspective of future works

In the literature review was possible to find several different designs and mechanisms acting to perform different movements of the body. There is a lot of intelligent orthosis being developed, but yet, is not possible to find an orthosis that can move the arm with accuracy and comfortability through all 8 basic body motions comprising all degrees of freedom of the joints. The robotic orthotic devices are definitely part of the future considering that is a non-invasive solution for the muscle diseases, and also present a possibility of regaining the arms functions for those that suffers with paralysis. The idea is to approach the body movements with the same naturality of the body itself in such a way that the robotic device can replace the impaired limb in the daily activities with efficiency until the muscle is healed.

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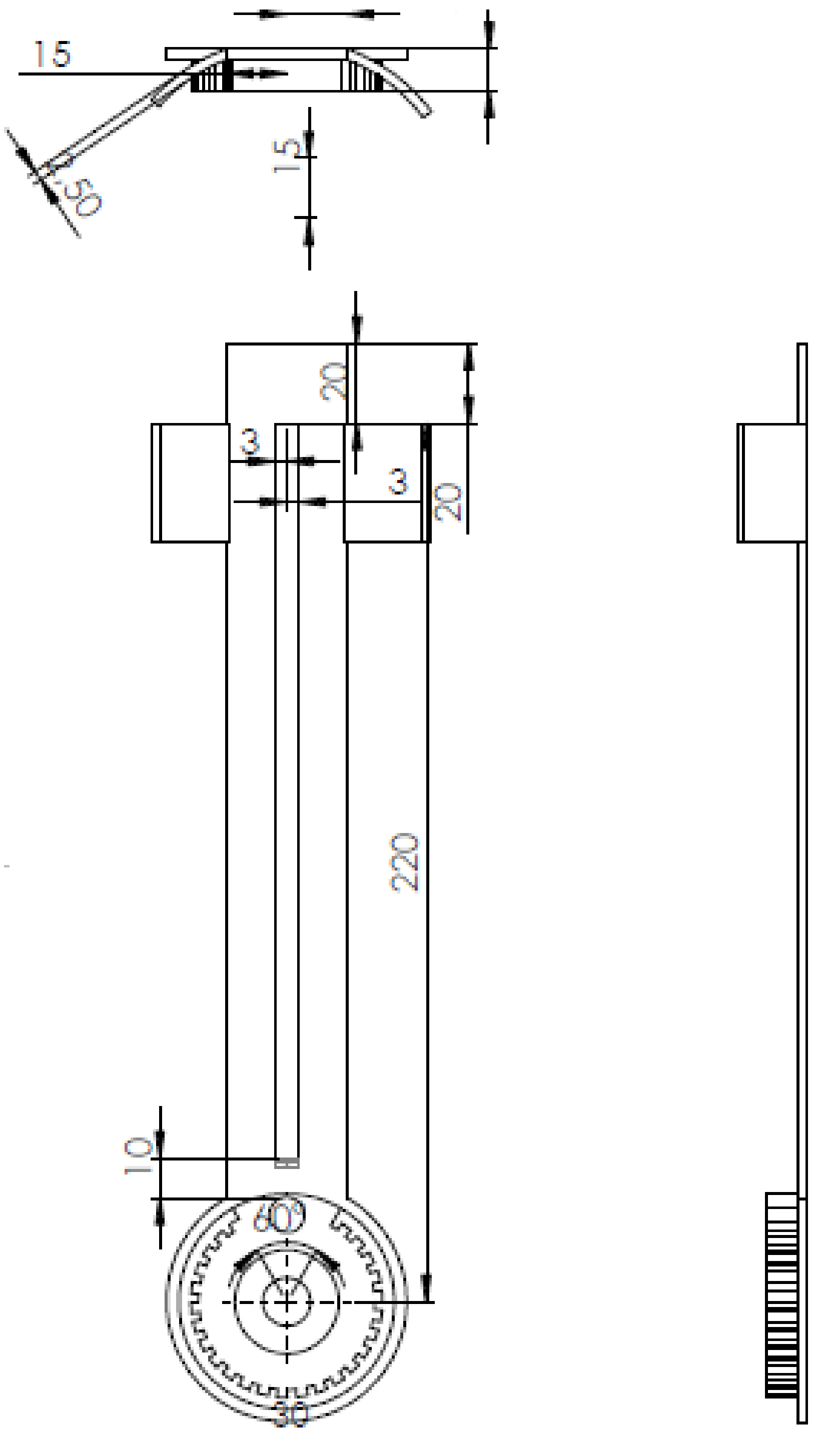
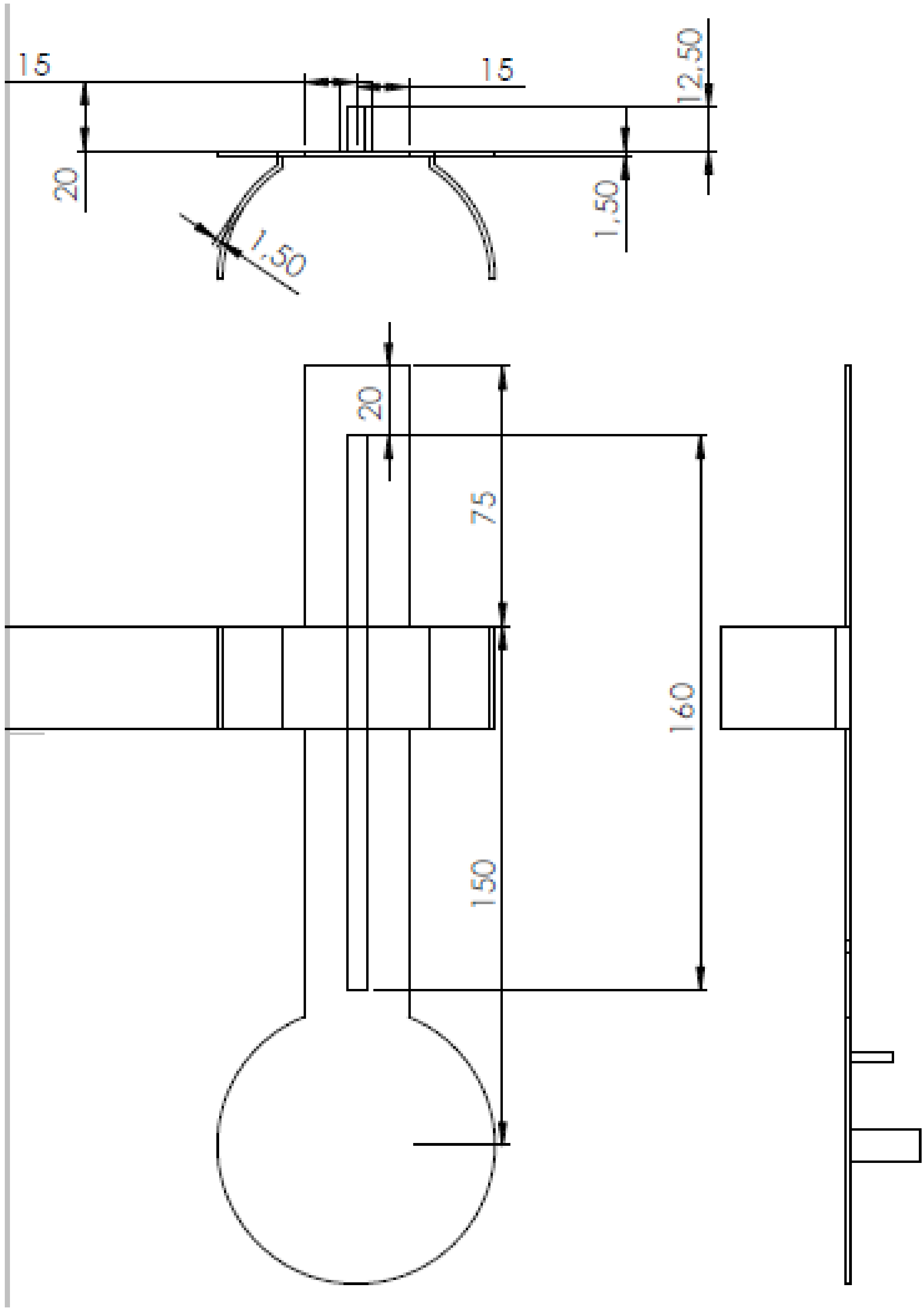
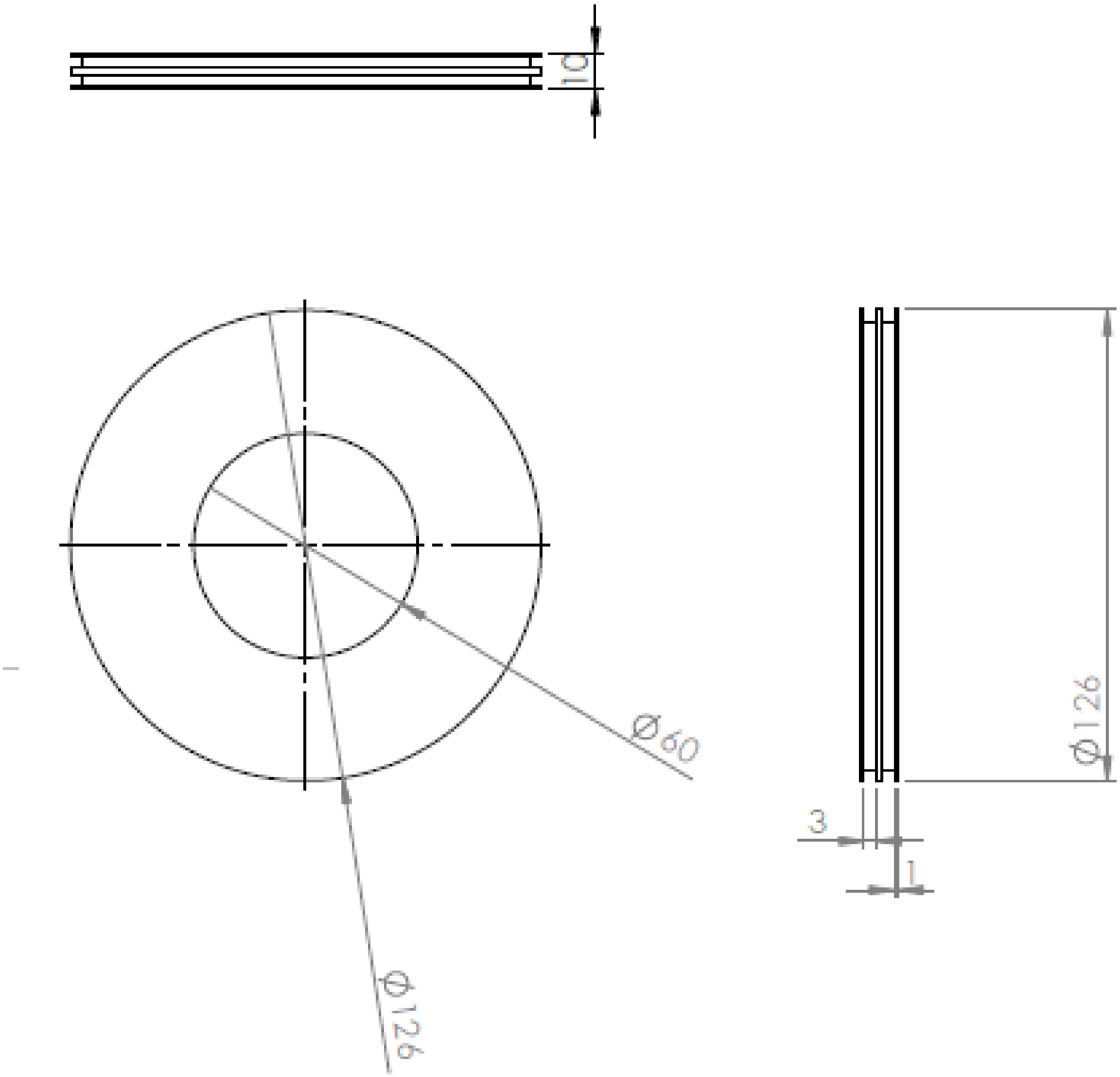
APPENDIX A: UPPER-ARM SUPPORT



