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Lower extremity exoskeleton for rehabilitation

Thesis
Autumn 2016
School of Technology
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SeAMK
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Thesis abstract

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The purpose of this thesis was to create a working 3D-model of a lower extremity exoskeleton. The project was provided by Universidad de Piura, in Peru, where the prototype of the exoskeleton will be manufactured and used for further research to make a working lower extremity exoskeleton.

The exoskeleton will be used for the rehabilitation of patients with mobility disorders in their lower extremities, like patients with hemiplegia. Studies prove that rehabilitation, with the help of the exoskeleton is more effective than the more traditional ways. Using the exoskeleton will also let a physiotherapist focus more on the patient and rehabilitation than the actual moving of limbs or body.

The thesis begins with the introduction of the background, the objectives and the cooperation partners of the project. The introduction is followed by a research of different kind of exoskeletons, which are divided into passive and active exoskeletons. After the research begins the project part, presenting different steps of the project, and finally in the last chapter there is a summary, summarizing the completed work.

Keywords: exoskeleton, lower extremities, hemiplegia, pneumatic artificial muscles (PAM).

SEINÄJOEN AMMATTIKORKEAKOULU

Opinnäytetyön tiivistelmä

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Tämän opinnäytetyön tavoitteena oli tehdä toimiva 3D-malli alaraajojen tukirangasta. Projektin mahdollisti Perussa toimiva Piuran yliopisto, jossa tukirangan prototyyppi myös valmistetaan ja sitä tullaan käyttämään hyväksi tulevassa tutkimustyössä, jossa kehitetään toimiva alaraajojen tukiranka.

Tukirankaa voidaan käyttää sellaisten potilaiden kuntouttamiseen, joilla on liikehäiriöitä alaraajoissaan, kuten esimerkiksi toispuolihalvaantuneilla potilailla. Tutkimukset osoittavat, että kuntouttaminen tukirangan avulla on tehokkaampaa kuin tavanomaisemmin keinoin. Tukirangan käyttämisen ansiosta fysioterapeutti pystyy keskittymään enemmän potilaaseen ja itse kuntouttamiseen, kuin vain ruumiinosien tai ruumiin liikuttelemiseen.

Opinnäytetyö alkaa johdannolla taustoihin sekä tavoitteiden ja projektin yhteistyökumppaneiden esittelyllä. Johdantoa seuraa tutkimusosuus, jossa käsitellään erilaisia tukirankoja, jotka on jaoteltu passiivisiin sekä aktiivisiin tukirankoihin. Tutkimusosuuden jälkeen alkaa projektiosuus, jossa esitellään projektin eri vaiheet. Viimeisenä kappaleena on yhteenveto koko työstä.

Asiasanat: ulkoinen, tukiranka, alaraaja, halvaus, pneumaattinen lihas.

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Terms and Abbreviations

Active joint	Joint that is active and can be controlled with the help of an actuator, which in this project is PAM. The opposite to a passive joint.
Augmentation	Making something greater or more intense. In augmentative medical exoskeletons, it means that the wearer does not get better after wearing it but must use it for the rest of his life. (Marinov, B 2016)
Bowden cable	Better known from bicycles where it is used for transmitting mechanical energy by the movement of an inner cable relative with a hollow cable housing, e.g. to brakes and gears.
DoF	Degree of freedom, a direction in which independent movement can occur.
Exoskeleton	Suit designed to increase the power or abilities (or both) of a wearer, or to help the wearer to move his body in a desired manner if moving would not be possible due to some disease or injury, e.g. resulting from an accident.
FoS	Factor of safety, which describes a system’s load carrying capacity.
Hemiplegia	A condition that affects one side of the body. This can be caused by an injury to such parts of the brain that control movements of the limbs, trunk, face, etc. This may happen before, during or soon after birth (up to two years of age approximately), when it is known as congenital hemiplegia (or unilateral cerebral palsy), or later in life as a result of an injury or illness, in which case it is called acquired hemiplegia. (Barnes, L. 2014)

LEE	Lower extremity exoskeleton. Exoskeleton that is made for lower extremities. See exoskeleton.
Lower extremity	Refers to the human leg, including the gluteal or hip region, thigh and foot. Opposite of the upper extremity. (New Health Advisor, 2016)
Microgravity	Very small amount of gravity, a condition when everything seems like weightless, e.g. in a spaceship. (NASA 2010)
PAM	Pneumatic artificial muscle or McKibben air muscle. It features high power to weight ratio. (Shadow robot company, 2016)
Passive joint	Joint that is passive and is there merely to allow necessary and smooth movements of the body. Opposite of an active joint.
PPR	Pulses per revolution. How many pulses an encoder can send during one revolution.
Rehabilitation	Improving of health conditions. For exoskeletons in rehabilitation it means that after using it, the health condition of the user should get better.
UDEP	Universidad de Piura (University of Piura). University in Peru, which has two campuses, the main campus in Piura and the second campus in Lima, the capital city of Peru.
Von Mises Stress	Calculation used to determine if the material under determination will meet the requirements that the designer has set for it in its current form. The calculation is accomplished by comparing results to the material’s yield stress, which constitutes the von Mises yield criterion. (McGinty, B. 2012)

Tables, Figures and Pictures

1 INTRODUCTION

The thesis was undertaken for the University of Piura, the main campus of which locates in Piura, like the name suggests, and the second campus is in Lima, the capital city of Peru, where the author was working. It is a University founded by Opus Dei in 1969, and it has about 7000 students.

The world is changing fast as technology evolves rapidly and people are living longer than ever before. The old ways of doing things are replaced by more powerful or effective means. In this project, evolution means replacing heavy and time consuming tasks of a physiotherapist who is working with patients who need help in rehabilitation of their lower extremity, especially patients with a hemiplegic disorder. Possibly this project can help people in developing countries around the world, who do not have the same possibilities as people in more developed countries.

1.1 Objective of the project

The main target of this research is to create a working eight degree of freedom lower extremity exoskeleton (LEE), where the thigh and knee joints are active, and the abduction / adduction and feet joints are passive. The exoskeleton can be used for the rehabilitation of patients with mobility disorders of musculoskeletal strength, motor control and gait. Secondly, the rehabilitation based use of the exoskeleton would also relief the heavy burden of the therapists in the traditional physical therapy and make it cheaper. Thirdly, if rehabilitation could be made cheaper it would be available to larger groups of people.

1.2 Cooperation partners

This project is done in cooperation with the University of Piura. There are two master students with the author in this project. The master students are working daily in their research topic for master program. They have a contact in Japan, professor Chiharu, who is providing the artificial muscle that will be used with the LEE.

The part of the author in this interesting project is to make a design of the exoskeleton by using SolidWorks program. This project is based in the main campus area of UDEP in Piura and everyone, except for the author, is working there. Giancarlo Villena Prado is responsible for the controls of the exoskeleton. Professor Castro is the supervisor of the project. Eliodoro Carrera Chinga is the supervisor of the author in Lima, but otherwise he is not related to this project.

2 EXOSKELETONS

This chapter will demonstrate some exoskeletons to show what they are being used for, and what they are capable of. Before going deeper in to the concept of an exoskeleton, a few things need to be explained. What is the difference between an endoskeleton and an exoskeleton? The endoskeleton means the bone structure of 206 bones inside of a human being, and most mammals, whereas the exoskeleton refers to a bone structure that is in the exterior of an animal such as insects or e.g. crabs or turtles. (BBC, 2014)

Today as the technology is evolving rapidly, the natural skeletons are not the only ones anymore, but we humans are developing skeletons for different purposes, mostly for human beings, some for making humans faster and some for helping to walk after a spinal injury. The next chapters will explain more specifically the differences between different kind of exoskeletons and their purposes. Firstly, these exoskeletons will be divided in two different groups, active and passive exoskeletons.

2.1 Active exoskeletons

Exoskeletons in this group are powered by some source of power, mostly by electricity or by pressurised air. They help the wearer to accomplish the desired movements more effectively, faster or for a longer time, or solely to move the body if it is not possible due to the physical condition at the time. They use sensors and actuators to work.

2.1.1 Exoskeletons for creating super human abilities

Just like almost all new technologies which can be adapted to the needs of armies around the world, this one does not make an exception. The wearer of these suits can somewhat obtain the abilities a superhuman in terms of carrying heavier loads, walking, running or climbing faster without extra effort.

Picture 1. Tactical Assault Light Operator Suit (TALOS), XOS 2. (Army-Technology 2014)

With the help of TALOS XOS 2 (Picture 1), the ratio of the wearer can be as high as 17:1 in lifting heavy objects. The suit works with high-pressure hydraulics. The wearer can also lift heavy objects repeatedly with no risk of injury or exhaustion, where this this suit can be very helpful as the military personnel is estimated to lift 7000 kg daily. (Army-Technology 2014)

2.1.2 Exoskeletons for space use

Requirements for a human's longer stay in microgravity, like in a spaceship or extra-terrestrial ground, differ greatly from staying on the surface of the earth, as there is just a little bit of gravity affecting the movements of an object or a person, meaning that minimal amounts of power are needed for moving around or lifting objects. In the short run this would be completely acceptable, but in the long run the muscles start to wither, meaning that a device for maintaining the leg strength is needed, especially on an extremely long flight e.g. to Mars. (NASA 2010)

Picture 2. NASA X1 exoskeleton. (NASA 2013)

In response for longer stays in microgravity, NASA developed X1 (picture 2), exoskeleton to aid astronauts to walk on extraterrestrial surfaces and to keep leg strength while in microgravity. This suit can also be used for assisting paraplegics to walk on earth, potentially for the first time. The possibility of maintaining leg strength in microgravity means in this case that this suit can be used as a resistor against leg movements. (NASA 2013)

2.1.3 Medical exoskeletons for rehabilitation

Medical exoskeletons are solely used for the rehabilitation of patients, mainly used in a controlled environment. It is also the largest and the most colorful group of exoskeletons. There are multiple different kind exoskeletons in this group for different purposes, like rehabilitating the upper or the lower body. There can also be found exoskeletons for home use, but still most of them are meant for clinics or hospitals. This type of exoskeleton is often large and requires personnel specialized in using and controlling the equipment, like putting the suit on the patient.

Picture 3. LokomatPro stationary LEE by Hocoma (Hocoma 2016)

LokomatPRO stationary LEE (Picture 3) can be used for gait rehabilitation with patients who have suffered e.g. spinal cord injuries. While it supports the patient's whole weight from the pelvis, it can be used when rehabilitating patients with extremely serious injuries. The robot assisted gait rehabilitation has been proved to be more efficient than conventional gait training.

Picture 4. ReWalk LEE rehabilitation device (ReWalk 2016)

ReWalk LEE rehabilitation device (picture 4) is portable and powered by electric motors. Its batteries can provide energy for moving and exercising the gait the whole day. Prices for this exoskeleton start from about 70 000 USD, which will most likely keep it out of reach for most buyers.

2.1.4 Medical exoskeletons for augmentation

Medical exoskeletons for augmentation are solely meant to augment person's abilities, not to rehabilitate them. Even if they are not designed for rehabilitation they can help a paralyzed person to walk. In picture 5 there is an example of one of them.

Picture 5. Phoenix exoskeleton from SuitX (Brewster, S. 2016)

This 12-kg suit, partly made from carbon fiber and designed by SuitX ,can help a paralyzed person walk again. Even if it is still more expensive than motorized wheelchairs, with a $40 000 price tag on it, it is a great option and offers some abilities that wheelchairs cannot offer. It can also be used for taking a few steps in the stairs and the wearer can make some natural movements with his legs instead of needing to sit continuously in a wheelchair. The legs can be controlled by the wearer with buttons integrated on crutches, which control the electric motors, and the battery pack can last up to eight hours of use. (Brewster, S. 2016)

2.2 Passive exoskeletons

Passive exoskeletons are made, e.g. for supporting heavy loads or the weight of heavy tools or for making it easier to work long times in uncomfortable positions. The group of passive exoskeletons is interesting group, while offering lots of opportunities in many fields, e.g. in fields where person needs to carry heavy tools in uncomfortable positions, and do something that requires high accuracy.

2.2.1 Exoskeletons for carrying heavy loads

At the moment, the exoskeleton type meant for carrying heavy loads can be found solely for military purposes, where it is important to be able to pass long distances while carrying as much supplies as possible with low metabolic costs and be constantly ready for a potential battle situation. In other words, the more the exoskeleton can help the soldier in reducing metabolic costs, the larger area it can cover, the more supplies and additional armour it can carry, meaning that the more independent the soldier can become. (Marinov, B. 2016)

Picture 6. Human Universal Load Carrier - HULC by Lockheed Martin (Lockheed Martin 2012)

Perhaps the most advanced exoskeleton in this field has been made by Lockheed Martin for US army. The exoskeleton’s actuators were first designed to be powered by batteries but because of increased requirements from the US army concerning the operating hours without recharging, they simplified the design by removing actuators and power sources, which reduced the weight from 24 kilograms (without batteries) to just 5 kilograms. The unpowered version works simply by transferring the weight of the exoskeleton and backpack to the ground via a frame. (Lockheed Martin 2012, Marinov, B. 2016)

2.2.2 Exoskeletons for making heavy tools anti gravitational

Anyone who has ever been working with heavy tools, has experienced fatigue in muscles due to the weight and possible vibrations that the tool features. Therefore, the exoskeletons that can be used for making heavy tools anti gravitational will most likely have a bright future.

Picture 7. FORTIS personal exoskeleton for heavy tool use by Lockheed Martin (Lockheed Martin 2016)

Above there is a picture of FORTIS personal exoskeleton. (picture 7) This exoskeleton can support the weight of heavy tools such as grinders, making working more accurate and while it is reducing muscle fatigue, it also allows working for longer periods. If the arms are working flexibly enough without twitching, this exoskeleton can be used when working in various and complex environments. (Lockheed Martin 2016)

3 EXOSKELETON PROJECT

The progress, problems and different phases of the project are presented in this part. Also, some components to be used are introduced as well as the modeling of the exoskeleton, which was in main part in this project for the author.

3.1 Planning

This project started in the beginning of August 2016 for the author. The planning was mostly made by exchanging emails between the author and one of the master students, Giancarlo Villena Prado, in Piura, but there have been also some meetings with the supervisor of the author, Eliodoro Carrera Chinga in the campus of Lima and the author himself.

In the very beginning of the project there were many differences in opinions on what this project was going to be all about, between Eliodoro and Giancarlo. Giancarlo's goal for what this project could achieve was very different from Eliodoro's. Eliodoro's suggestion was that the exoskeleton should be merely capable of automatically moving the legs for a patient who is laying down on a bed or sitting on a chair, and so rehabilitating the patient. This would also help the physiotherapist in the hard work, as it would be possible to just set the program and the wanted time for the exoskeleton, which would then let the physiotherapist concentrate on listening to the patient or helping another patient.

The author had previous experience in using 3D modeling programs but none with SolidWorks. But the first step before starting to learn how to use it, was to figure out how to use SolidWorks with OSx as there is no version available for Mac. Soon the author found out that Seinäjoki University of Applied Sciences offers a license for VMware Fusion, which is a program allowing the use of Windows or another user interface inside the OSx without rebooting.

There was also another program which author had never used before, and which was told to be necessary for making the calculations for the project. The program is called MapleSim. It runs inside of Maple, which is a similar program to a better-known program, Matlab.

3.2 First cardboard model

The first model was designed for rehabilitating a patient in a reclining position. In the picture 8 the leg is straight in its starting position ready to start moving towards its end position in picture 9. The bar that is connected from the right side of the hip pulley to the right side of the knee pulley is guiding the movement of the shank in a way that keeps the shank parallel with the trunk during the whole movement. Additionally, it allows the use of just one muscle controlling one of the pulleys. The purpose of this model was to make it completely automatic where the user, the physiotherapist, would just have to set the wanted time and then be free to do other duties.

Picture 8. The first cardboard model made by the author, in its starting position made for a reclining patient.

Picture 9. First cardboard model in the end position.

This was the first model, and this was what the author had been told to be the goal of the project. After sending a video to Piura, where the functions of the model were explained, it was soon to be clarified to the author that this was what was desired. But they wanted a model that could be used for rehabilitating a patient who is sitting on a chair as well, meaning that it would require at least two muscles for controlling the thigh and the shank separately. Due to this also the idea of connected pulleys had to be discarded, even though it was still possible alternatively to attach the muscle to the knee pulley and separate the connection of the pulleys with a bar that can be set free. This idea was never developed because the demands regarding the functions of the exoskeleton were increasing continuously.

3.3 Actuators

It was clear since the beginning of the project that actuators to be used in this project should be pneumatic artificial muscles (PAM), or by another name McKibben air muscles after the creator of first PAM, a nuclear physicist Joseph Laws Mckibben. (Gurstelle, W. 2014)

Picture 10. PAM to be used in the project, above in a pressurized state and below in an unpressurized state. (Kanda 2015)

The PAMs used in this project were ordered from Kanda Tsushin Kogyo Co. Ltd, from Japan. The 1200 N and 1800 N muscles were selected by Giancarlo. Per the datasheet, the muscles can reduce their length by 17 % of the rubber part that can be seen in the picture 10 as a dark long part in the middle of the muscle. With the 300 mm long muscles that are to be used in the exoskeleton, it means: 300 mm x 0.17 = 51 mm leeway. A 90-degree movement, which is required from a knee pulley (figure 1), it would mean that the maximum diameter of the pulley is 65 mm (radius = (180 ° x 51 mm) / (90 ° x π) = 3.24 cm). With a 120-degree movement, which is required from the hip pulley (figure 2), the maximum diameter of the pulley is 48.7 mm (radius = (180 ° x 51 mm) / (120 ° x π) = 2.43 cm).

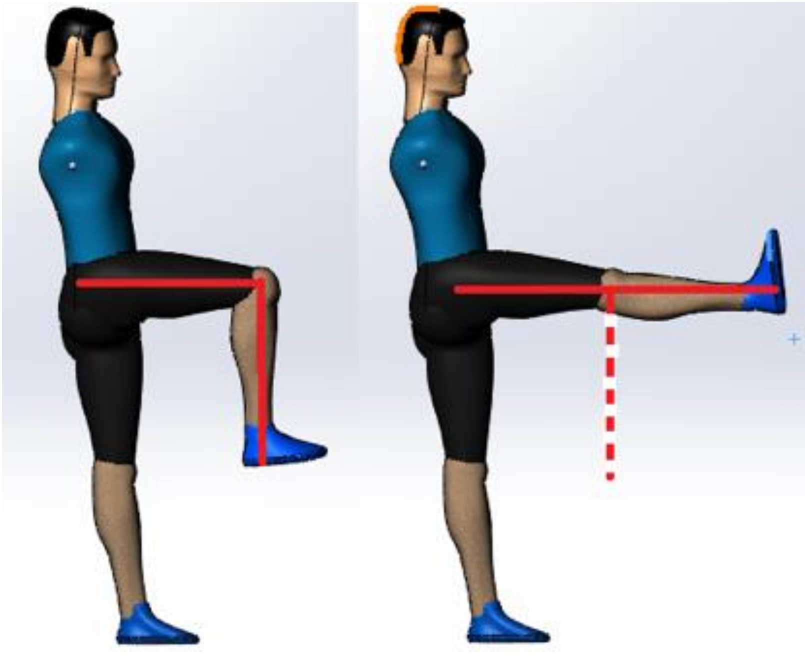

Figure 1. Demonstrating the required movement of the knee.