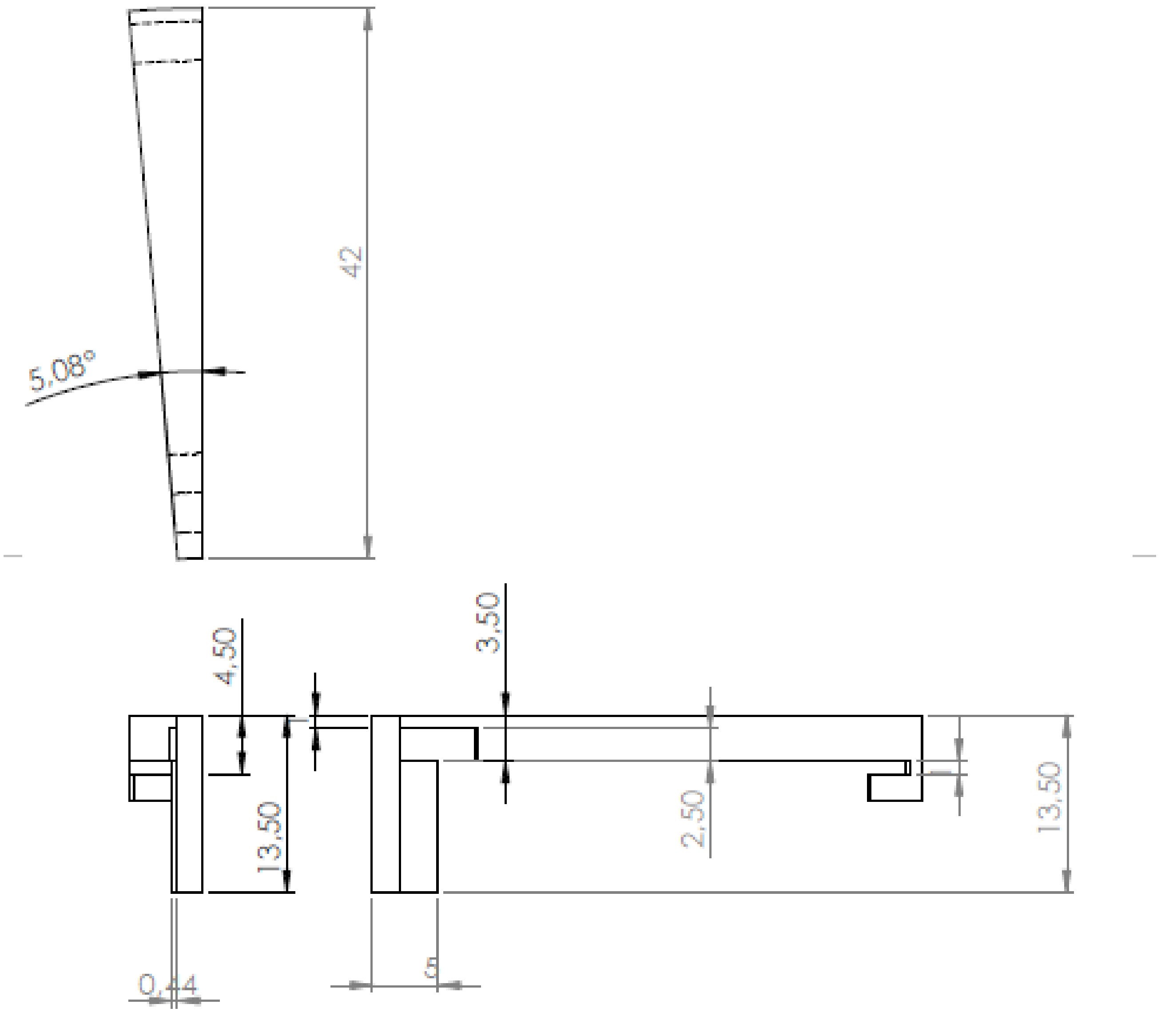
APPENDIX B: FOREARM SUPPORT



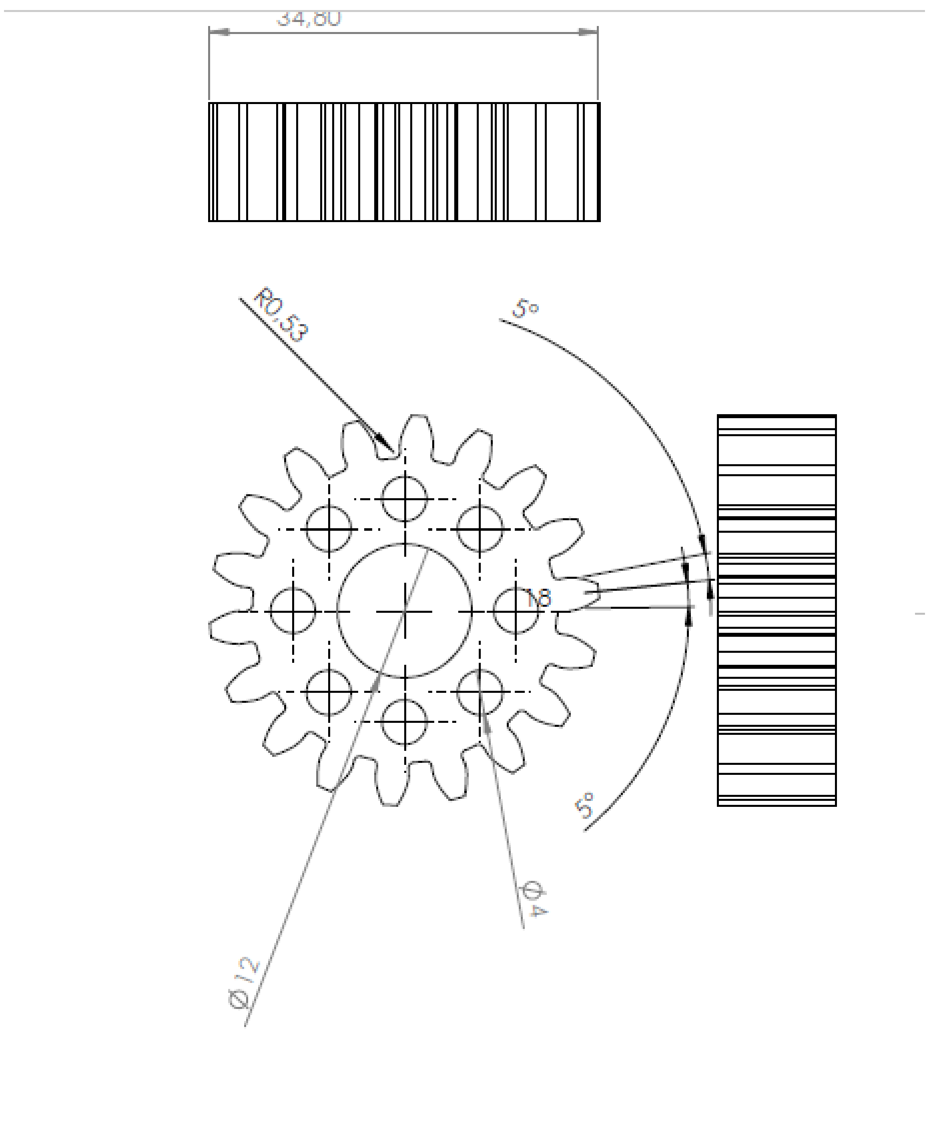
APPENDIX C: BOWDEN CABLE



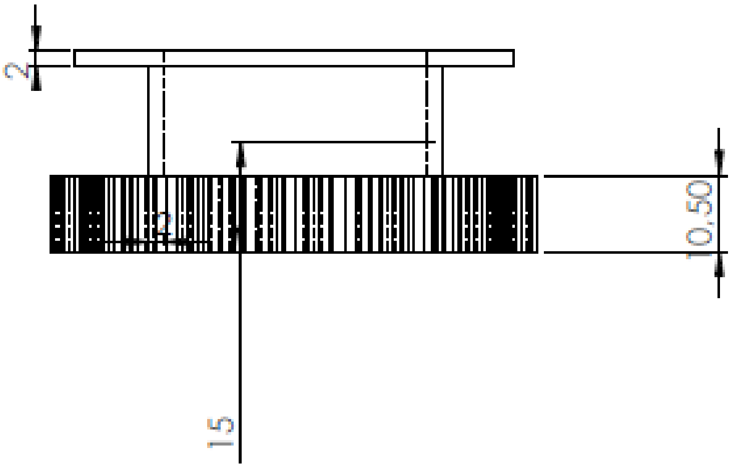