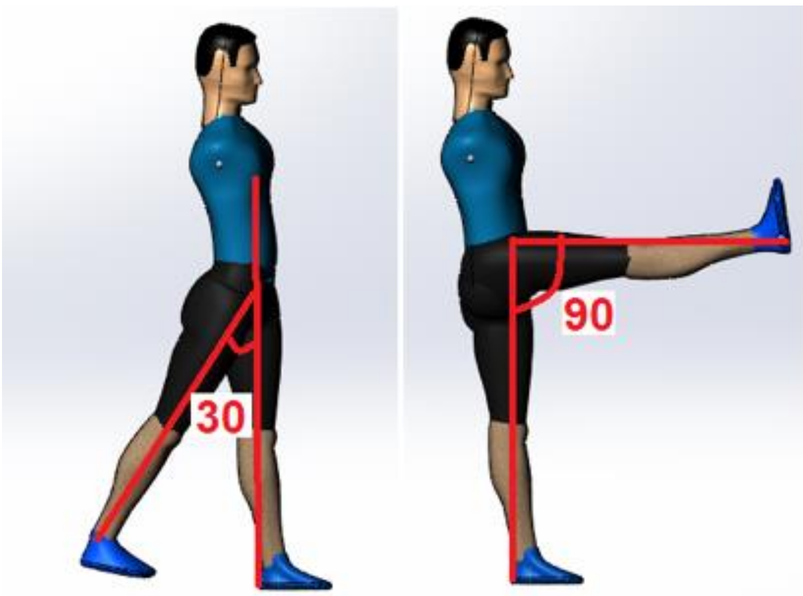

Figure 2. Demonstrating the required movement of the hip.

3.4 Segment properties of human body

The properties of a human body as length and weight were in very important position in this project. The lengths of the body parts, which can be read from table 1 and table 2, helped creating correct size components for every body part and to fit different sized persons. It is also very important that the joints are placed in correct places to allow smooth movement without unnecessary twisting that could occur if the joints of the exoskeletons would be fixed to a body but not corresponding locations of human joints. With the help of the segment weight and distance to the center of gravity it was possible to calculate the forces affecting the exoskeleton and to make simulations on how thick and what shape the components need to be, in order to achieve the necessary strength, while being as light as possible.

Table 1. Body segment parameters. (Tözeren, A 2000)

Segment	p(%)	m (%)	I_1(kg-m_2)
Head	0.5358	0.0730	0.0248
Upper arm	0.4360	0.0270	0.0213
Forearm	0.4300	0.0160	0.076
Hand	0.5060	0.0066	0.0005
Trunk	0.4383	0.5080	1.3080
Thigh	0.4330	0.0988	0.1502
Lower leg	0.4330	0.0465	0.0505
Foot	0.4290	0.0145	0.00308

Explanations of the table 1

- p stands for the distance measured from the centre of gravity of the body part to the proximal endpoint expressed as a fraction of the segment length.
- m stands for the weight of a body part as a percentage of the whole-body weight.
- I_1 stands for the mass moment of the inertia with respect to the centre of mass of a body segment about the transverse and longitudinal axis, respectively, for a subject with the mass of 74.2 kg and the standing height of 1.755 m. (Tözeren, A 2000)

Table 2. Relative weight and length of body segments for adult men and women (Tözeren, A 2000)

	Men		Women	
Body segment	Weight (%)	Length (%)	Weight (%)	Length (%)
Whole body	100	100	100	100
Head and neck	7.1	13.8	9.4	
Trunk	48.3	30.0	50.8	30.0
Upper arm	3.3	17.2	2.7	19.3
Forearm	1.9	15.7	1.6	16.6
Hand	0.6	10.4	0.5	10.4
Thigh	10.5	23.2	8.3	24.7
Shank	4.5	24.7	5.5	25.6
Foot	1.5	4.2[a]	1.2	

Explanations of the table 2

- The numbers in this chart are percentages of the weight and length of the body, respectively
- [a] in foot column refers to height of the foot, not its length. (Tözeren, A 2000)

3.5 First SolidWorks model

In the beginning of this project, the author thought what would be the best way to create a LEE in order to make it as light as possible, finding out that a tubular design has higher strength when compared with the more conventional square design. The first SolidWorks design was made with a 1 inch (25.4 mm), 5052 – H36 aluminium pipe with a 1 mm wall as a construction material for the frames between the joints. Anyhow this idea changed to another, due to several reasons that will be explained further on in this chapter. (Kalyanshetti, M.G. Mirajkar, G.S. 2012)

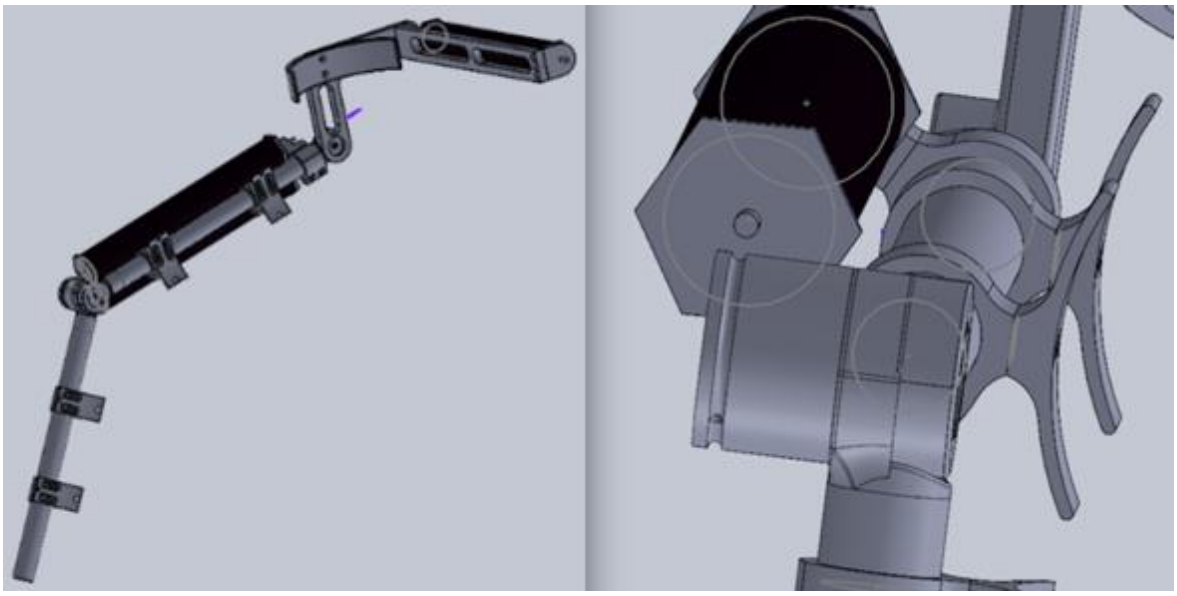

Figure 3. First model of the exoskeleton with PAMs located next to thigh.

The problems of this model started already when the author started locating the PAMs next to the thigh, noticing that the PAMs were too long to be there for an average height Peruvian child. This was because the pneumatic muscles are 326 mm long whereas the average length of the thigh of a Peruvian child is just about 350 mm, leaving just 24mm for attaching the muscle to the frame. Even if it would still be possible to attach the muscle in that space, it would lead to another problem, when second pulley for thigh is inserted, there would be no space. If the muscle would have been attached to the very end of that frame it would have been possible to adjust the length of the frame without the need to adjust the wires connected between the muscles and the pulley as well. One of the reasons for not using a tubular design is that when compared to a square design, the joint parts need to be welded together, whereas the square design can be machined from one flat piece which, of course, saves some steps and money.

Figure 4. Internal telescopic tube locking device which was planned to be for adjusting the length of the frames. (Pete 2013)

Adjusting the mechanism presented above in figure 4, which was to be used for adjusting the length of the frames, was one of the reasons why the tubular frame was abandoned. The reason why it was not used is that, after extensive research, the author was not able to find a manufacturer who would have been selling a suitable device for this application. Even if this device is comparably simple, creating it would have needed some research, experiments and most importantly time.

3.6 Joint pulley and its operating principle

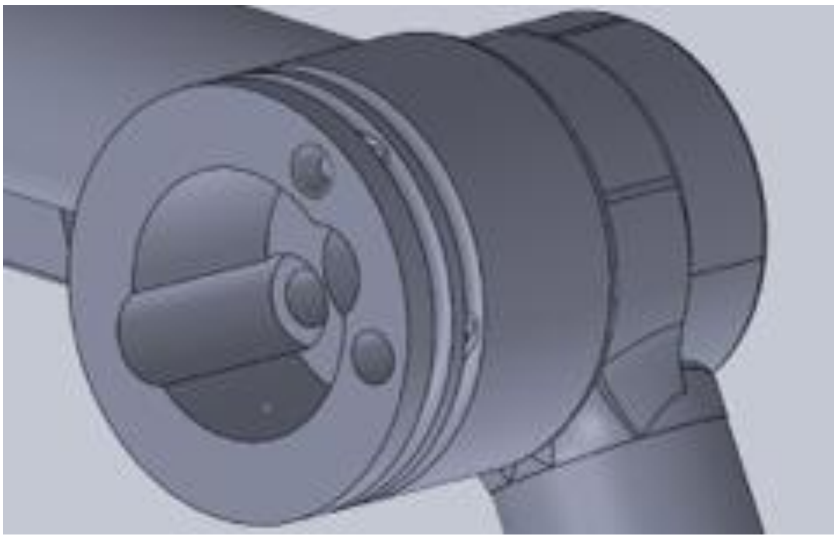

Figure 5. Early model of the knee joint pulley, where the two holes in the slots are designed for locking the wires connected to the muscles.

The pulley design has been relatively similar during the whole design process, of course, there have been many changes in dimensions but the basic idea has stayed the same. One of the important features in this pulley is that by setting M5 set screws into the holes on the front side of the pulley the wire can be locked easily without additional components.

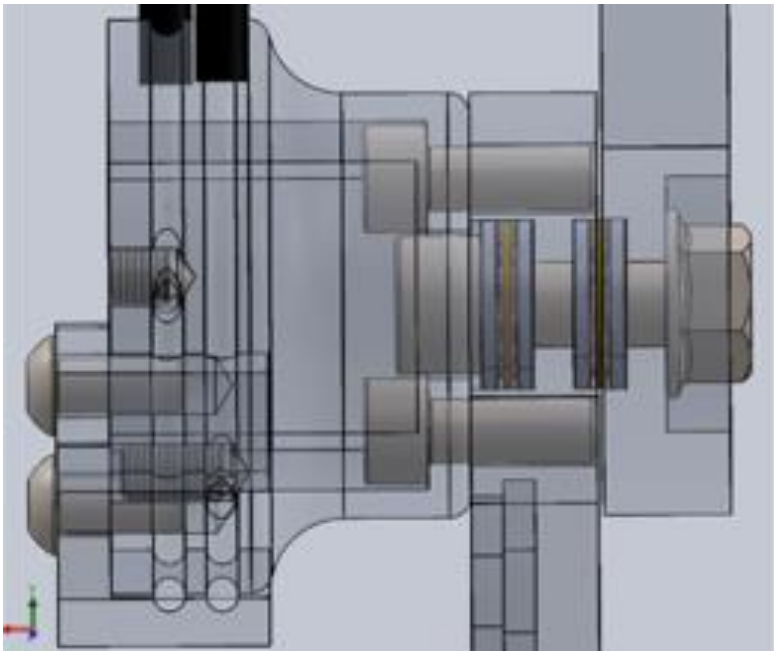

Figure 6. First idea for allowing the movement of the joints was created by using two ball thrust bearings. This figure shows also the set screws for locking the wires.

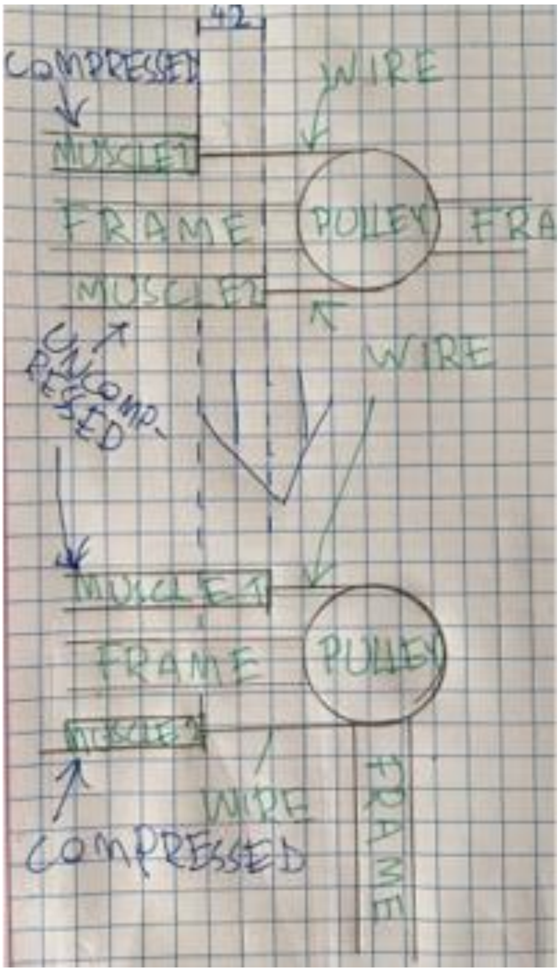

Figure 7. Operating principle of the design with two muscles and a pulley explained.

The operating principle of the joints and muscles is following: both muscles are to be fixed on the same level. The shorter muscles in the figure 7 signify compressed muscles and the longer muscles stand for uncompressed muscles. In other words, the upper drawing states the situation where the muscle 2 is uncompressed and the muscle 1 is compressed, whereas in the lower drawing they are in the opposite positions. Therefore, the muscles must be working together, when muscle 1 is compressing the muscle 2 needs to be decompressing.

3.7 Transferring the actuators to a backpack

Some of the reasons for transferring PAMs from next to the frame to a backpack were already explained in chapter 3.5 First SolidWorks model. Anyhow, the main reason for this was that the actuators used are simply too long to be in their original location. If the LEE was to be used just for adults then there would not be any problems, but since it must be suitable from an average size Peruvian 12-year-old descendant to an average size Peruvian male, there was a major problem. Therefore, the author had another solution to this problem, transferring the actuators into backpack. However, this solution brought a few other problems to be solved, which will be explained in this chapter.

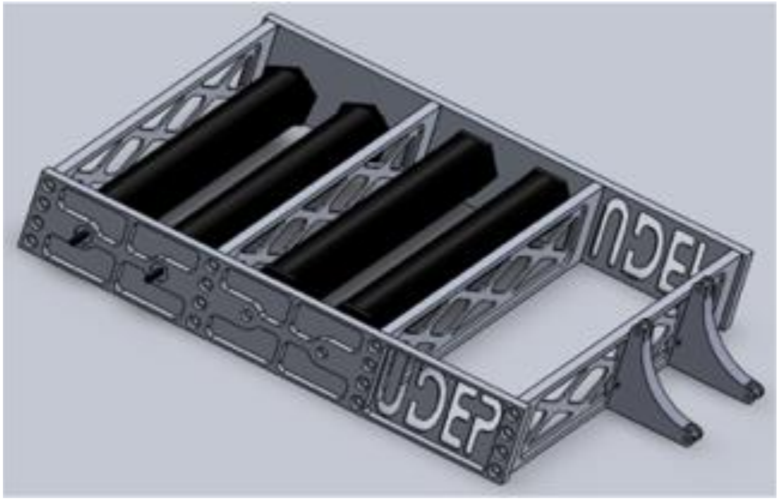

Figure 8. First design of the backpack had space for just 4 muscles and it was comparably heavy.

Just like it was mentioned before, the goal of this project has changed multiple times. First there was supposed to be an external source of pressurized air to be used by the actuators, and exoskeleton solely on one side of the body, and that is the reason why the first design of the backpack in figure 8 has also space for just 4 muscles, since the actuators can operate merely in one direction, and one controlled degree of freedom requires 2 muscles, as explained in chapter 3.6.

Even if the design of the backpack in figure 8 was functional, it was still too heavy with frame weighing 1250 grams with lightening holes, to be used in an exoskeleton weared by adolescent. Where the design might have not been either so compelling in the eyes of younger person, there was space for pressure tank below the backpack and some space for controlling equipment as can be seen in the figure 8. Air pressure bottle for this project has been adapted from better known use as a filling station for guns in game called paint ball, in figure 9.

Figure 9. The power source for the actuators, Air Venturi 4500 PSI carbon fiber tank (Pyramyd Air 2016)

The high-pressure carbon fiber tank from Air Venturi weighs 1.85kg and has a diameter of 4.5 inches (11.43cm), it is 13 inches (33cm) tall from bottom to top valve. Maximum filling pressure of the tank is 4500 PSI which equals to over 300 bars and will most likely last several hours with the actuators whose maximum pressure is just 5 bars.

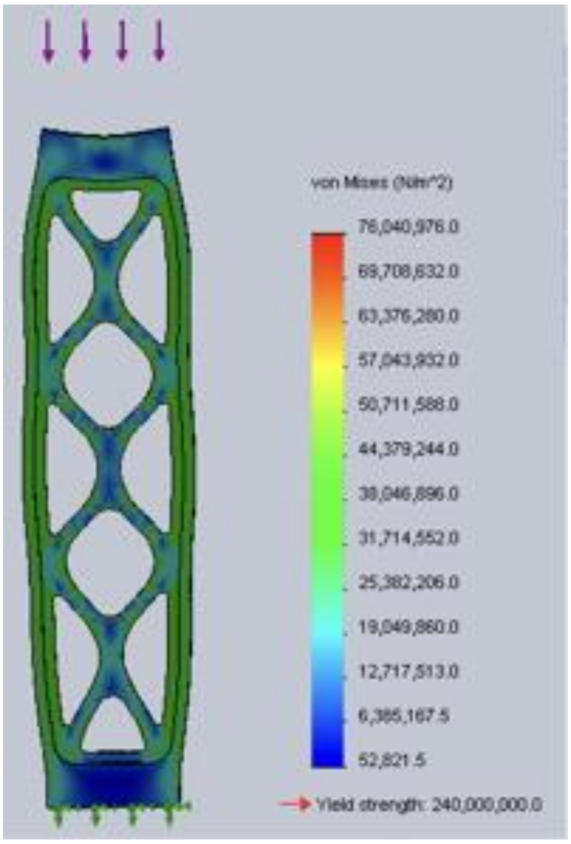

Figure 10. Horizontal plate of the first backpack model under simulation in SolidWorks Simulation Xpress Analysis Wizard.

SolidWorks Simulation Xpress Analysis Wizard can be used for determining if component can take the requirements that designer has set for it. In figure 10 can be seen horizontal plate of first backpack model, which can be seen installed in figure 8. The plate that is in the middle of the actuators would take maximum force of about 3600N from two 1800N actuators which are closest to it, therefore 3600N was selected for this simulation, simulation resulted in FoS of 3, which is 1.5 times more than necessary, meaning that this part could have been made even lighter in terms of lightening holes. Just to give some comparison, if this plate was to be made of 5052- H36 aluminum, it would weigh 540 grams without lightening holes and 130 grams with them.

Figure 11. Finding a place for the backpack in the system.

Figure 11 presents stage of the project where backpack was still just a fresh idea under development, and the backpack in this form did not make it further than this point. However, it taught many things for the author, e.g. that the muscles cannot be installed in horizontal position, because they would take too much space from back of an adolescent, other lesson learned from this, was that the structure of the backpack was simply too heavy duty, while not being convenient in eyes of younger person, and in the end, would have been also more expensive to machine all the slots and lightening holes.

The assembly in figure 11 was already converted in to more convenient form of square design from the tubular design. It still had actuators next to thigs, which were designed to be used for controlling knee joints, while PAMS in the backpack were meant to be controlling hip joints.

3.8 Finding more convenient backpack model

To achieve a lighter and more likeable design for the backpack, author had to think of something completely different and new. From idea of putting the actuators inside of a tube, developed more applicable idea of building a case around them, from very thin sheet aluminum with as broad arcs as possible, recognizing that correctly located shapes in sheet metal can make structure stronger, than point-blank sheet metal is.

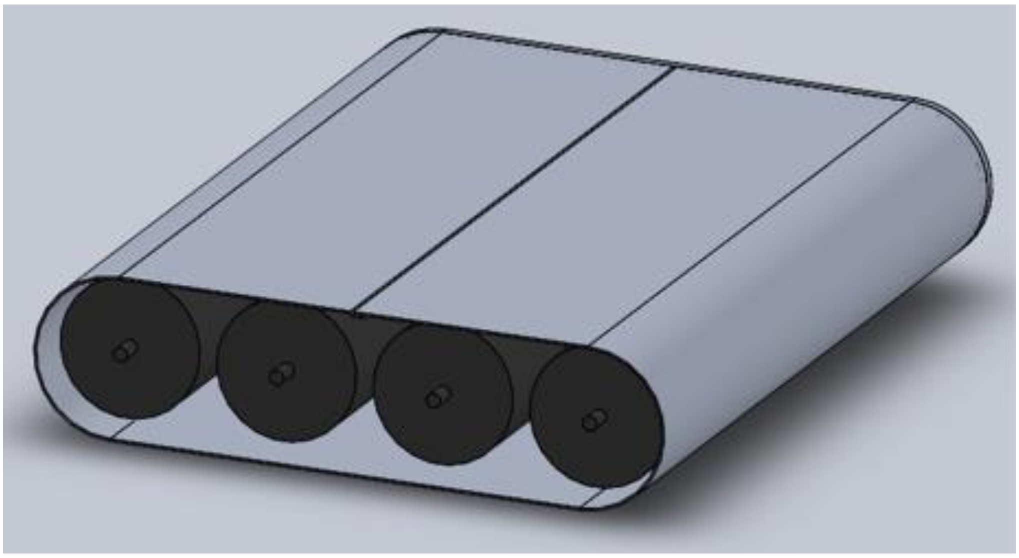

Figure 12. Four PAMs inside of an 1x4 aluminum case.

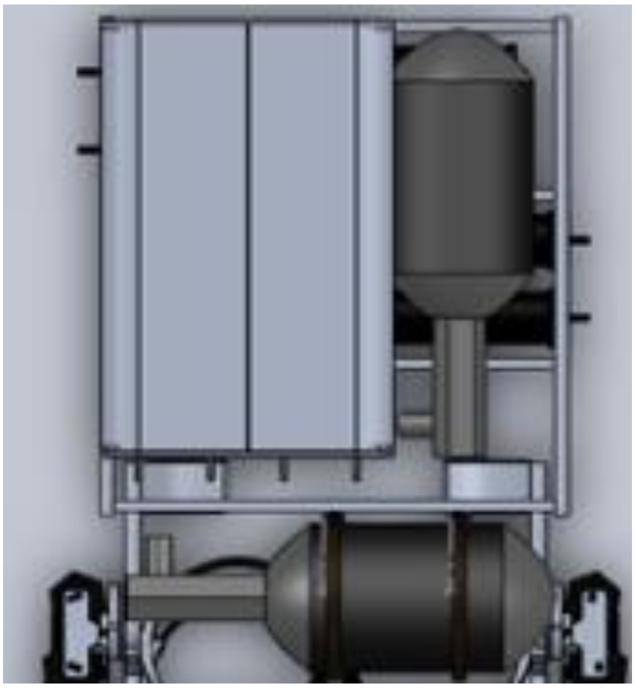

Figure 13. Comparison between sheet aluminum case and machined design.

Figures 12 and 13 reveal how much unnecessary space frames of the machined backpack take, from figure 12 it is easy to see how little unnecessary space there is around the muscles, just enough space for the muscles expand inside the case. The case was designed to be made from 0.8mm thick 5052 H-36 aluminum sheet, and the ends of the case is to be made from same alloy as the case but 8 mm thick. The weight of this case was around 800 grams without actuators.

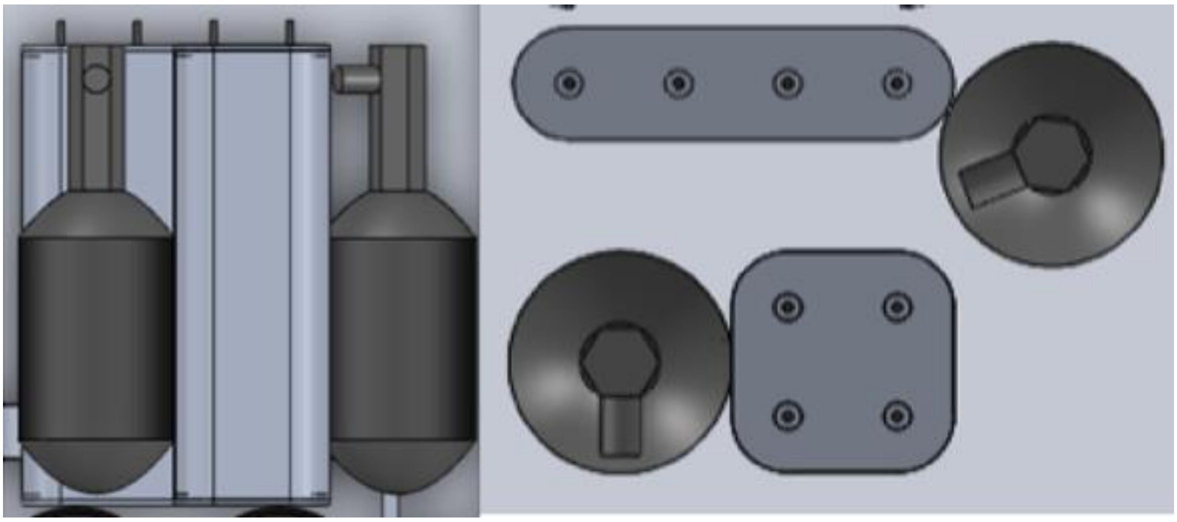

Figure 14. 1x4 case in comparison with 2x2 case. On the left from lateral perspective and on the right from above.

Figure 14 above presents 1x4 case and 2x2. Several models of different components and comparisons between them had to be made in process of finding most convenient design for this project. While 1x4 model brings weight as close to body as possible, its design is not matching so well with the tank, and it is 80 grams heavier than 2x2 model. These being the reasons why 2x2 model was selected.

3.9 Connecting backpack with rest of the system

Until this point the backpack was not connected with rest of the system, and it was still a question if those parts should be connected mechanically or not. Decision of using Bowden cables for transmitting force from the actuators to pulleys did not leave much options, as disconnecting and connecting cables every time with the suit when it is worn, would have been too time consuming, and in the end, it is most likely better to have all parts connected, in this way forces transmitted to hip pulleys, support can be divided to upper trunk too.

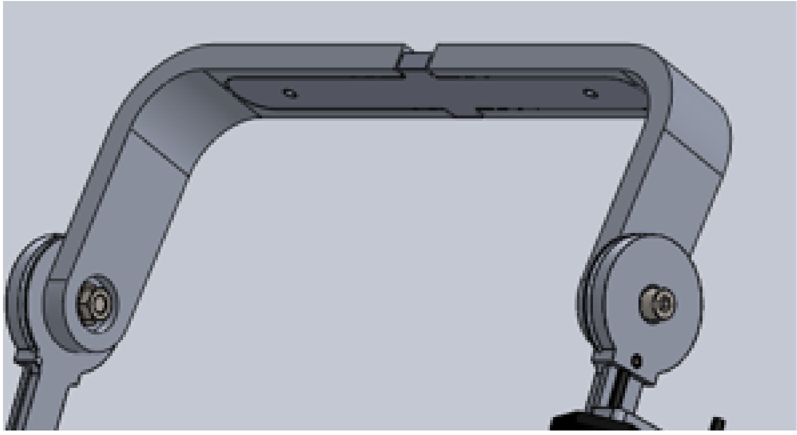

Figure 15. The joints for connecting the backpack and legs together.

Design of NASA’s X1 exoskeleton design inspired author in creating joints that can be seen in figure 15. The joints at this point were adjustable solely in width, the bending radius as seen in the figure might seem large but per The Aluminum Association the 90-degree cold bending radius must be 4.5 times larger than thickness of this alloy, which is 12 mm. Pulleys were integrated in frames which extend downwards next to thigh, however this solution did not pass simulations as it made frame too weak and limited hip flexion to just 90 degrees. (Cumberland 2016)

Figure 16. The actuator case and the tank connected to the system with 3mm sheet aluminum.

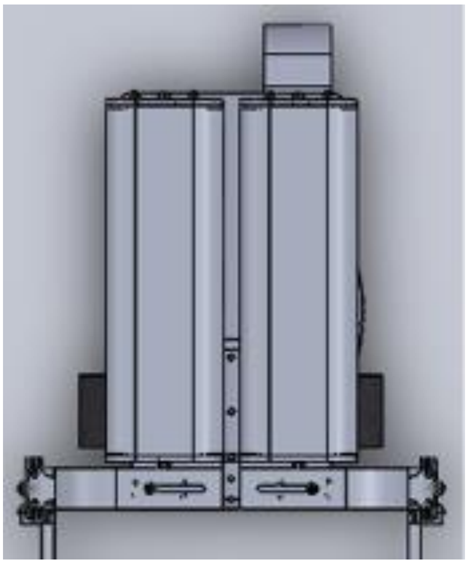

Figure 17. All 8 actuators in backpack, inside of two cases.

Figure 16 shows how 4 actuators and the tank look like balanced together in the backpack, however this idea had to be abandoned as it was decided that all muscles should be moved to backpack. In figure 17 can be seen how 2x2 design of the cases was easy to double to fit 8 PAMs, also in this time it had been decided that power source for the actuators was going to be external, explaining removal of the tank from the design.

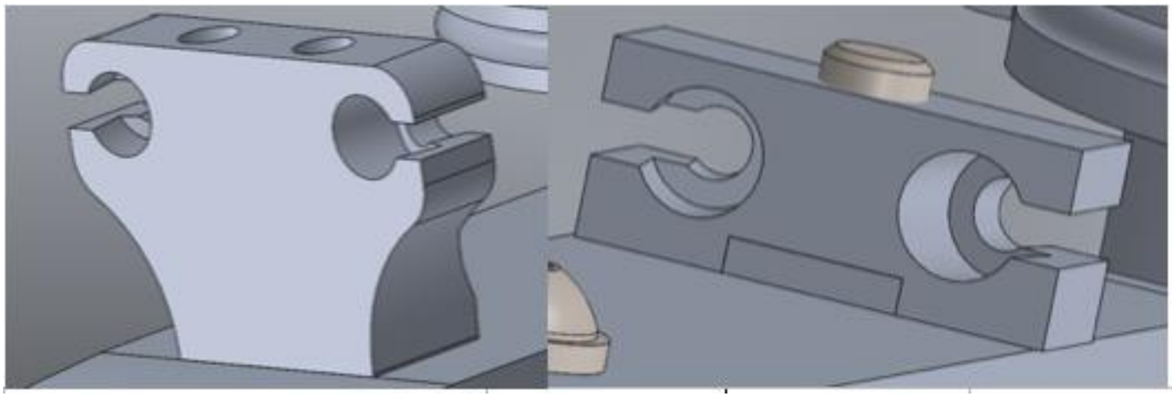

Figure 18. The brackets for attaching the Bowden cables close to pulleys. The bracket on the left is for hip joint and on the right for knee joint.

With today's programs, it is unbelievably easy to create photorealistic figures of components and even whole systems under design, which helps finding possible problems, and can give a glance of how the final product is going to be. Following figures, 19 and 20 suggest what is the finished LEE going to look like.

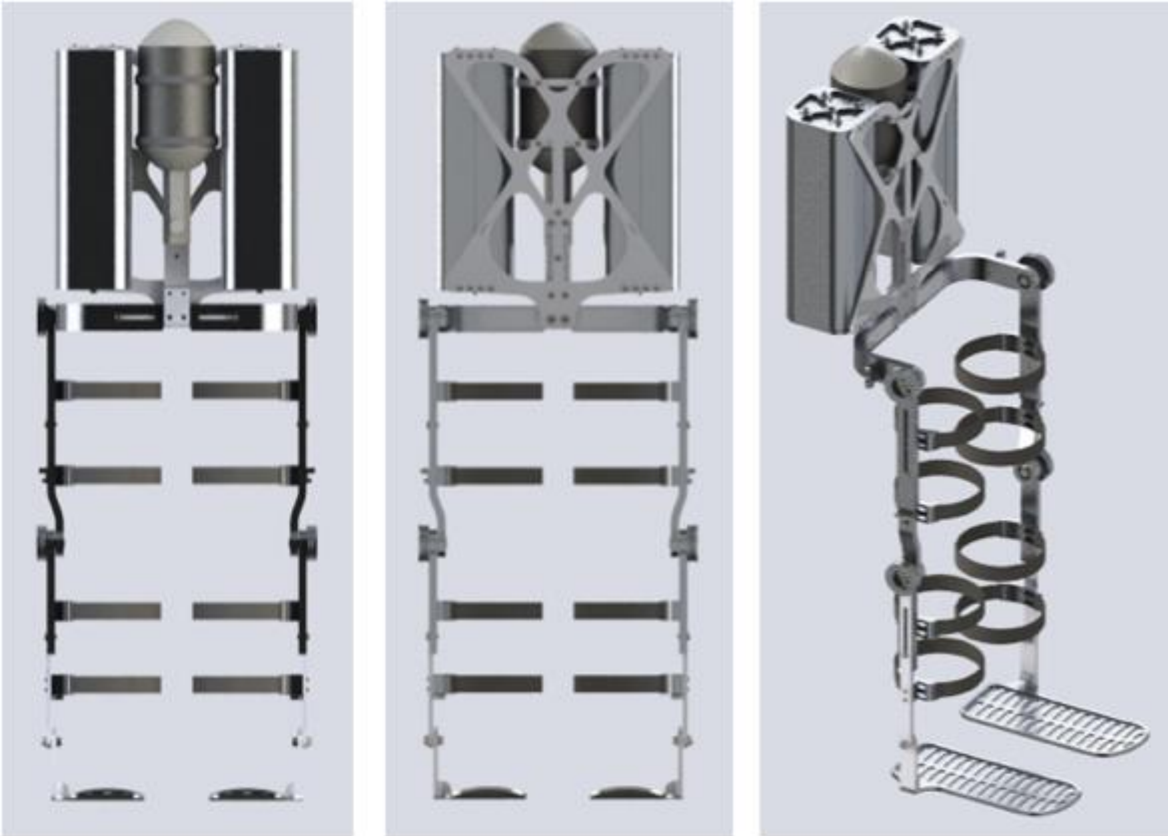

Figure 19. Rendered figures of the almost complete exoskeleton.

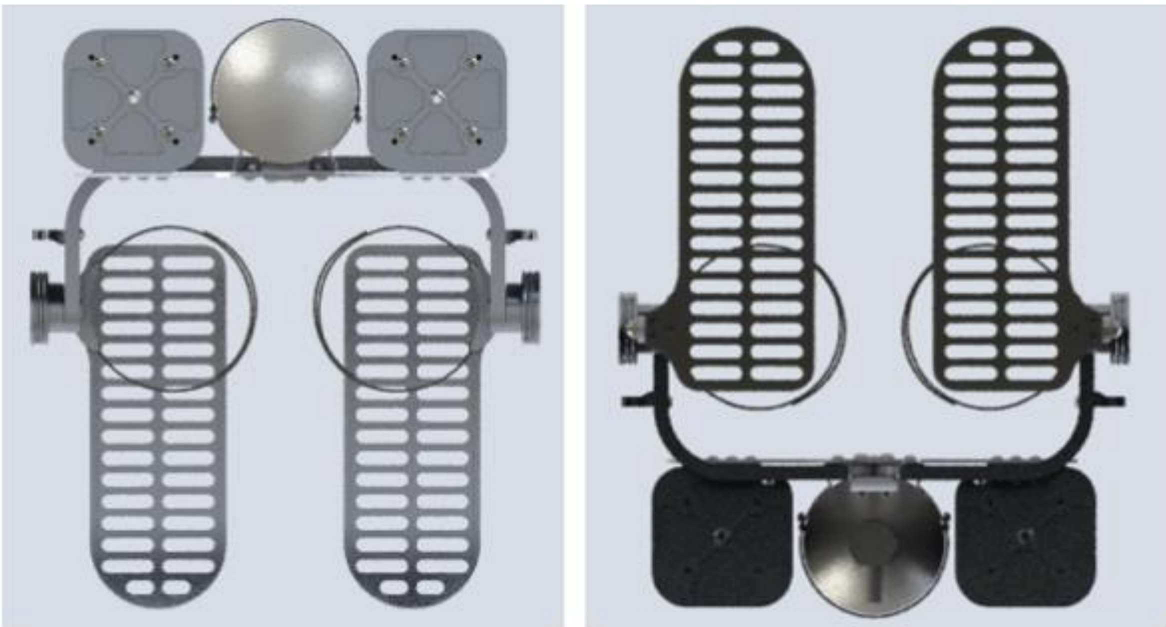

Figure 20. Rendered figures of the exoskeleton, from above and below.

From figures 19 and 20 it is easy to find some differences with the previous design. Foot part have been added to the design, assisting patient to keep balance while practicing gait with a help of a torsion spring which is to be installed around the axle of foot joint in that way that it will help returning foot in 90-degree angle in relation to shank, the foot part will also help carrying weight of the backpack and rest of the system, by transferring it straight to ground. Another main difference when compared to previous designs are hidden joints (figure 21) added to points where legs and backpack are connected, making abduction and adduction possible while enabling smoother gait.

3.10 Contact points in system

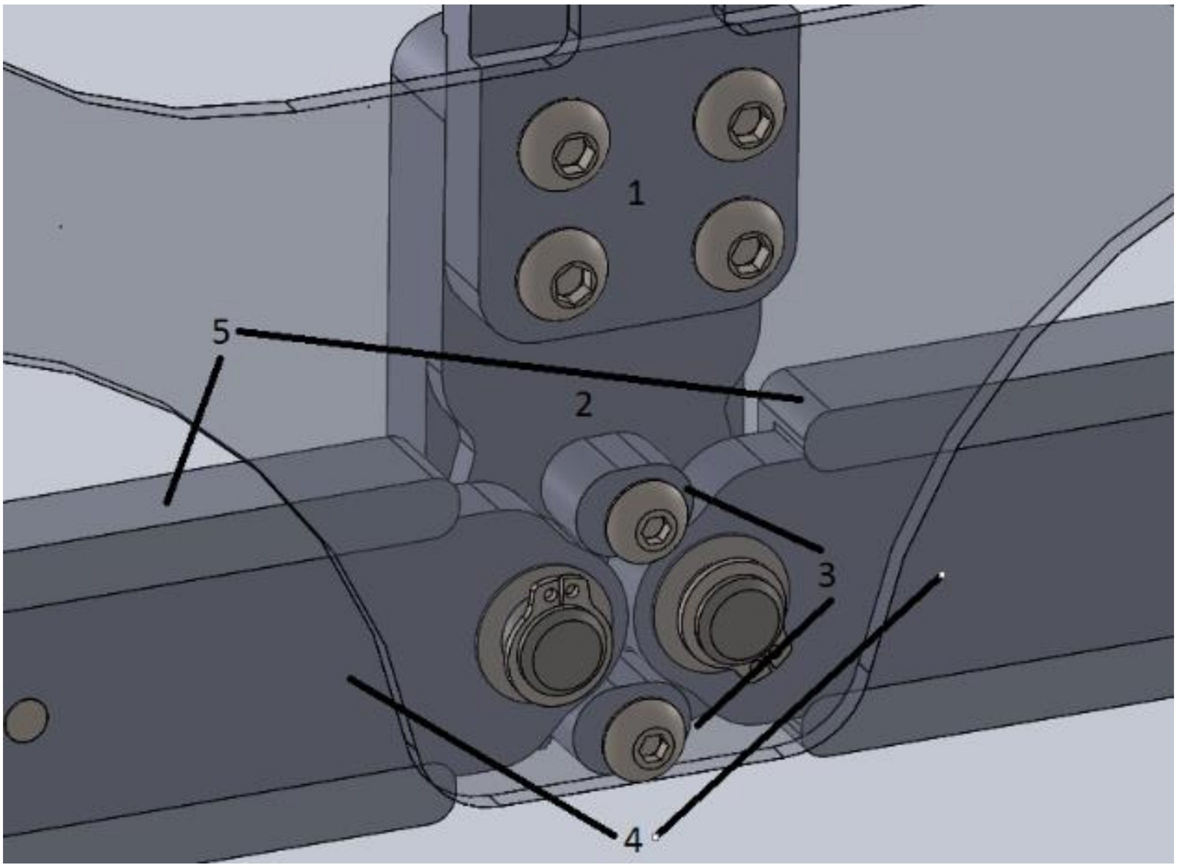

Figure 21. Point of contact below backpack.