APPENDIX D: ANGLE PIN

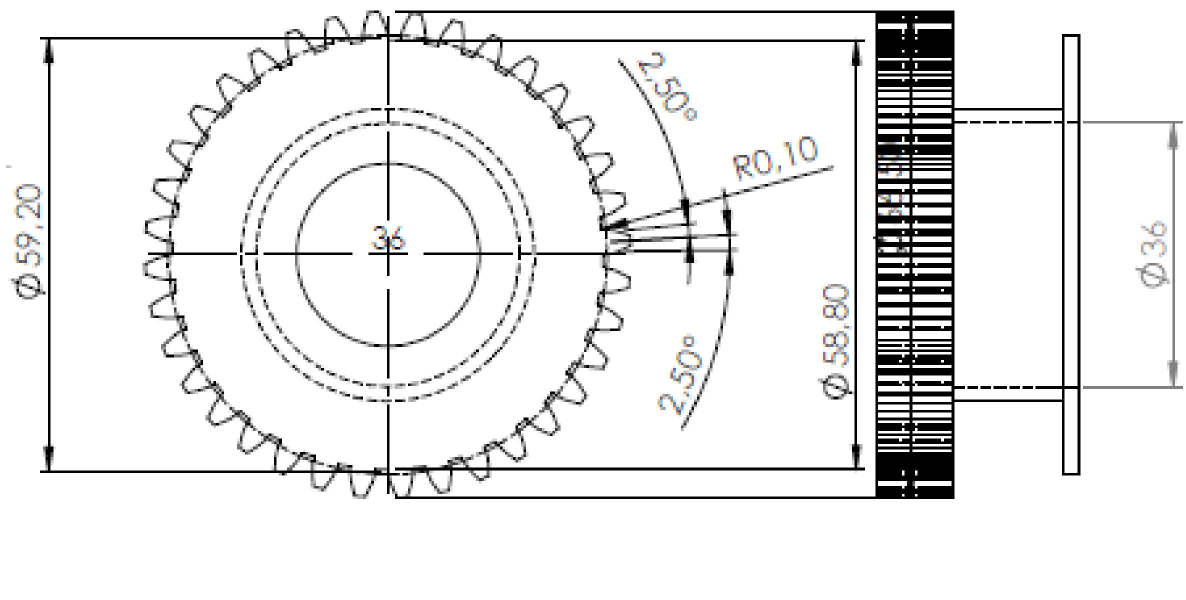


APPENDIX E: PINION

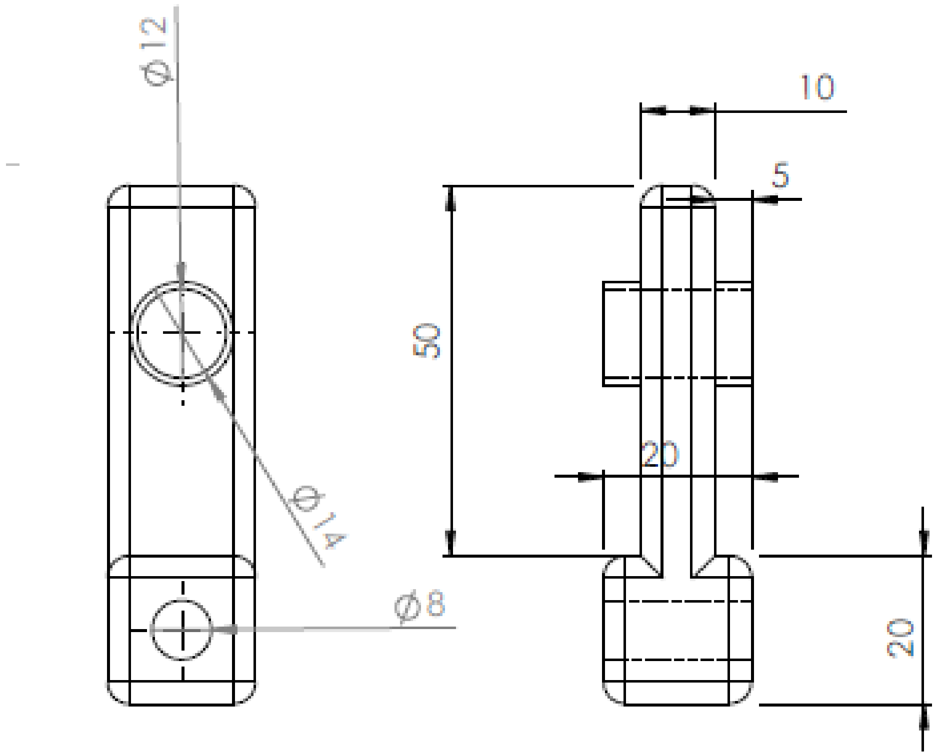


APPENDIX F: GEAR

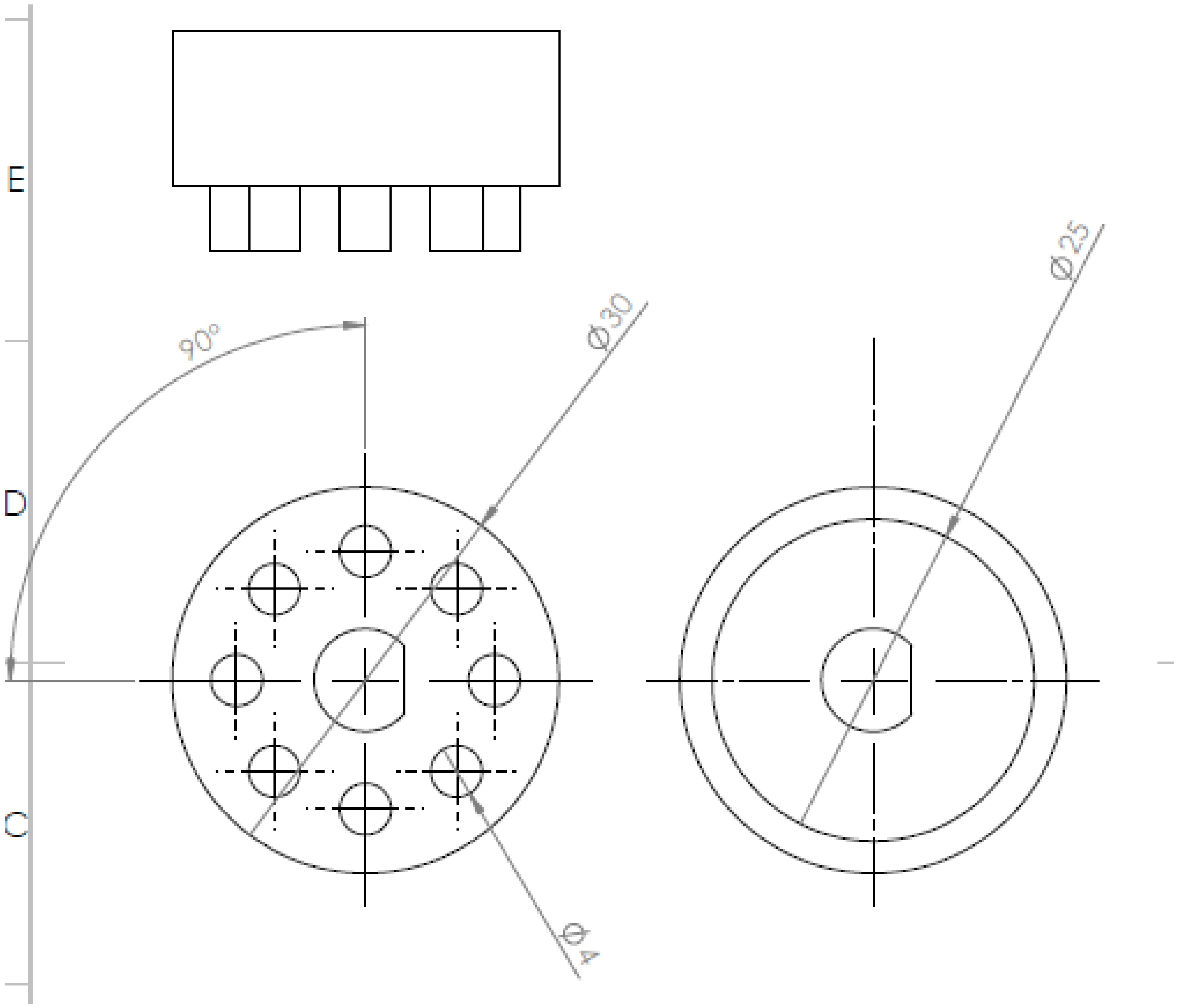