Figure 21 above explains purpose of different parts in exoskeleton. Parts 1 and 2 are made from different pieces allowing thinner material thickness, and therefore less waste than from machining from one piece, number 3 refers to guards limiting abduction and adduction movement to 10 degrees, number 4 refers to joints attached to number 2 by 10mm axles, the joints are sandwiched with 0.5mm shim plates on both sides to minimize friction, and holes for axles are coated with Teflon eliminating need to use bearings in this uncontrolled joint which moves in comparably slow speeds, number 5 refers to joints connecting hip joints, they are also allowing width adjustment of the waist by sliding over parts referred to number 4.

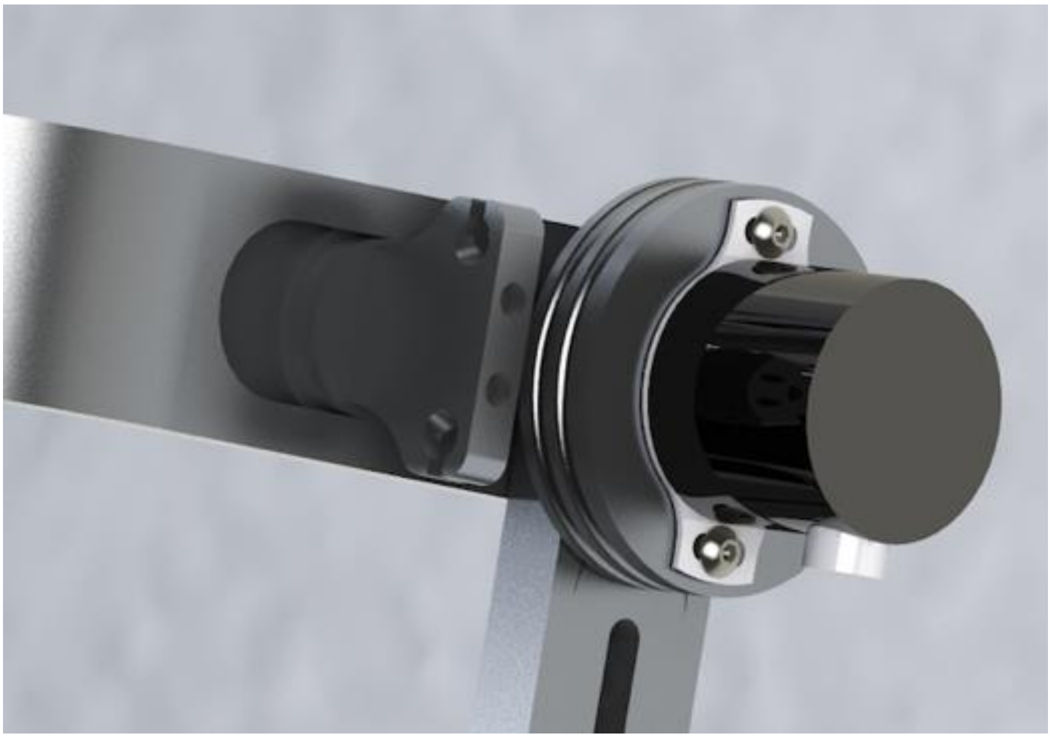

Figure 22. Adjustable hip joint with angle encoder attached to pulley.

Figure 23. Shaped axle head and perfectly fitting machined slot for preventing twirling and making it possible to get reliable readings from angle encoder and sinking it to frame allows adjustment of the hip.

In figures 22 and 23 can be seen adjusting mechanism for the distance between outermost part of bottom and the middle of the hip joint. The figures show as well optical incremental encoder GH38 produced by CALT, which has a resolution of 2500 PPR, that will be used for tracking movement of the hip joints and knee joints. The maximum speed of the encoder is 6000 rpm and location of the pulley can be tracked every 0.14 degrees or 7 times in one degree, proposing it will surely be accurate enough for its purpose. (Aliexpress 2016)

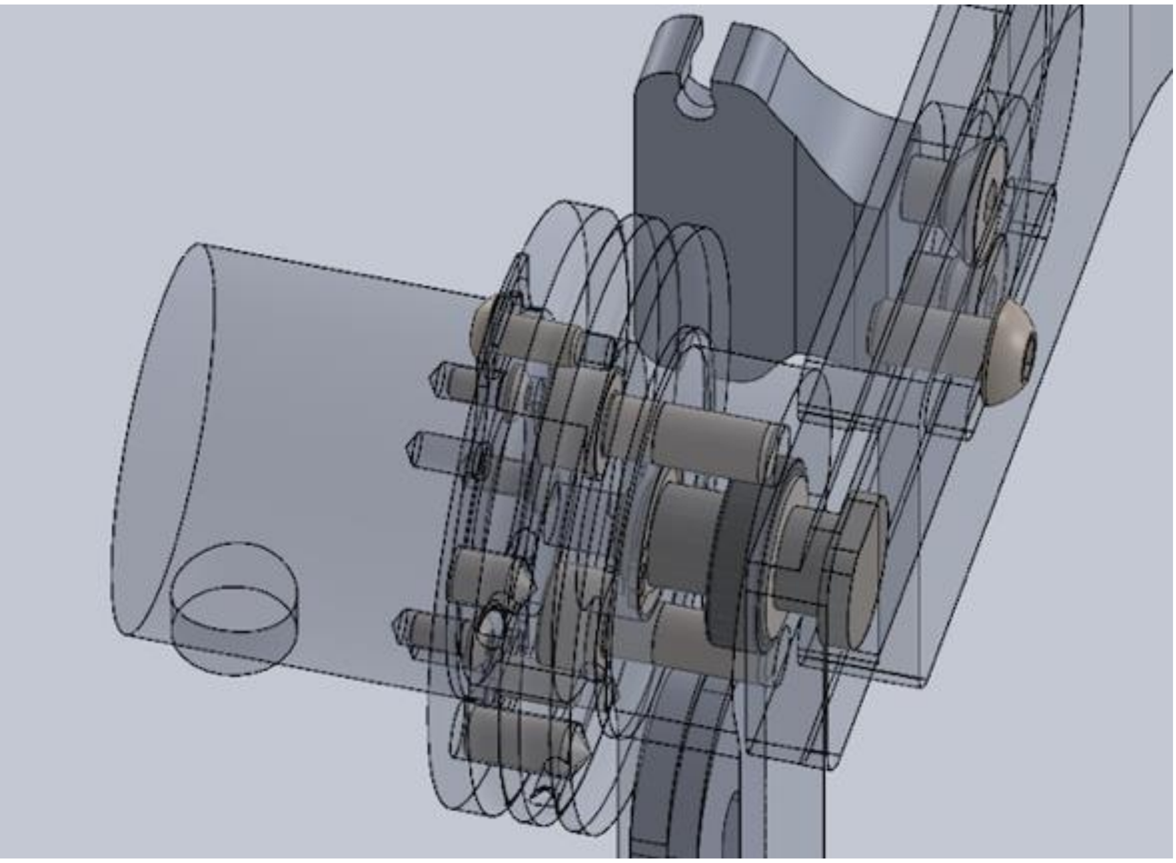

Figure 24. Partly transparent figure of the knee pulley explains operating principle in more understandable way.

One of the major changes on this latest design, when compared to design in figure 6 was change from using two ball thrust bearings, to using just one single row deep groove ball bearing. The change of bearing type allowed one other big difference in design, since the bearings does not need to be compressed anymore to work, the bolt axle was replaced with more practical and bigger axle, which is unable to turn due to its design, and therefore the head of the axle can be used for measuring angle difference in respect to thigh frame. The axle is simply locked in lengthwise direction with a retention ring. There is a shim plate between bearing and sliding frame preventing touch between them and therefore minimizing friction. Next to pulley can be seen the Bowden cable bracket, which is attached to the sliding frame with two M6 countersink bolts, making it possible to slide inside slot machined to hip joint.

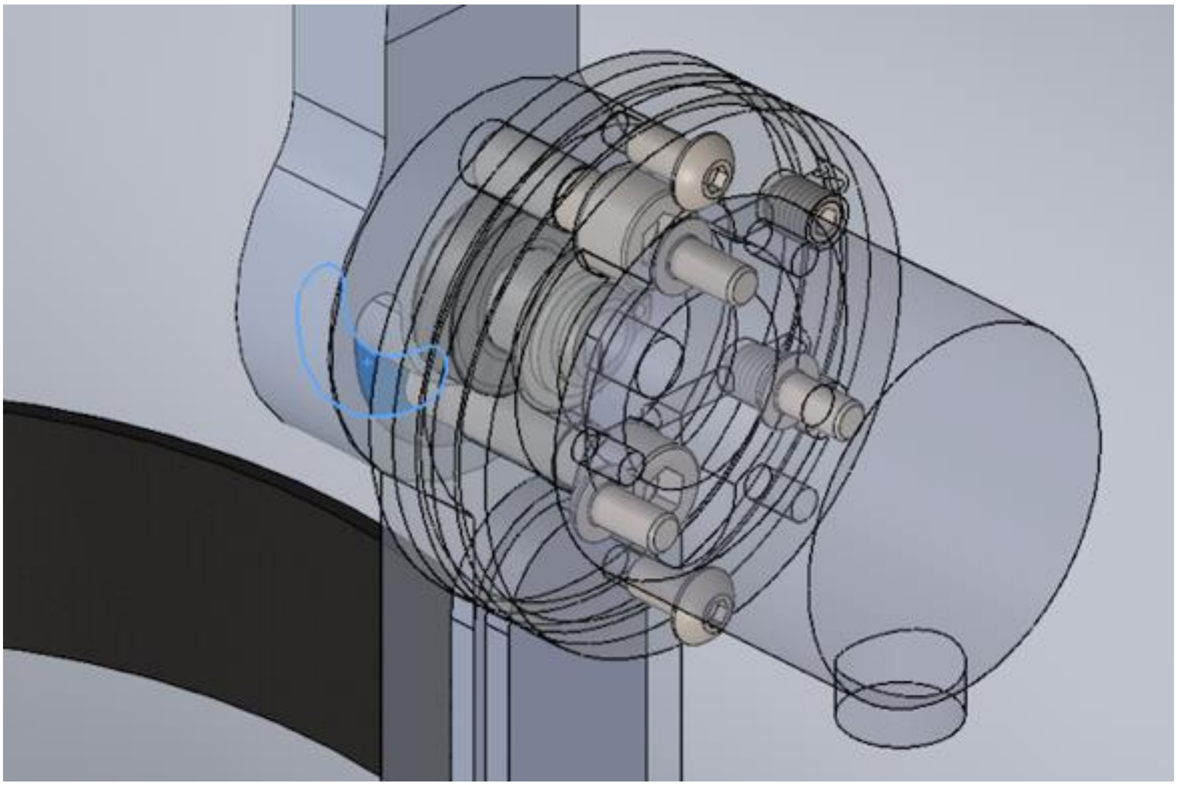

Figure 25. Partly transparent figure of the knee joint.

Figure 25 shows partly transparent figure of the knee joint, the design of this joint is very like the hip joint, but with one major divergence, due to knee and its vulnerability there must be a limiter preventing higher angles than 180 degrees, to prevent very undesirable incident in figure 26. Machined slot in the inner frame works as a limiter, slot is highlighted in the figure 25, as another part of the limiter works a M6 bolt used for attaching pulley to the outer half of the frame. The pulleys attached to the knee joint are dimensioned thus, that the actuators will use all of their potential length, and therefore should not be able to allow such event, anyhow e.g. too high pressure might cause muscle to contract excessively, consequently precautions need to be taken.

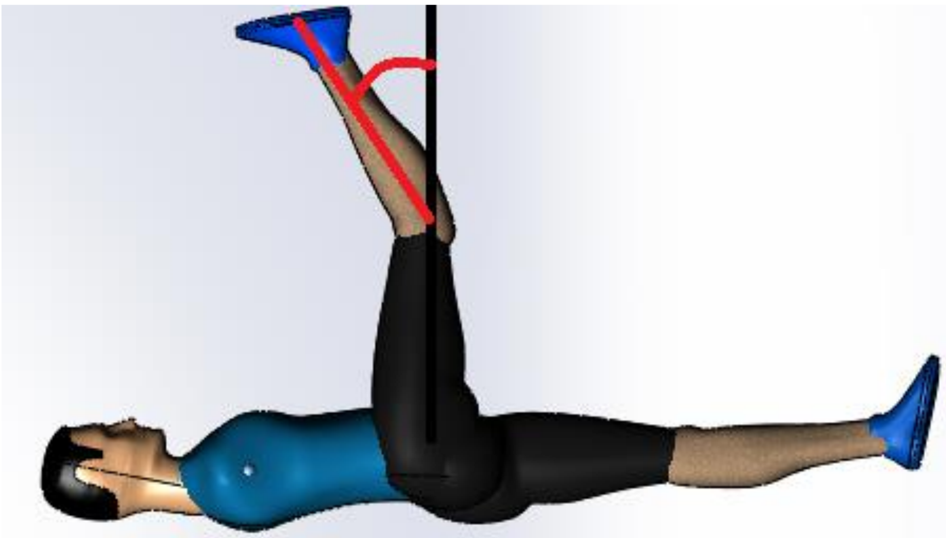

Figure 26. Undesirable event of the knee joint.

Figure 27. The foot part in closer examination.

Just like mentioned before, foot part (figure 27) was added to assist patient to keep balance during practicing gait, while carrying some of the weight of the system. Foot part is attached to upper shank frame with similar 10 mm axle as in previous joints, without bearing, and the axle hole will be coated with Teflon as abduction/adduction joint to minimize friction. Figure 27 shows rendered model of the foot, where torsion spring is installed around the axle, other end of the axle is attached with bracket and the axle is slotted so that other end of the curved spring can be installed into that slot. Foot will be attached to the system with band tied to the pins showed in the figure. 2 mm thick rubber shown in the figure will be attached to the bottom with adhesive, to absorb shocks and to prevent sliding on slippery surfaces.

3.11 Final design

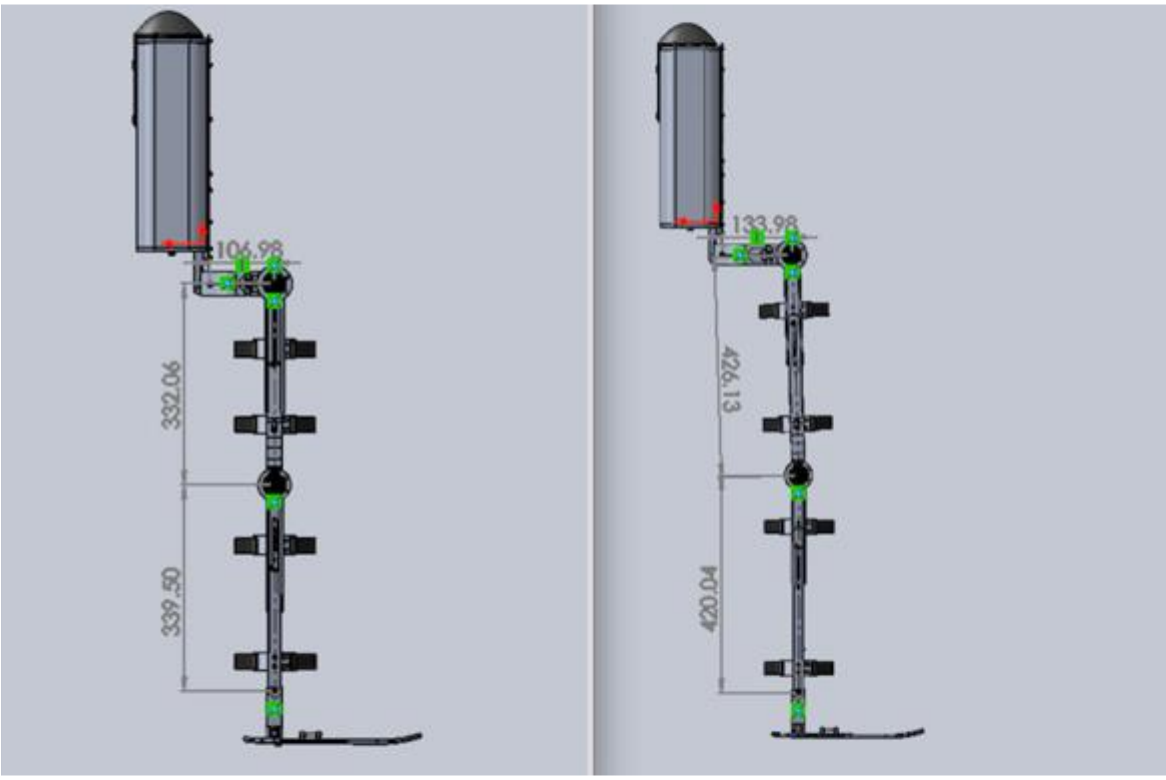

Figure 28. The adjustability range of hip, thigh and shank. On the left side, minimum lengths and on the right side maximum lengths.

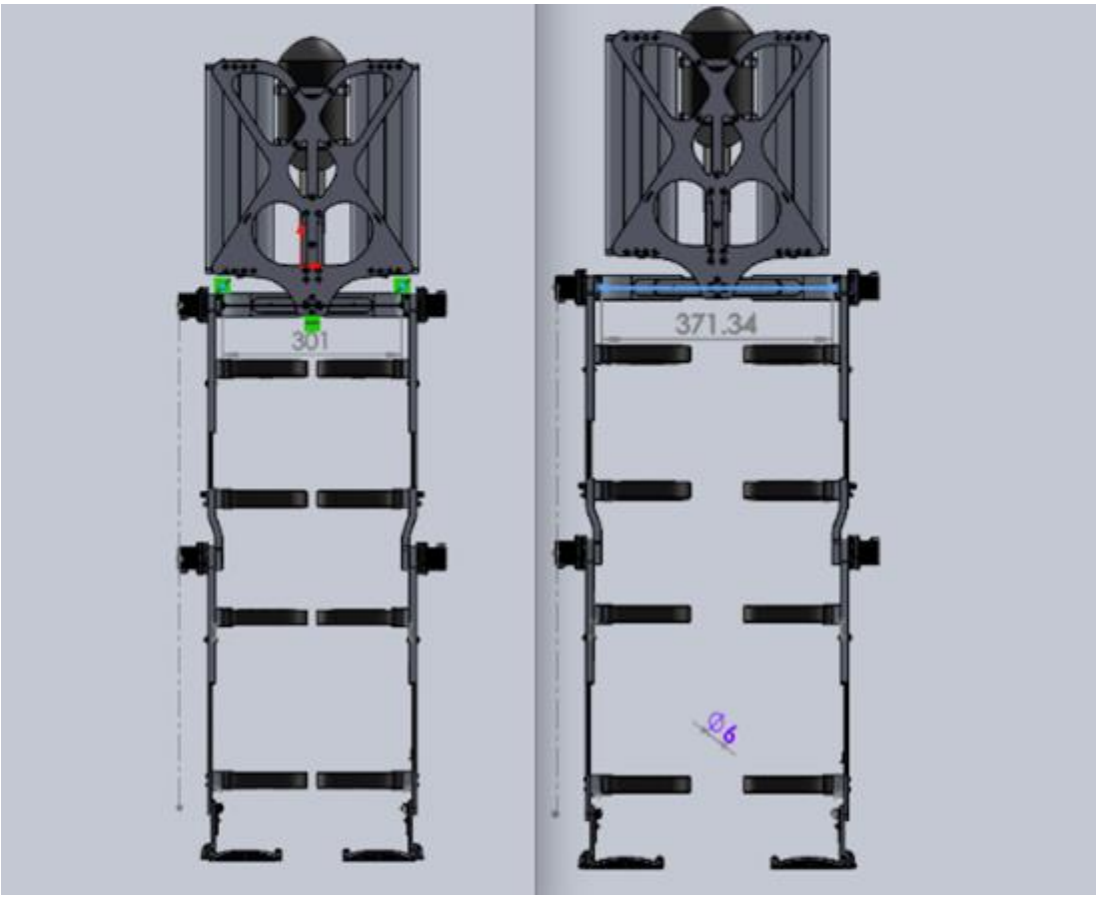

Figure 29. Adjustability range of waist width. On the left side, minimum width and on the right side maximum width.

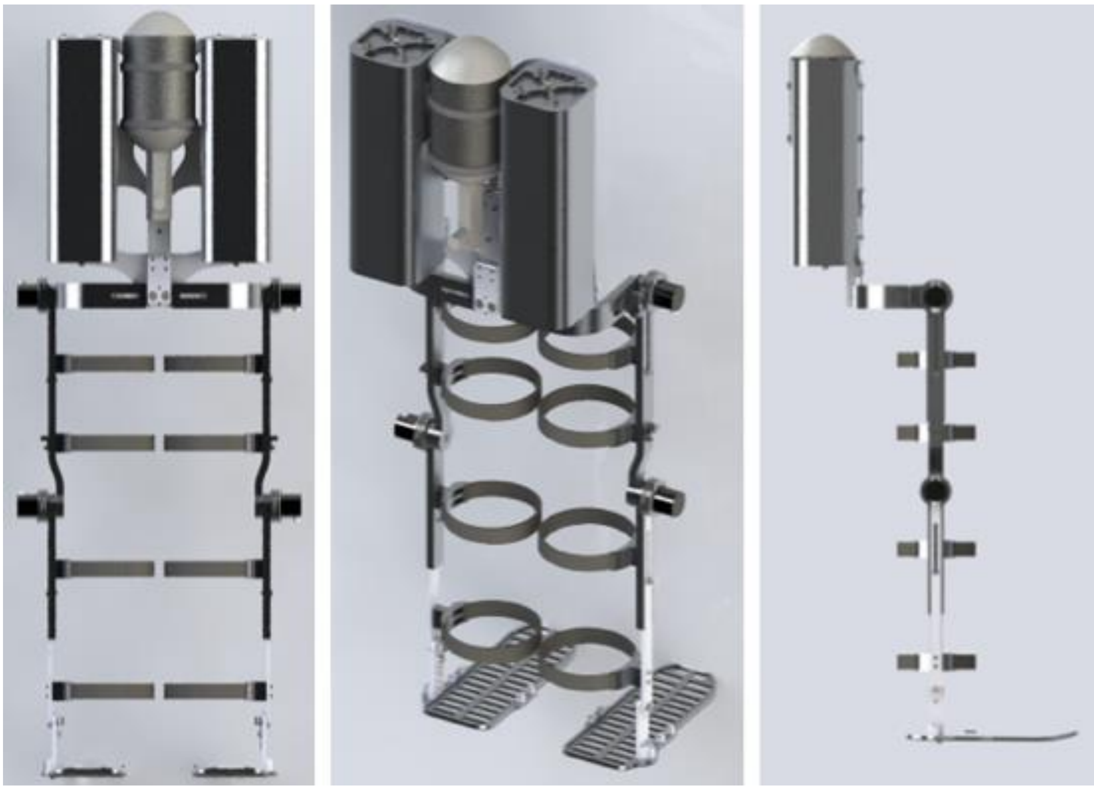

Figure 30. Rendered figures of the finished exoskeleton.

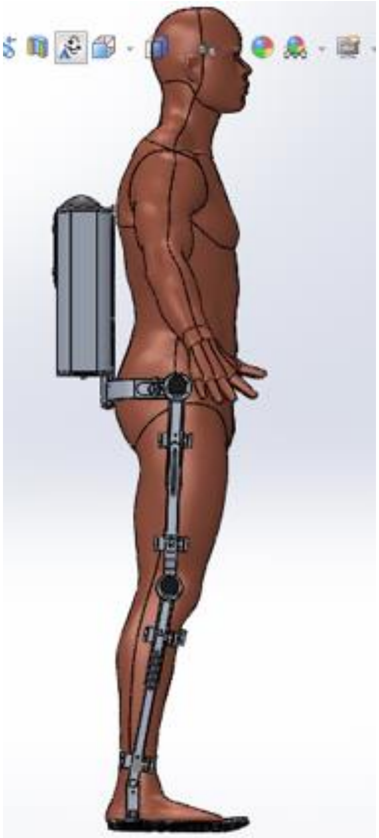

Figure 31. View from right side of the exoskeleton fitted for average Peruvian.

Figure 32. View from front side of the exoskeleton fitted for average Peruvian.

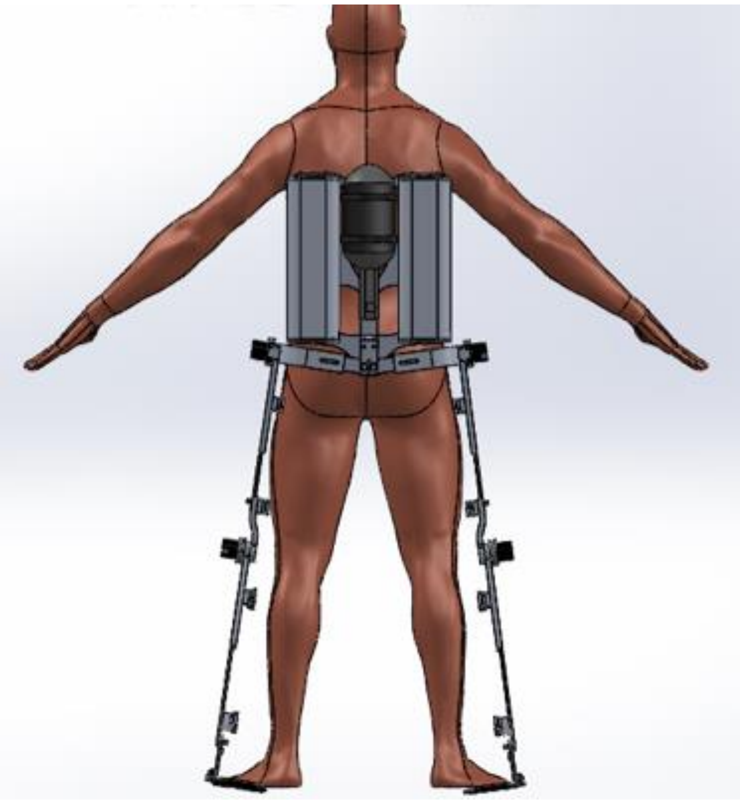

Figure 33. View from behind of the exoskeleton fitted for average Peruvian.

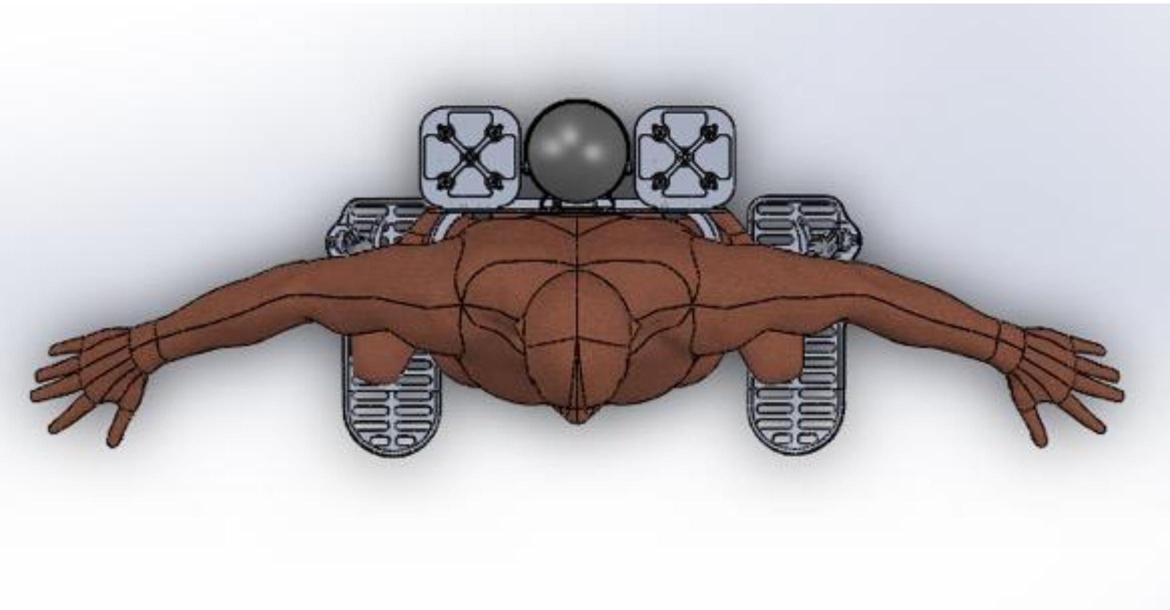

Figure 34. View from above of the exoskeleton fitted for average Peruvian.

Human model in the figures above has twisted legs being the reason why it does not fit perfectly in its position. Anyhow figures show that the exoskeleton is fitting for the human model perfectly.

4 SUMMARY

The purpose of this thesis was to create a working 3D model of a lower extremity exoskeleton using SolidWorks program, for the rehabilitation of patients with hemiplegia. The exoskeleton is a prototype and it will be used for research at Piura campus of UDEP, once it has been manufactured.

Engineering of the thesis started first by studying the already existing different kind of exoskeletons with different kind of uses. The model changed multiple times during the process, from a relatively simple 2 DoF rehabilitation device used for sitting or recumbent patients attached to one side of the body, to a comparably complicated 8 DoF system that is used for rehabilitating the gait of hemiplegic patients attached around the patient’s both legs and the upper body.

Designing of the system did not always go as planned and the received information on how the device should be and what kind requirements it should meet, were received gradually as the project progressed. If the author would have known the goals right from the beginning of the project, many unnecessary steps could have been avoided and the project would have likely progressed a lot smoother than it did and possibly been finished earlier. Anyhow, all those unnecessary and necessary steps have taught the author multiple valuable lessons, especially on using SolidWorks.

In the future when the exoskeleton has been manufactured, assembled and worn by a patient, it can be evaluated in terms of functioning, suitability and usability for the patient. Afterwards when those studies have been made, the final model can be created based on this prototype.

Per the initial plan, the 3D-model of the LEE was to be transferred into the Mechatronics Concept Designer (MCD) of SeAMK for further examination of the different powers and trajectories, and afterwards the aim was to control that 3D-model with the OPC-link. Anyhow the project’s first parts grew so extensive that it was found needless by the supervisor, Markku Kärkkäinen, to increment it per the initial plan, as it already met the requirements set for a thesis.

Since the moment that this project was offered to the author by professor Eliodoro Carrera Chinga of UDEP, it has remained extremely interesting and educational during the whole-period of running it. When the thesis was started, the author did not have very much knowledge of exoskeletons or where and why they are being used, which made the project challenging and required a lot of research to be made.

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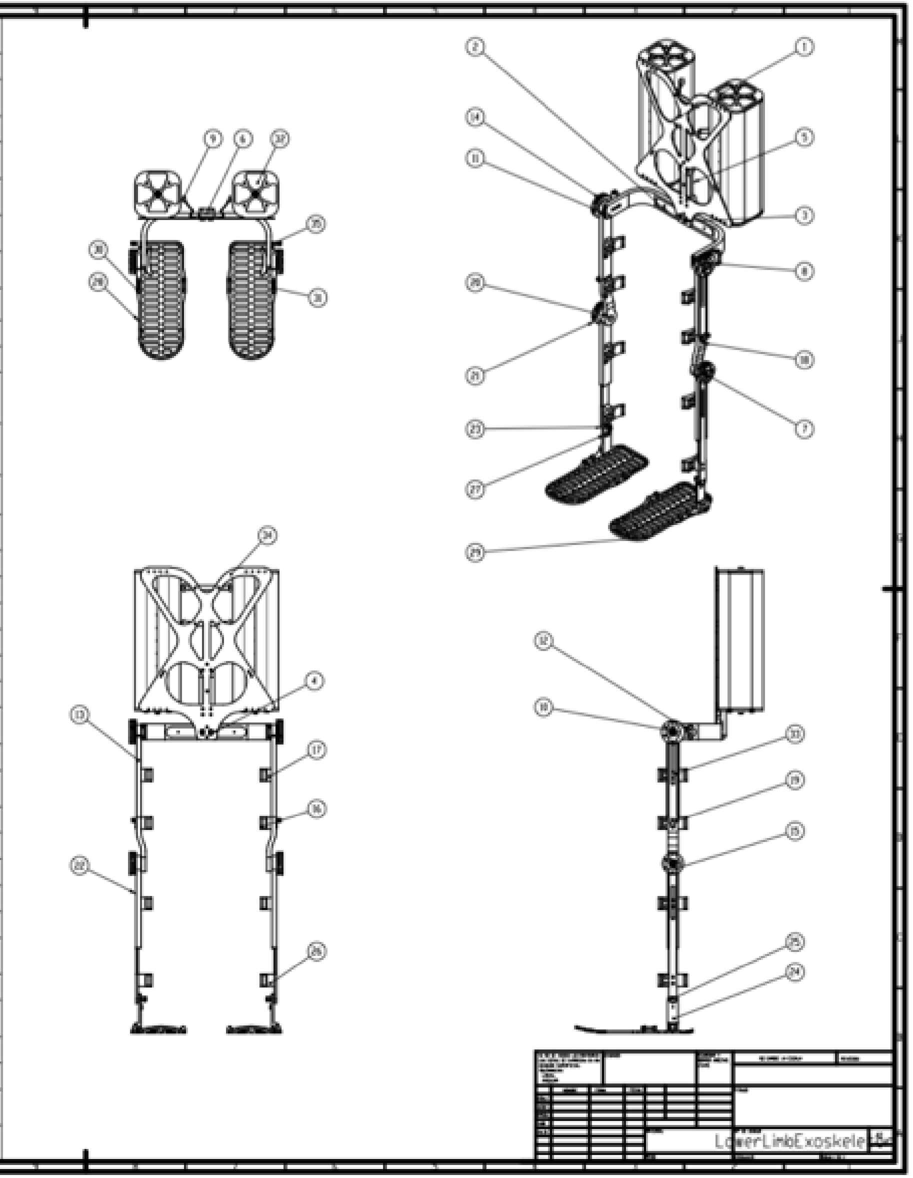
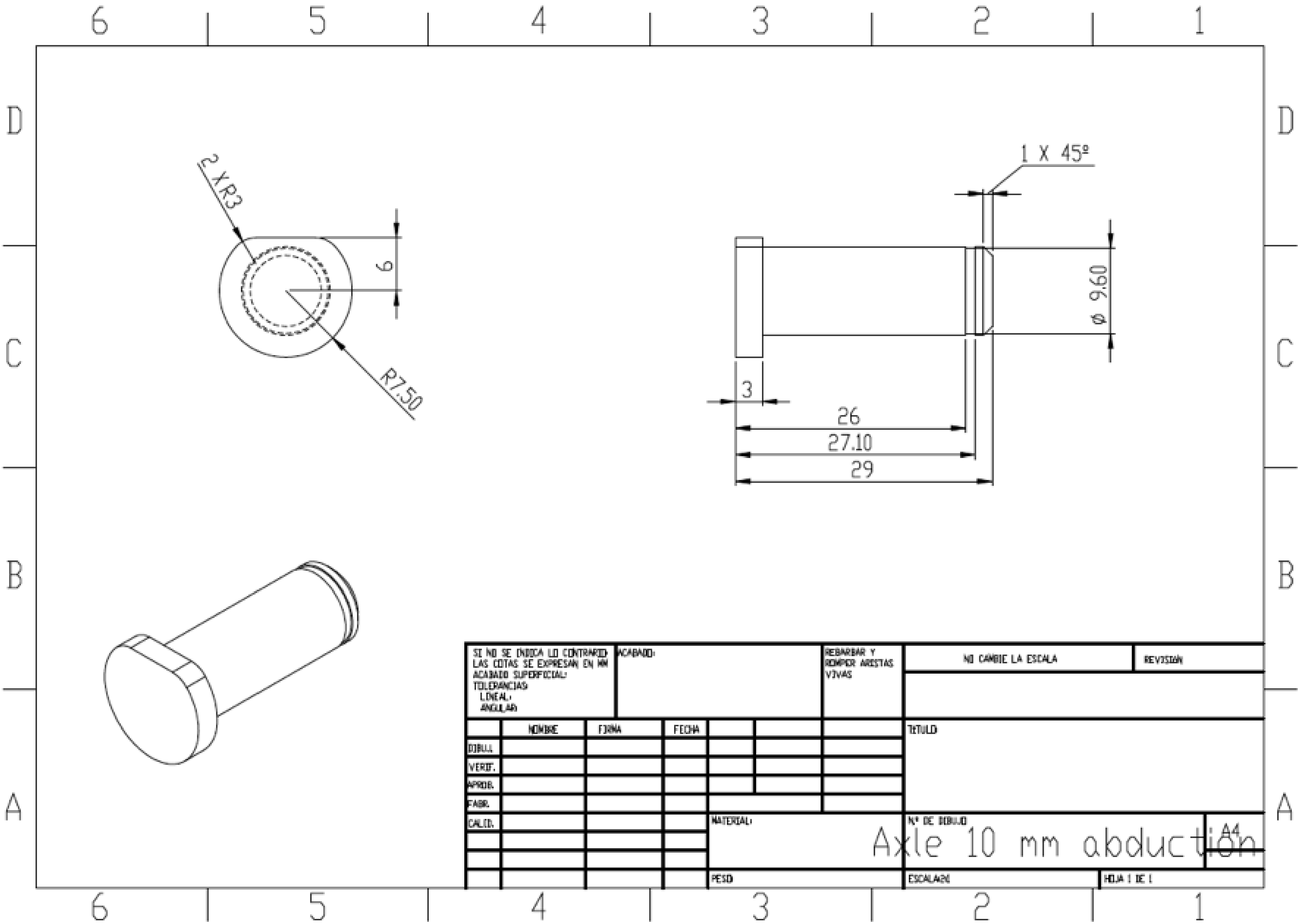
APPENDICES