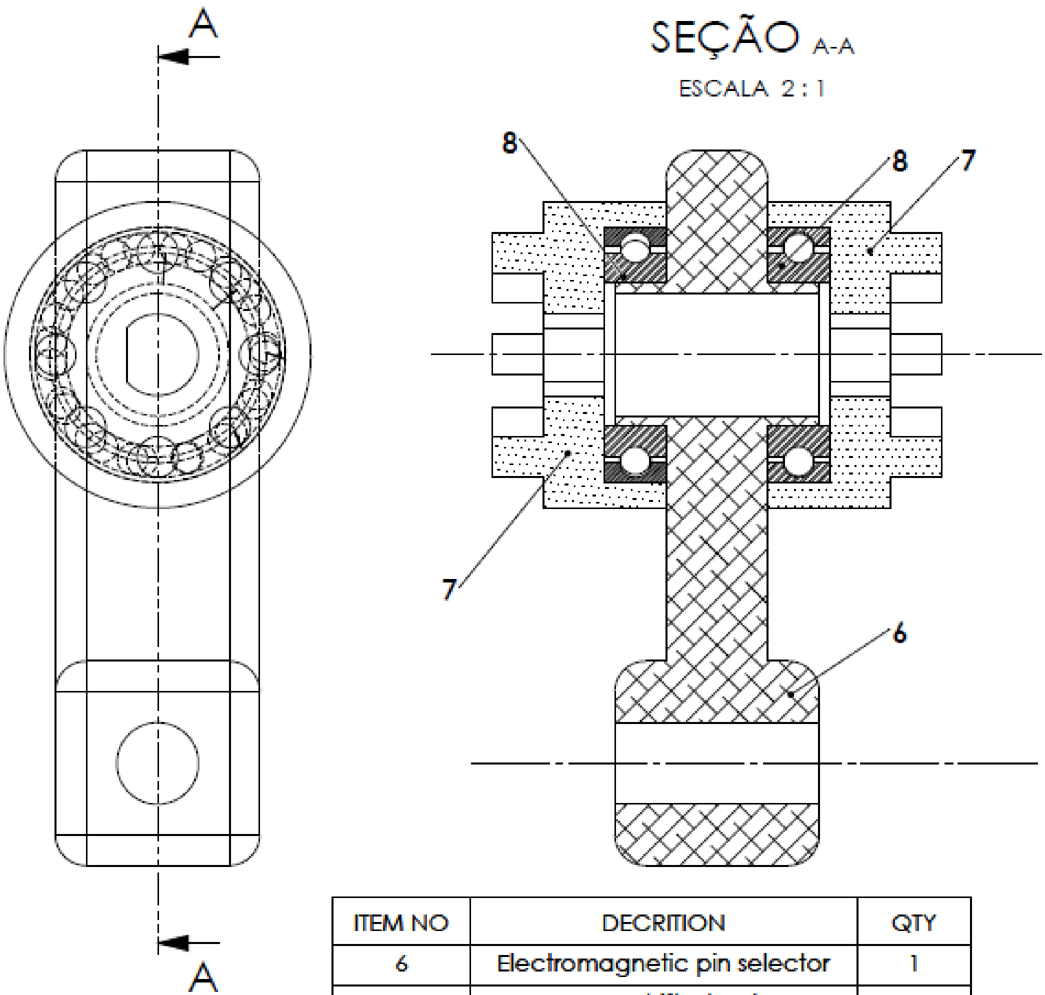
APPENDIX G: MAGNETIC PIN SELECTOR



APPENDIX H: GEAR SHIFT WHEEL

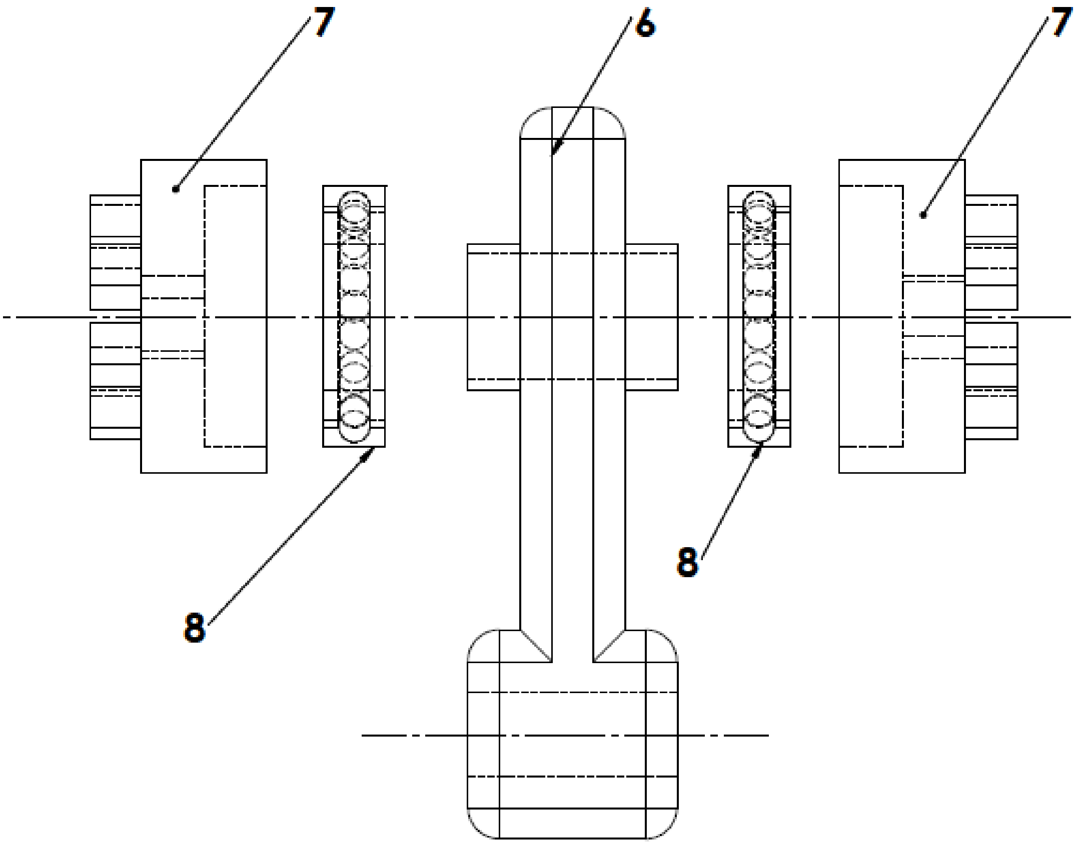