APPENDIX 1. Drawings of the LEE

APPENDIX 1. Drawings of the LEE

Nº DE ELEMENTO	Nº DE PIEZA	CANTIDAD
1	Band 13	2
2	Turning middle joint 11	2
3	Buffer for middle joint	2
4	Axle 10 mm abduction	2
5	Turning web stiffener 12 upper	1
6	Turning web stiffener 13 lower	1
7	circlip for shafts normal_din	6
8	shim-support ring2_din	15
9	Clip 10	4
10	Axle 10 mm waist 11	2
11	Waist joint to backpack 12 with hip slide behind	2
12	Waist joint to backpack 12 with hip slide front	2
13	Square waist joint 40 mm 17 single bearing	2
14	Joint pulley 20 two grooves 59 mm	2
15	Encoder bracket	4
16	BAND SUPPORT NEW	8
17	Spacer 11	6
18	Wire guide 10	2
19	Wire bracket 10	2
20	Axle 10 mm knee 11	2
21	Joint pulley 21 two grooves	2
22	Square shank joint 13	2
23	Lower shank frame 14 with shoe	2
24	Shoe joint 13	2
25	Axle 10 mm foot 15	2
26	Spacer +6 12	2
27	Spring lock 10	2
28	Shoe aluminum 13	1
29	Shoe aluminum 13 left	1
30	Shoelace bracket 10	8
31	parallel pin unhardened_iso	4
32	Backpack build 1 2x2	2
33	Square knee joint 17	2
34	Web spine 10 turning middle	1
[illegible]	[illegible] pulley	2

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29
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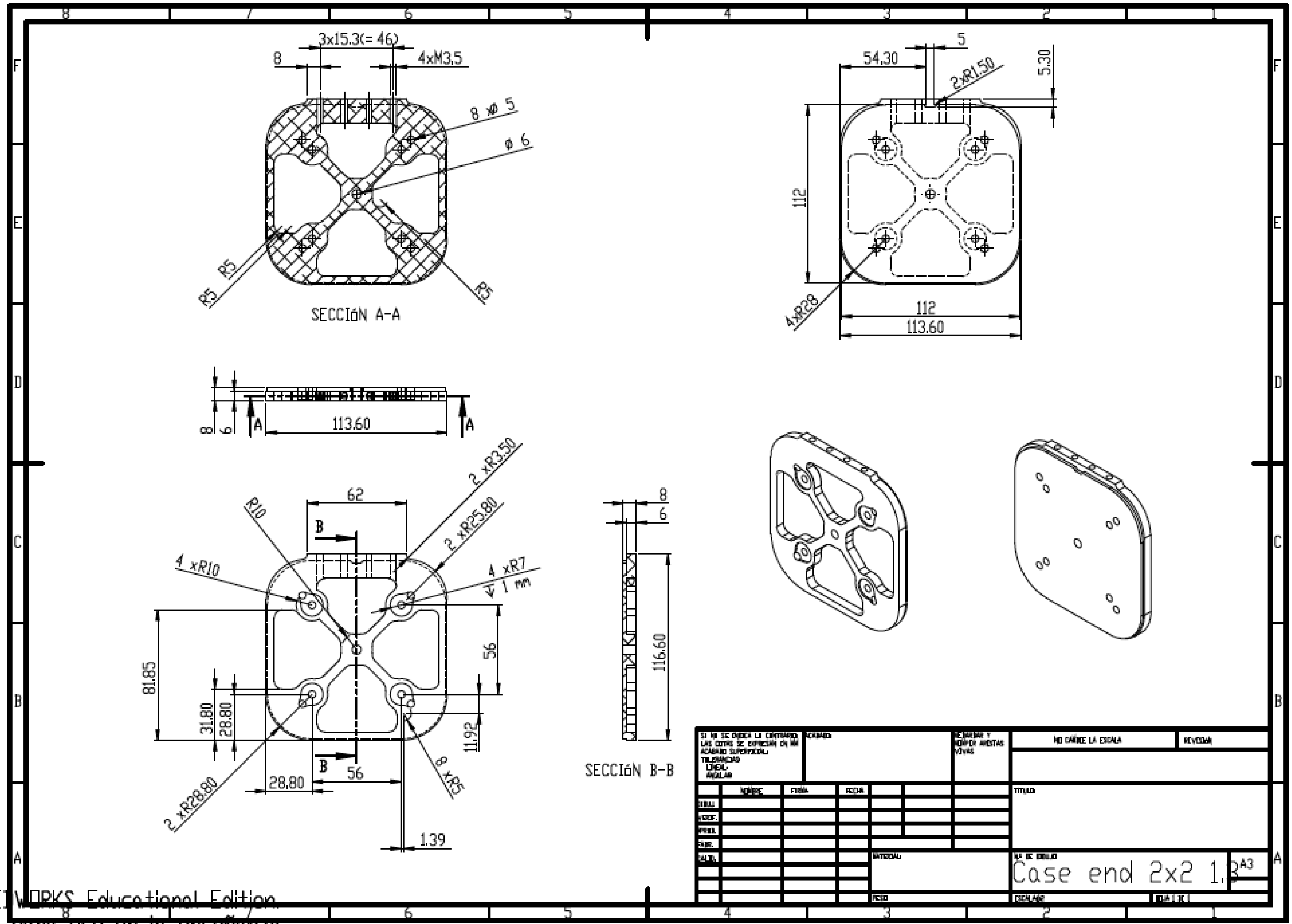
3x15.3(= 46)
8
4xM3.5
8 ⌀ 5
⌀ 6
R5
R5
R5
SECCIÓN A-A
54.30
5
2xR1.50
5.30
112
4xR28
112
113.60
8
6
A
113.60
A
62
R10
2 xR3.50
2 xR25.80
B
4 xR10
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↓ 1 mm
56
81.85
31.80
28.80
11.92
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28.80
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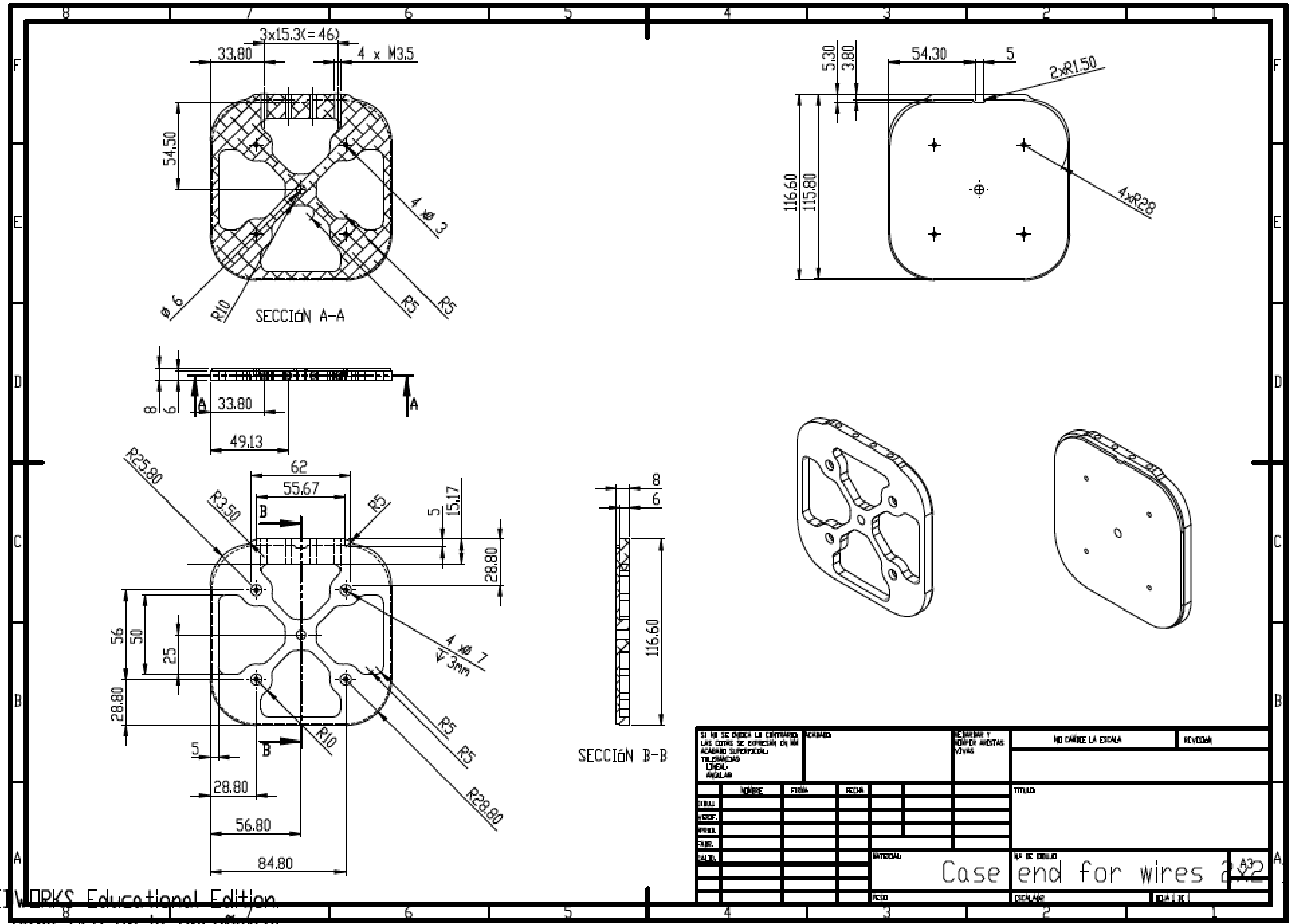
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49.13
R25.80
R3.50
62
55.67
R5
B
5
15.17
28.80
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28.80
4 x ø 7
↧ 3mm
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R10
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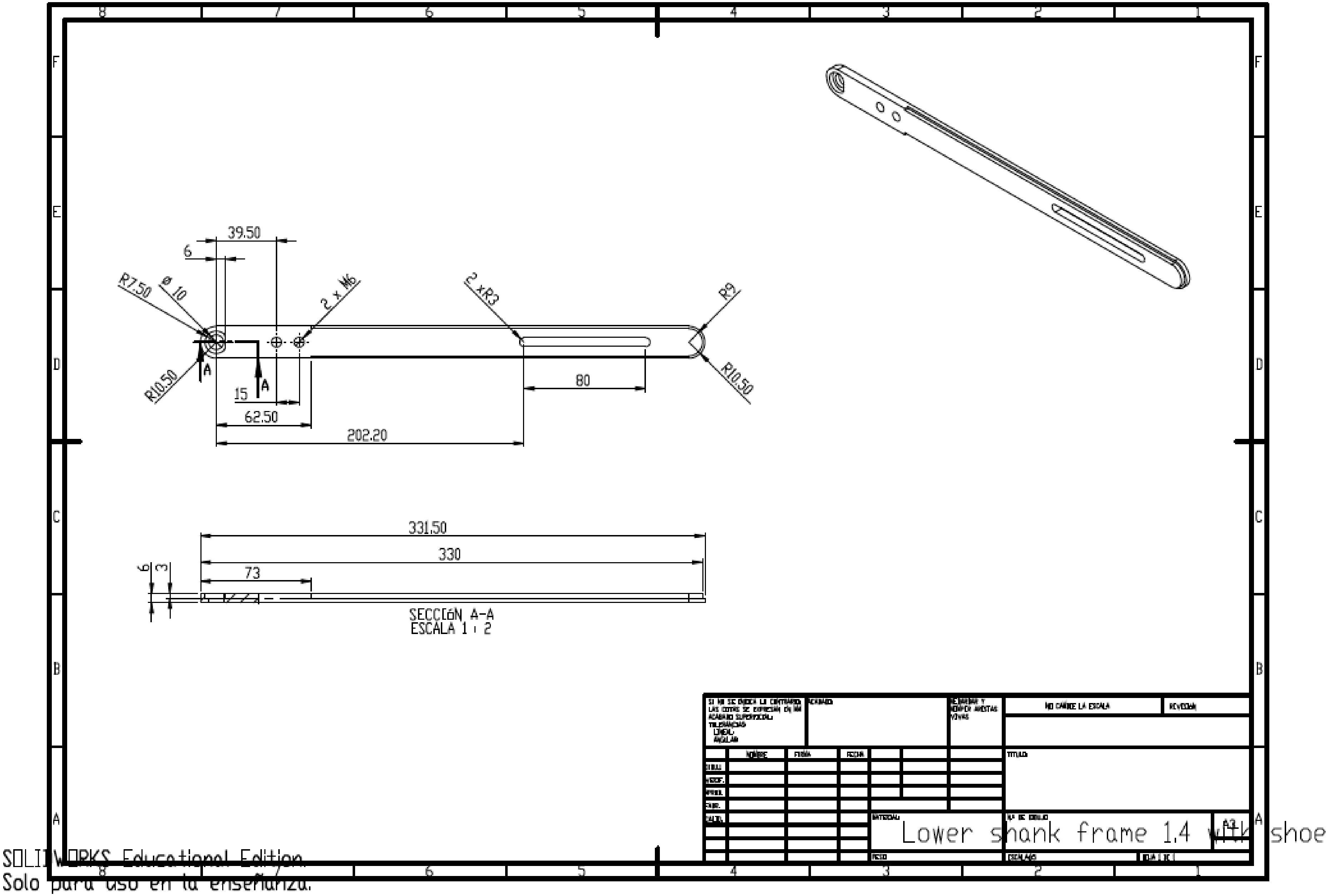
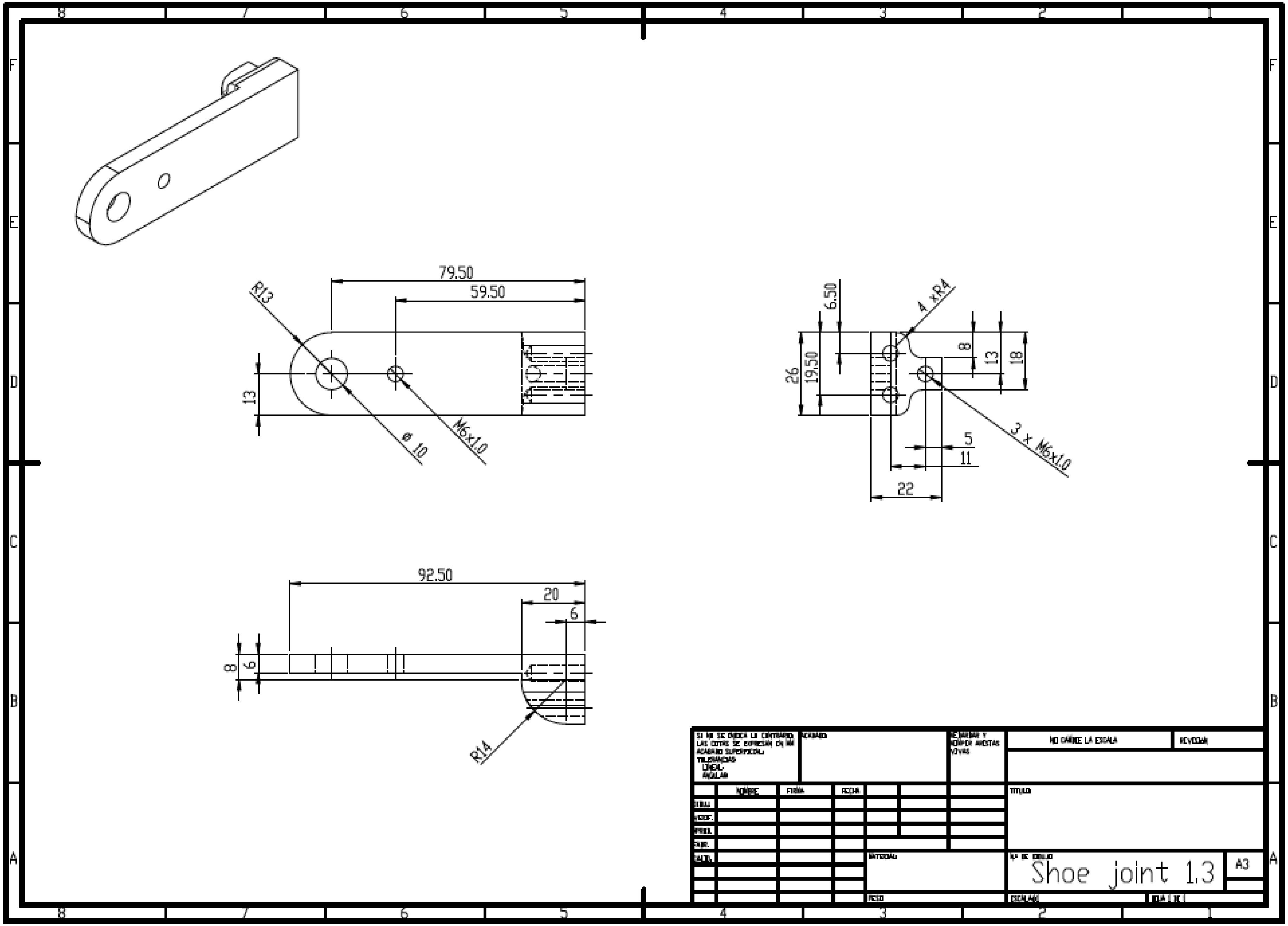
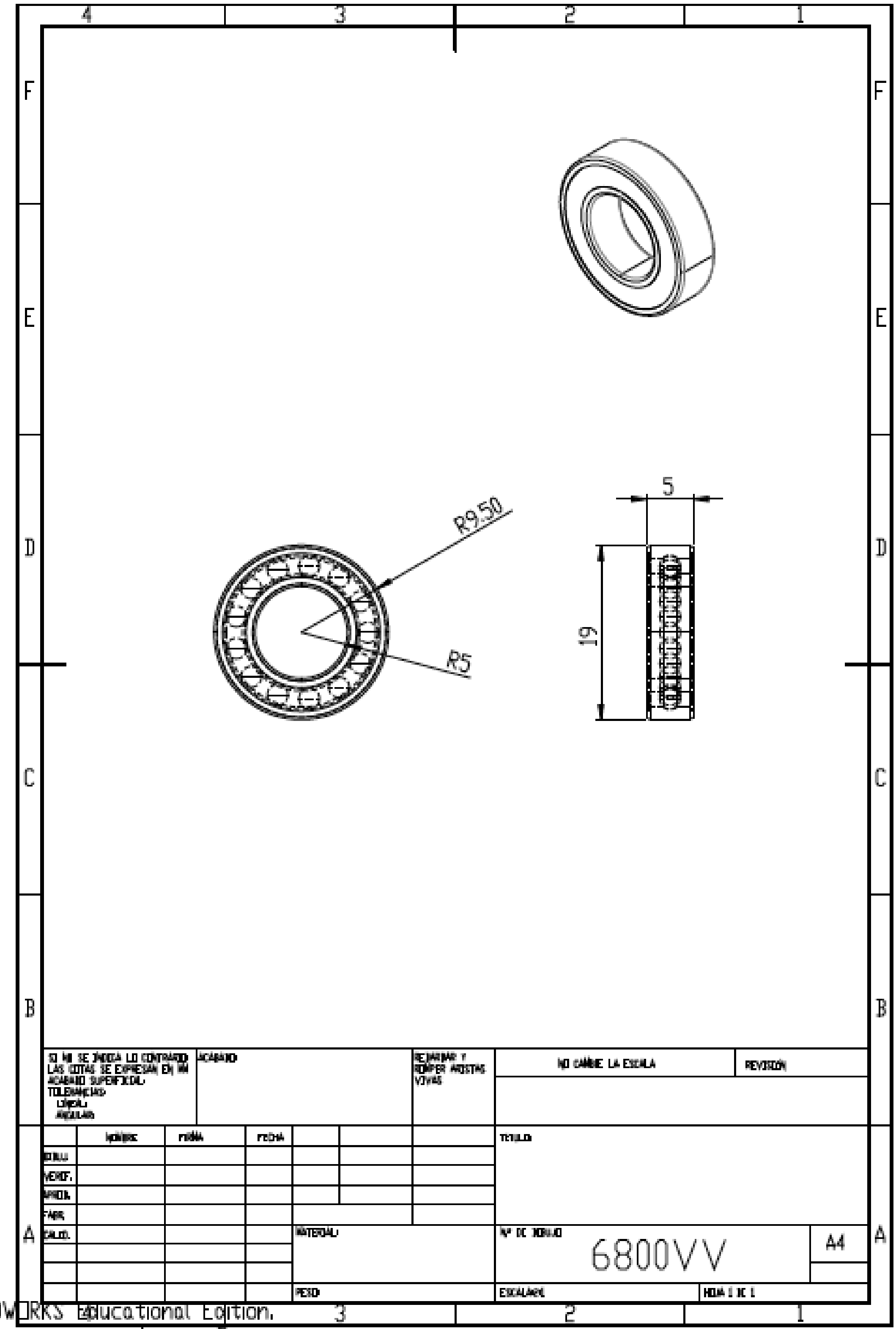
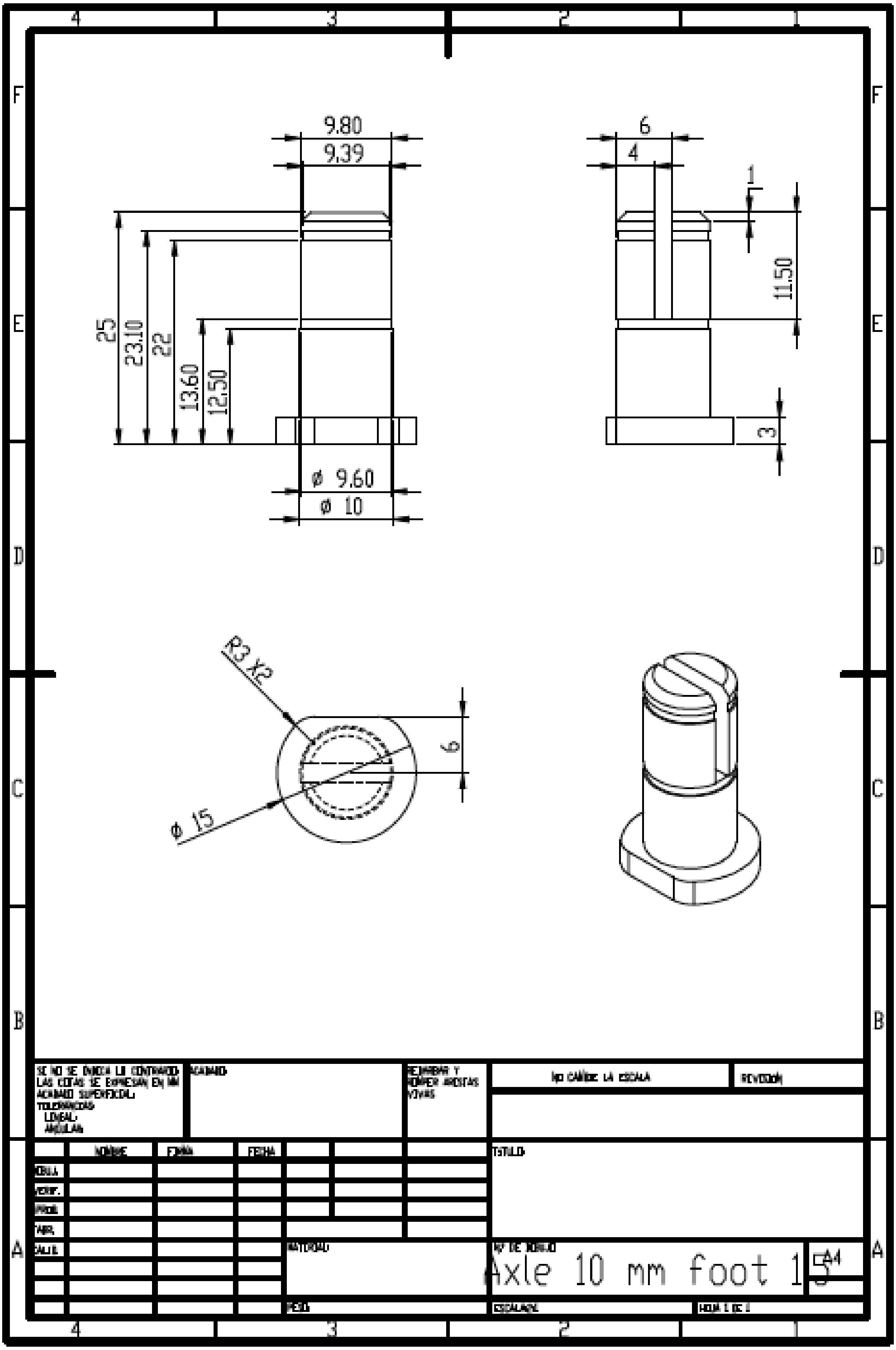
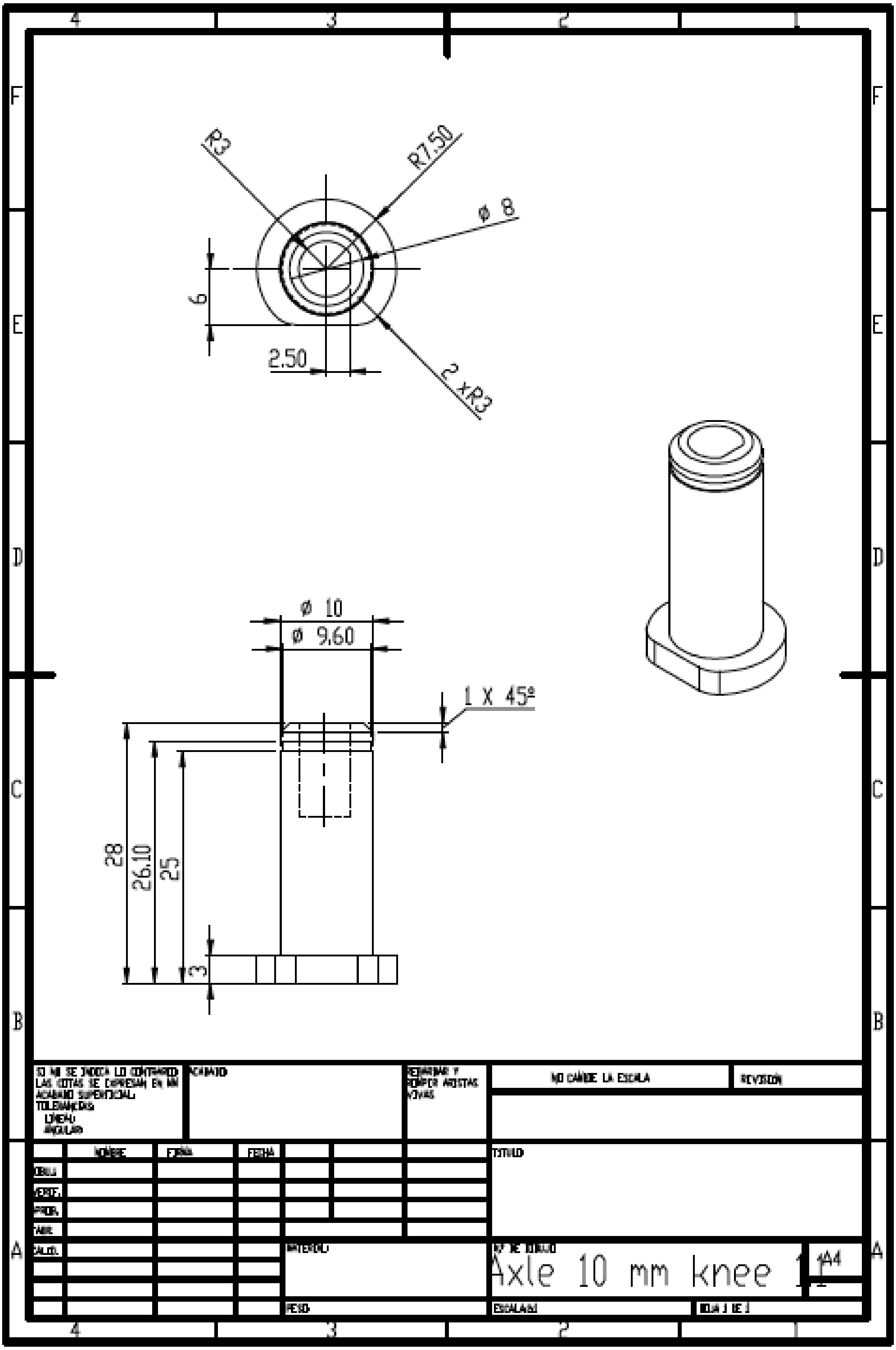
56.80
84.80
R28.80
8
6
116.60
SECCIÓN B-B
5.30
3.80
54.30
5
2xR1.50
116.60
115.80
4xR28
NO CAMBIE LA ESCALA
REVISIÓN
TÍTULO:
NOMBRE
FIRMA
FECHA
MATERIAL:
N.º DE DIBUJO
Case end for wires 2x2
A3
PESO:
ESCALA:
HOJA 1 DE 1