APPENDIX I: CUT VIEW GEAR SELECTION SYSTEM



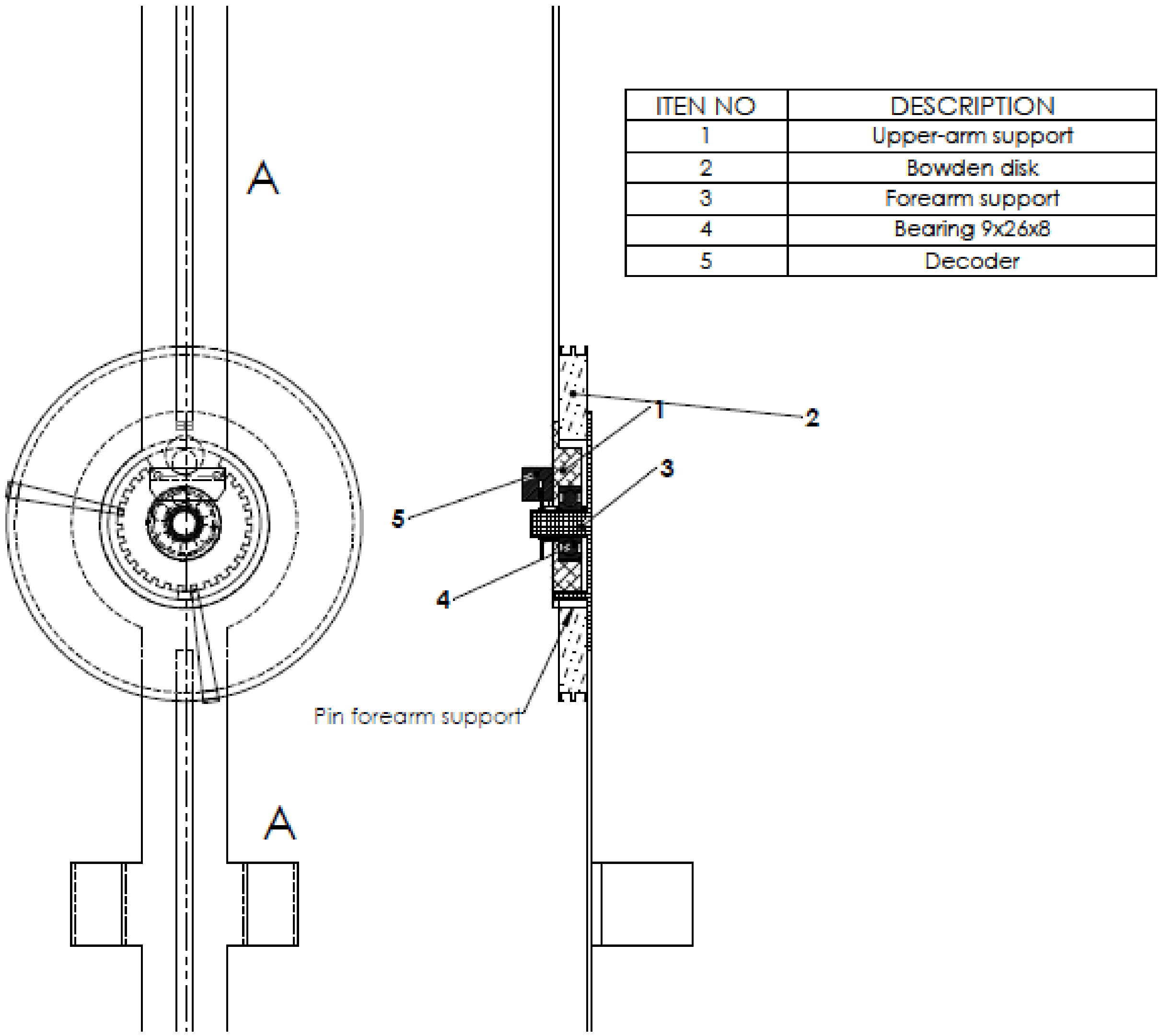
ITEM NO	DECRITION	QTY
6	Electromagnetic pin selector	1
7	Gear shift wheel	2
8	Bearing 9x26x8	3

APPENDIX J: EXPLODED VIEW GEAR SELECTION SYSTEM



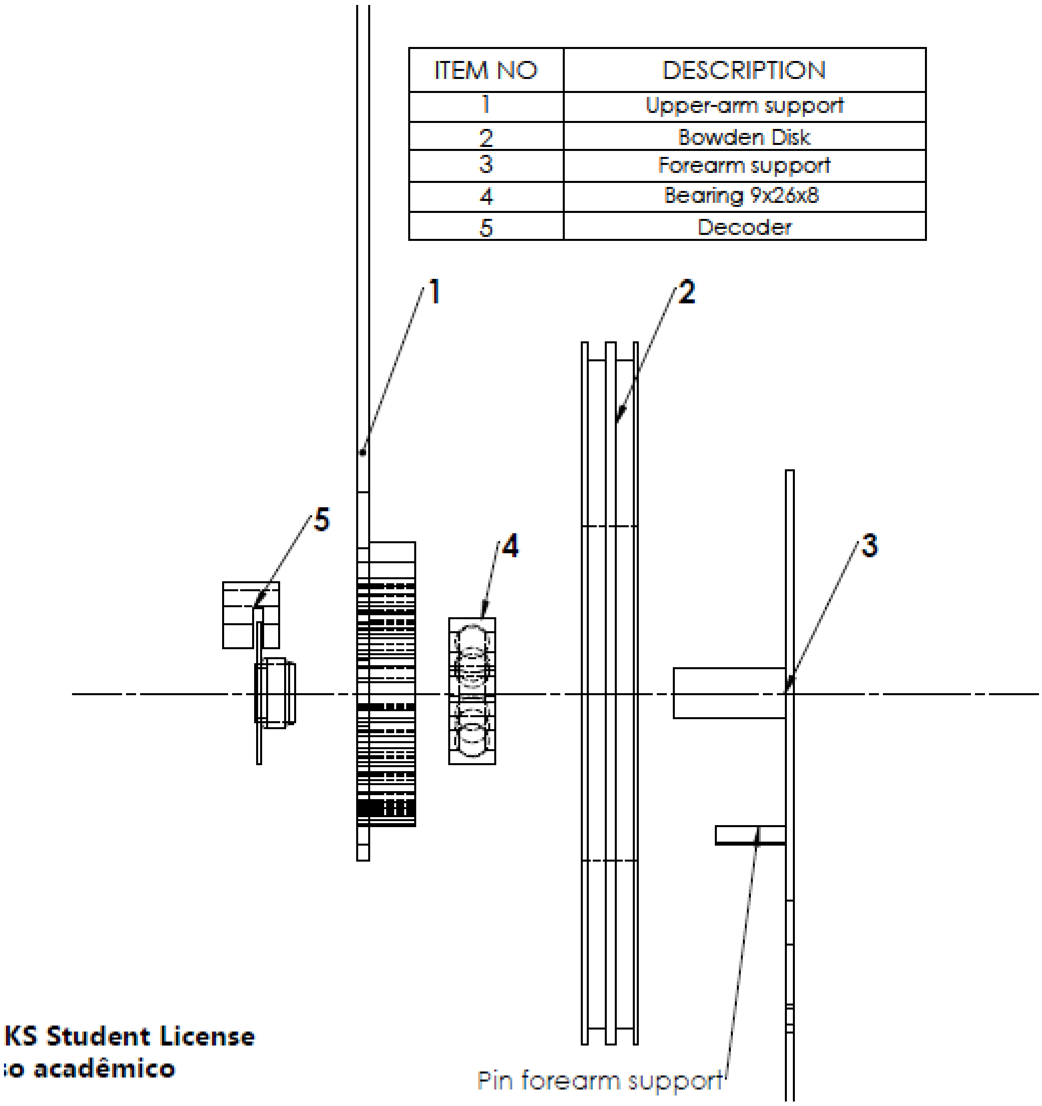
ITEM NO	DESCRIPTION	QTY
6	Electromagnetic pin selector	1
7	Gear shift wheel	2
8	Bearing 9x26x8	2