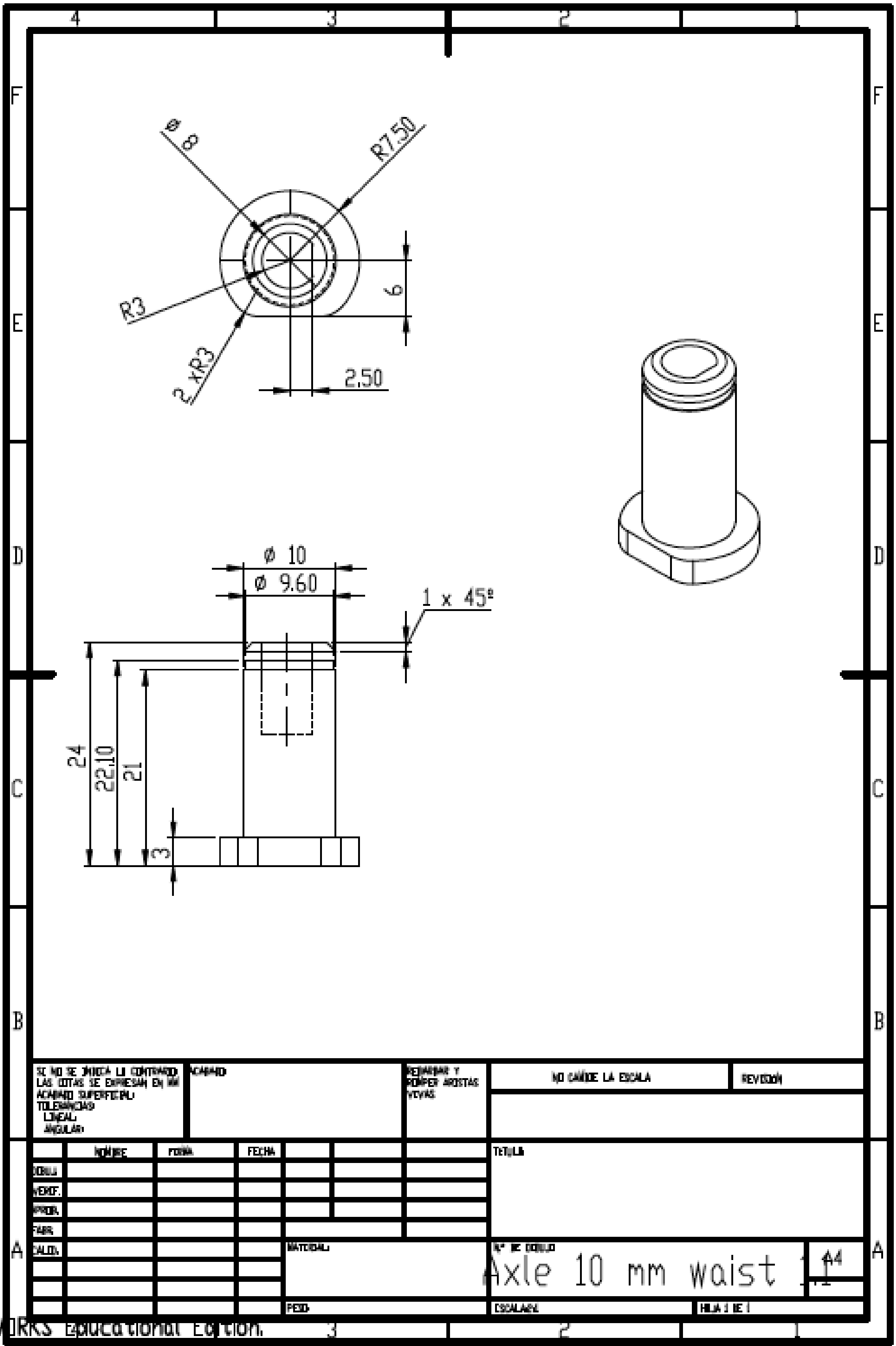

39.50
6
R7.50
⌀ 10
2 x M6
2 x R3
R9
A
A
R10.50
15
62.50
202.20
80
R10.50
331.50
330
73
6
3
SECCIÓN A-A
ESCALA 1 : 2
NO CAMBIE LA ESCALA
REVISIÓN
TÍTULO:
MATERIAL:
N.º DE DIBUJO
Lower shank frame 1.4 with shoe
A3
PESO:
ESCALA:1:5
HOJA 1 DE 1
SOLIDWORKS Educational Edition.
Solo para uso en la enseñanza.

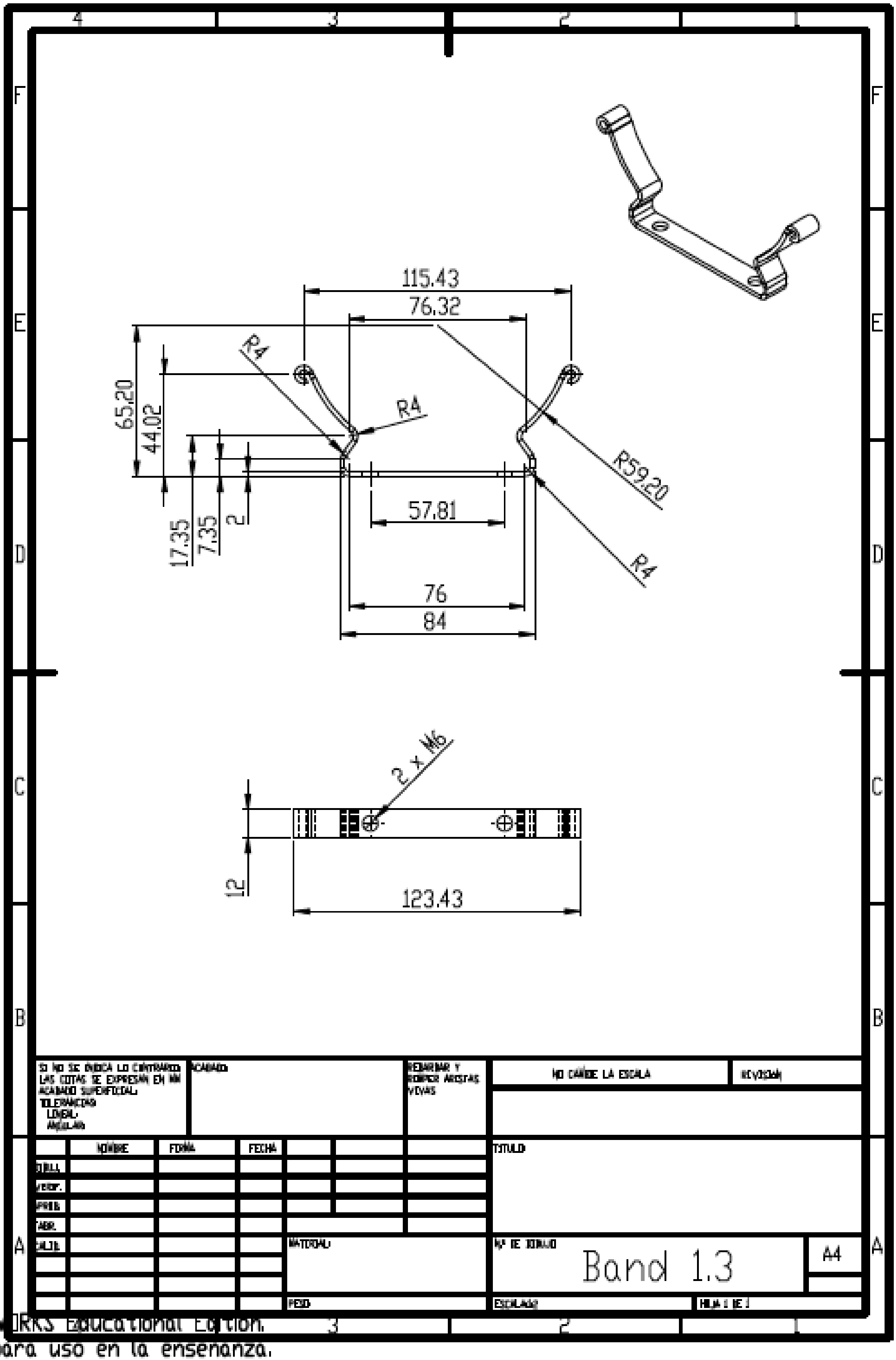

79.50
59.50
R13
13
ø 10
M6x1.0
6.50
4 x R4
26
19.50
8
13
18
5
11
3 x M6x1.0
22
92.50
20
6
8
6
R14
Shoe joint 1.3
A3

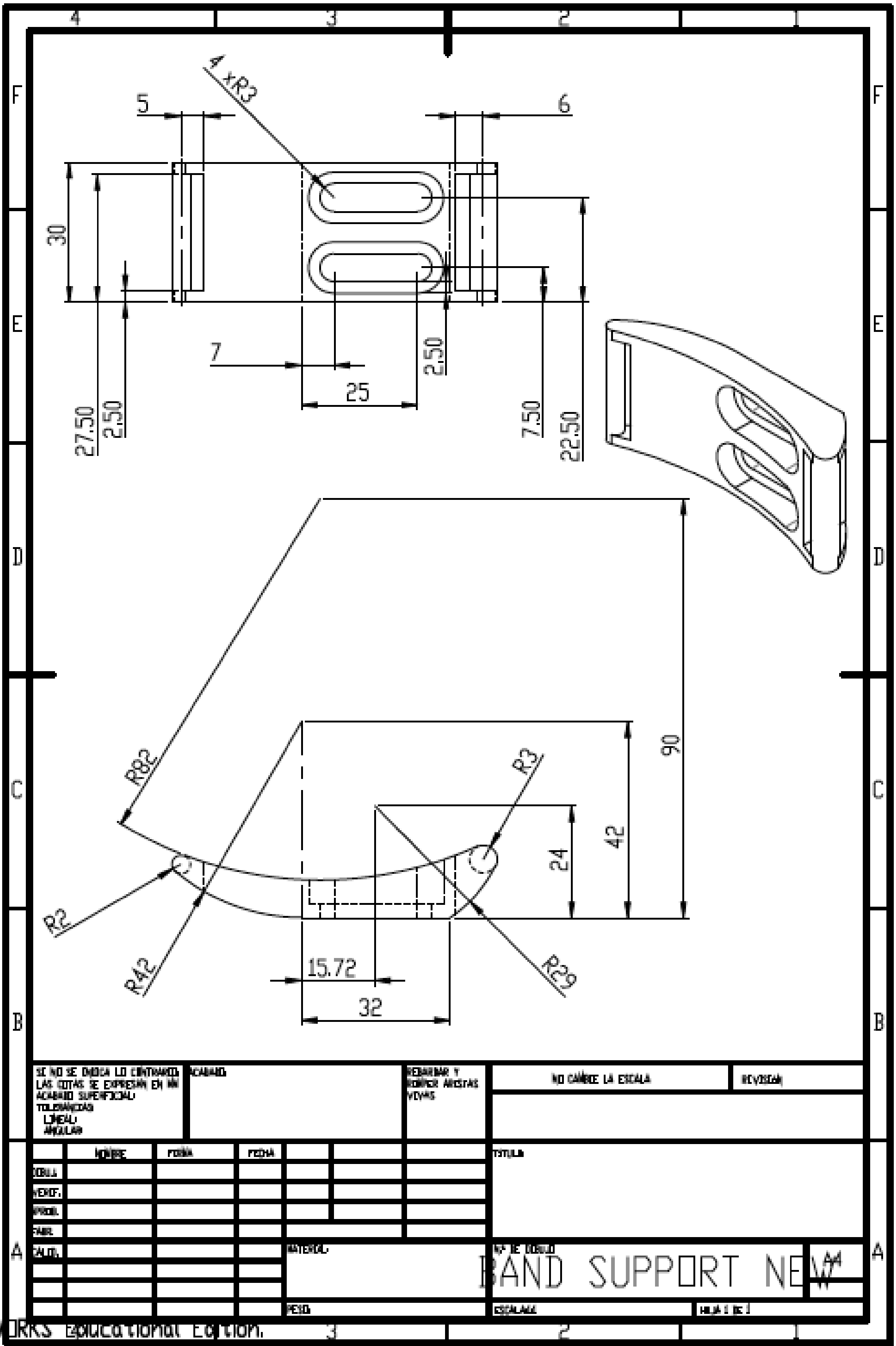

R9.50
R5
5
19
SI NO SE INDICA LO CONTRARIO: LAS COTAS SE EXPRESAN EN MM ACABADO SUPERFICIAL: TOLERANCIAS: LINEAL: ANGULAR:
ACABADO:
REBARBAR Y ROMPER ARISTAS VIVAS
NO CAMBIE LA ESCALA
REVISIÓN
NOMBRE
FIRMA
FECHA
DIBUJ.
VERIF.
APROB.
FABR.
CALID.
TÍTULO:
MATERIAL:
N.º DE DIBUJO
6800VV
A4
PESO:
ESCALA:1:1
HOJA 1 DE 1