APPENDIX K: ORTHOSIS CUT VIEW



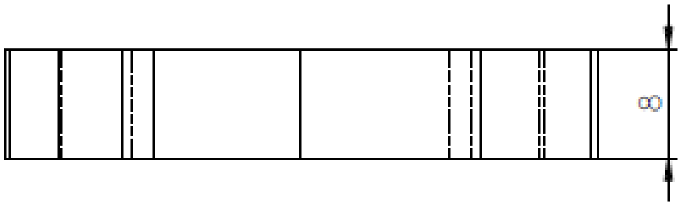
ITEN NO	DESCRIPTION
1	Upper-arm support
2	Bowden disk
3	Forearm support
4	Bearing 9x26x8
5	Decoder

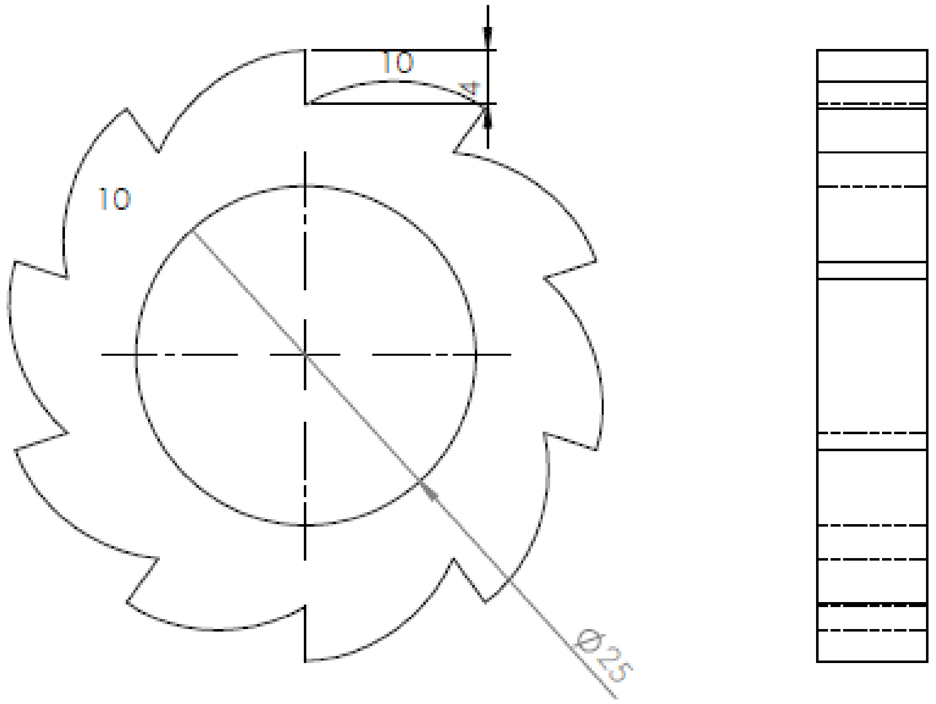
APPENDIX L: ORTHOSIS EXPLODED VIEW



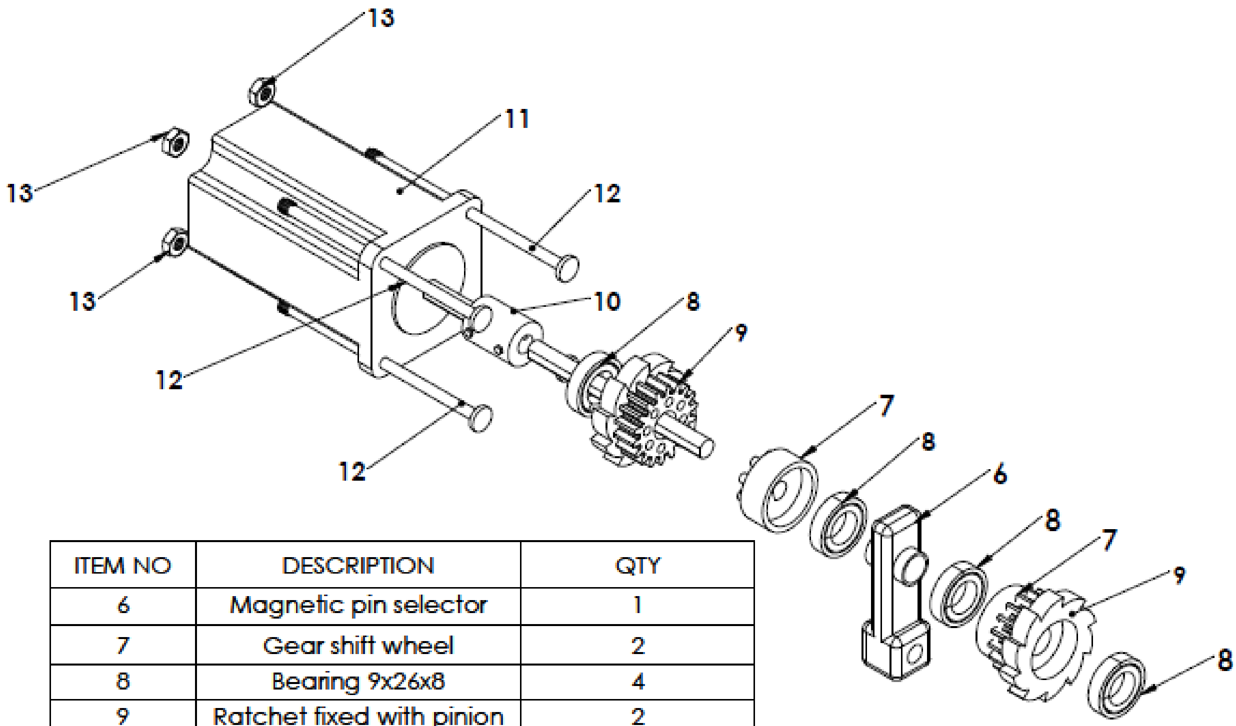
ITEM NO	DESCRIPTION
1	Upper-arm support
2	Bowden Disk
3	Forearm support
4	Bearing 9x26x8
5	Decoder

APPENDIX M: RATCHET





APPENDIX N: MOTOR SHAFT EXPLODED VIEW



ITEM NO	DESCRIPTION	QTY
6	Magnetic pin selector	1
7	Gear shift wheel	2
8	Bearing 9x26x8	4
9	Ratchet fixed with pinion	2
10	Shaft coupling 8x25	1
11	Motor 60BYGH401	1
12	Motor screw 1x10	4
13	nut 1x10	4

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APPENDIX M: ORTHOSIS