9.80
9.39
6
4
1
11.50
25
23.10
22
13.60
12.50
3
ø 9.60
ø 10
R3 X2
6
ø 15
NO CAMBIE LA ESCALA
REVISIÓN
NOMBRE
FIRMA
FECHA
ACABADO
TITULO
MATERIAL
ESCALA
PESO
Axle 10 mm foot 15
A4


R3
R7.50
ø 8
6
2.50
2 xR3
ø 10
ø 9.60
1 X 45º
28
26.10
25
3
SI NO SE INDICA LO CONTRARIO: LAS COTAS SE EXPRESAN EN MM
ACABADO SUPERFICIAL:
TOLERANCIAS:
LINEAL:
ANGULAR:
ACABADO:
REBARBAR Y ROMPER ARISTAS VIVAS
NO CAMBIE LA ESCALA
REVISIÓN
NOMBRE
FIRMA
FECHA
DIBUJ.
VERIF.
APROB.
FABR.
CALID.
TÍTULO:
MATERIAL:
N.º DE DIBUJO
Axle 10 mm knee 11
A4
PESO:
ESCALA:1:1
HOJA 1 DE 1


ø 8
R7.50
R3
2 xR3
6
2.50
ø 10
ø 9.60
1 x 45º
24
22.10
21
3
SI NO SE INDICA LO CONTRARIO: LAS COTAS SE EXPRESAN EN MM ACABADO SUPERFICIAL: TOLERANCIAS: LINEAL: ANGULAR:
ACABADO:
REBARBAR Y ROMPER ARISTAS VIVAS
NO CAMBIE LA ESCALA
REVISIÓN
NOMBRE
FIRMA
FECHA
DIBUJ.
VERIF.
APROB.
FABR.
CALID.
MATERIAL:
TÍTULO:
N.º DE DIBUJO
Axle 10 mm waist 1:1
A4
PESO:
ESCALA:
HOJA 1 DE 1


115.43
76.32
65.20
44.02
R4
R4
R59.20
R4
57.81
17.35
7.35
2
76
84
2 x M6
12
123.43
SI NO SE INDICA LO CONTRARIO:
LAS COTAS SE EXPRESAN EN MM
ACABADO SUPERFICIAL:
TOLERANCIAS:
LINEAL:
ANGULAR:
ACABADO:
REBARBAR Y ROMPER ARISTAS VIVAS
NO CAMBIE LA ESCALA
REVISIÓN
NOMBRE
FIRMA
FECHA
DIBUJ.
VERIF.
APROB.
FABR.
CALID.
MATERIAL:
TÍTULO:
N.º DE DIBUJO
Band 1.3
A4
PESO:
ESCALA:
HOJA 1 DE 1



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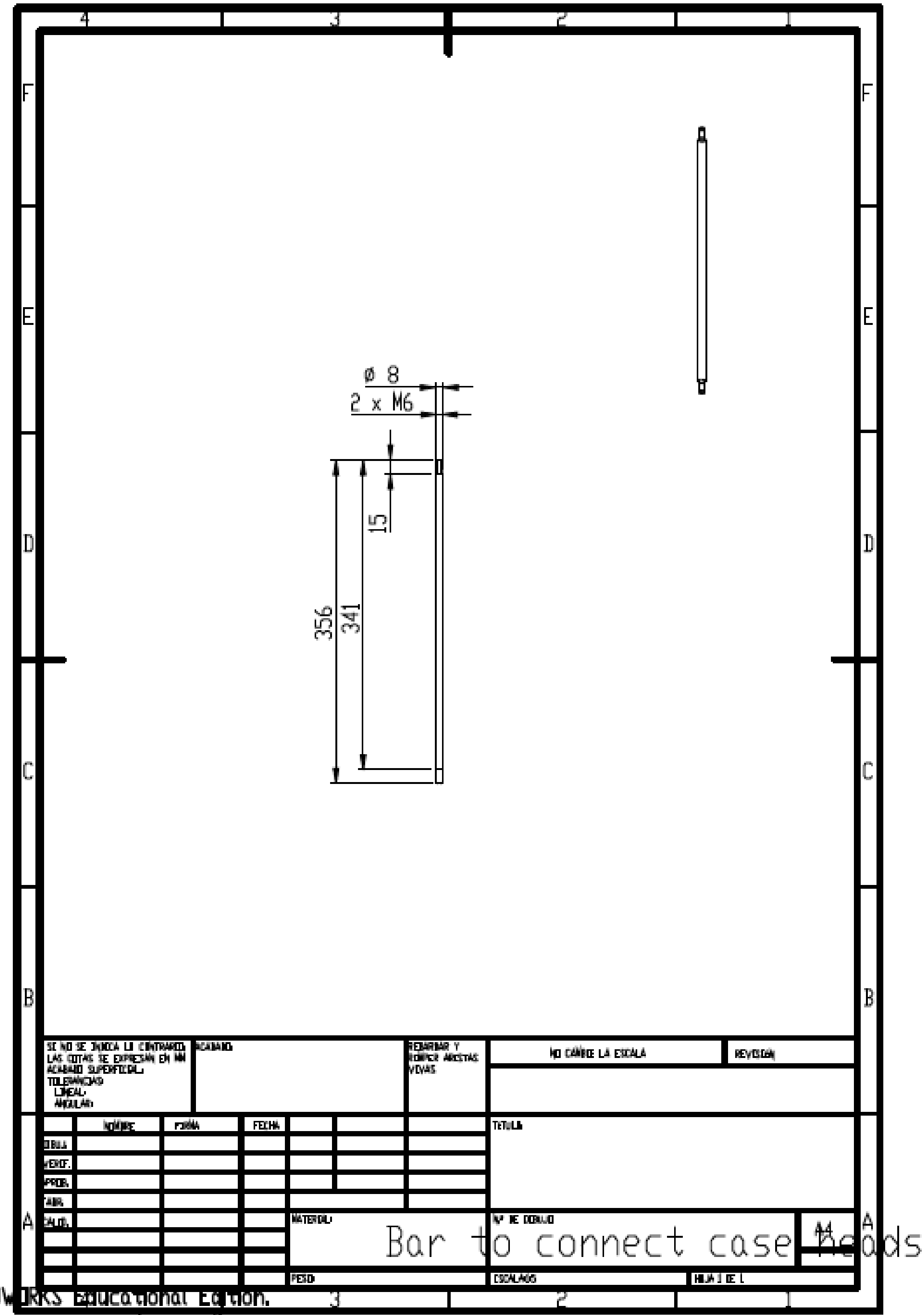
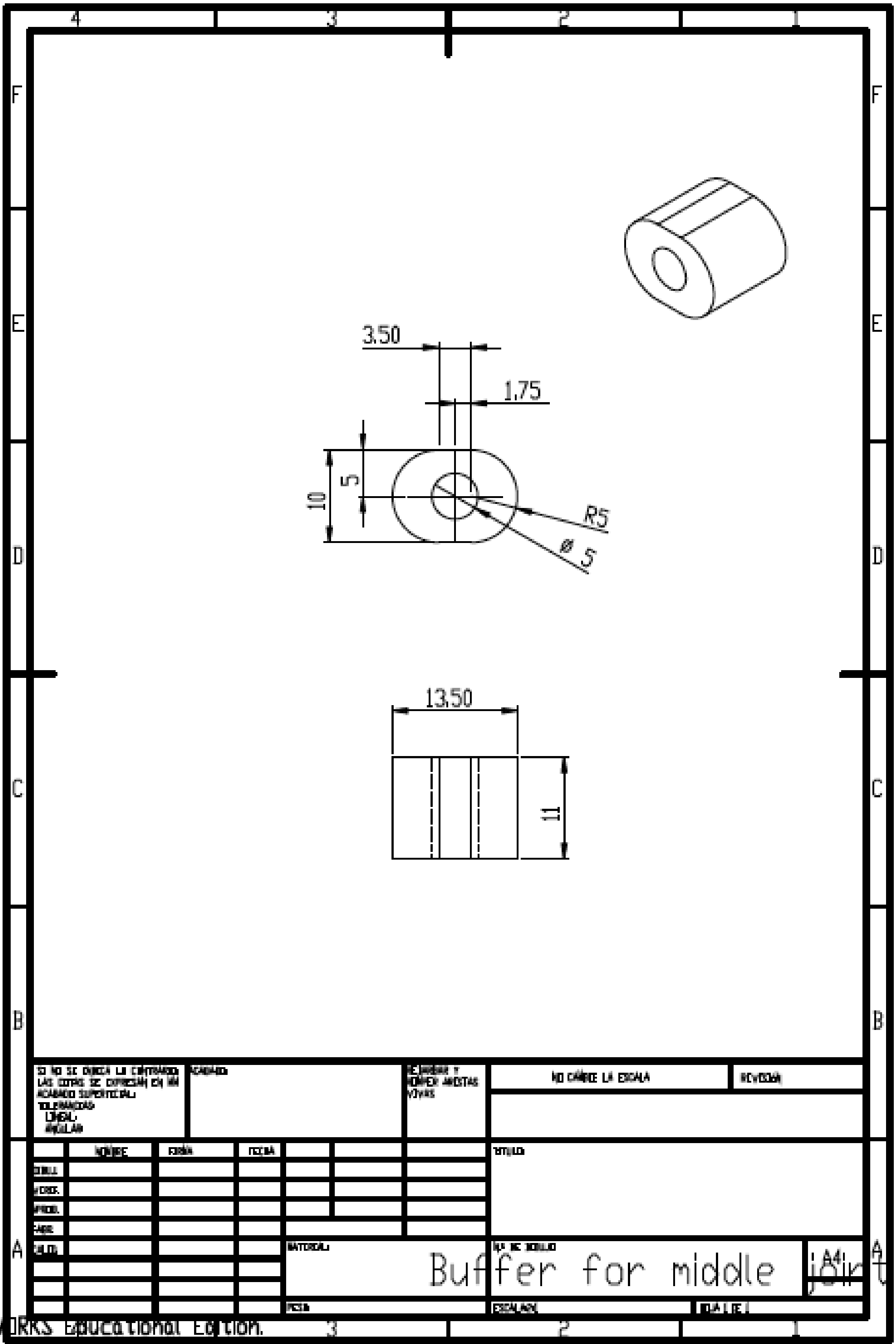
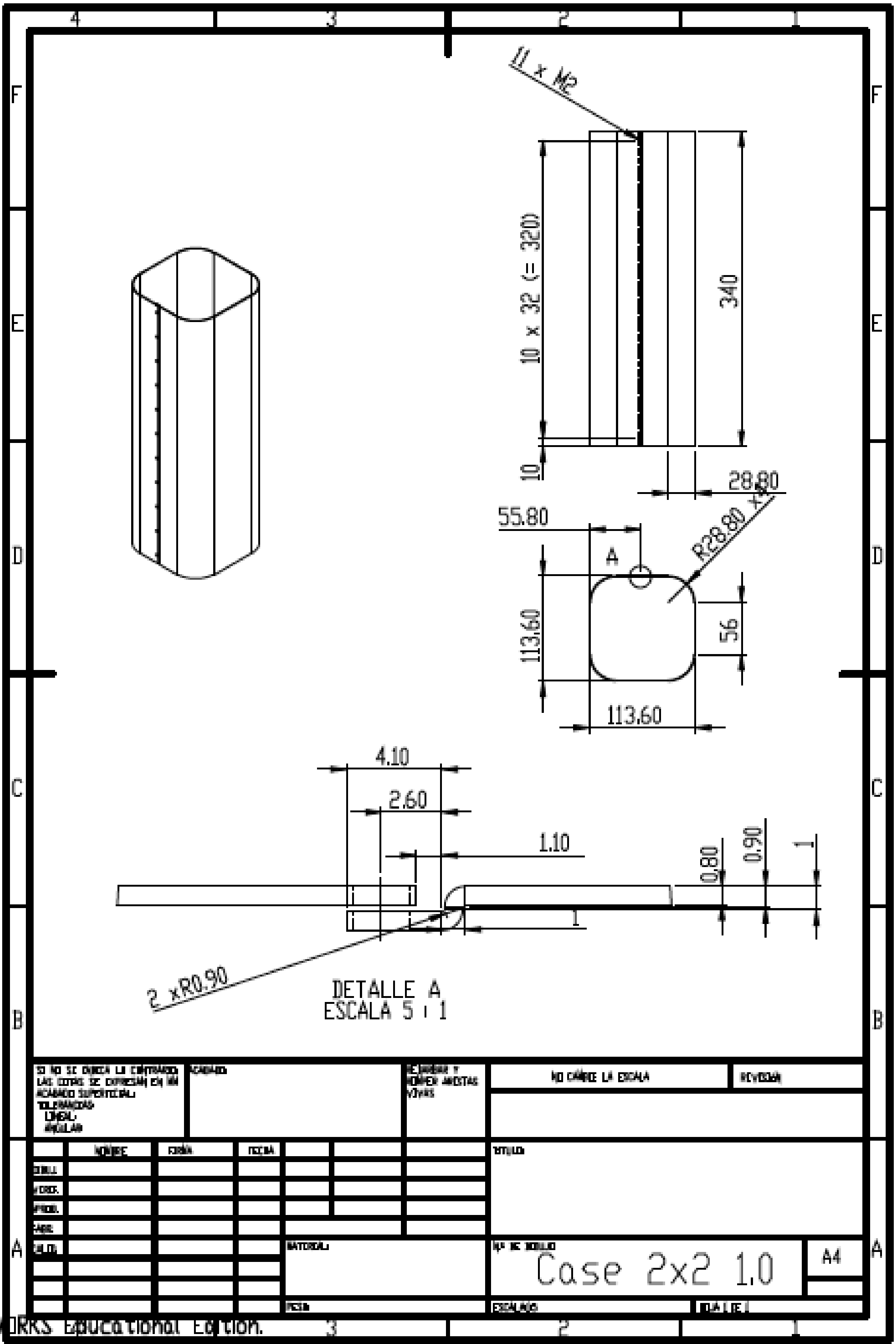
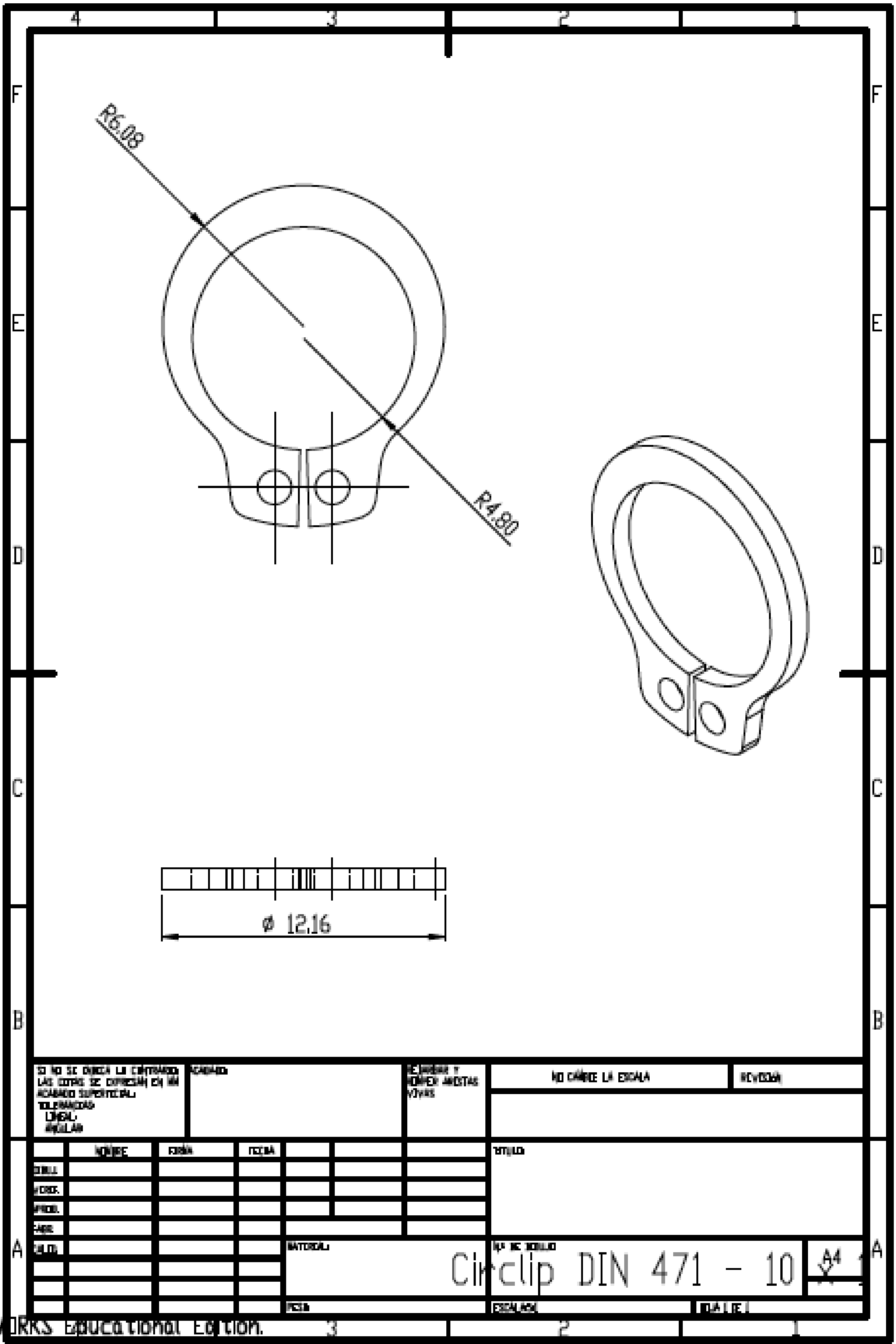
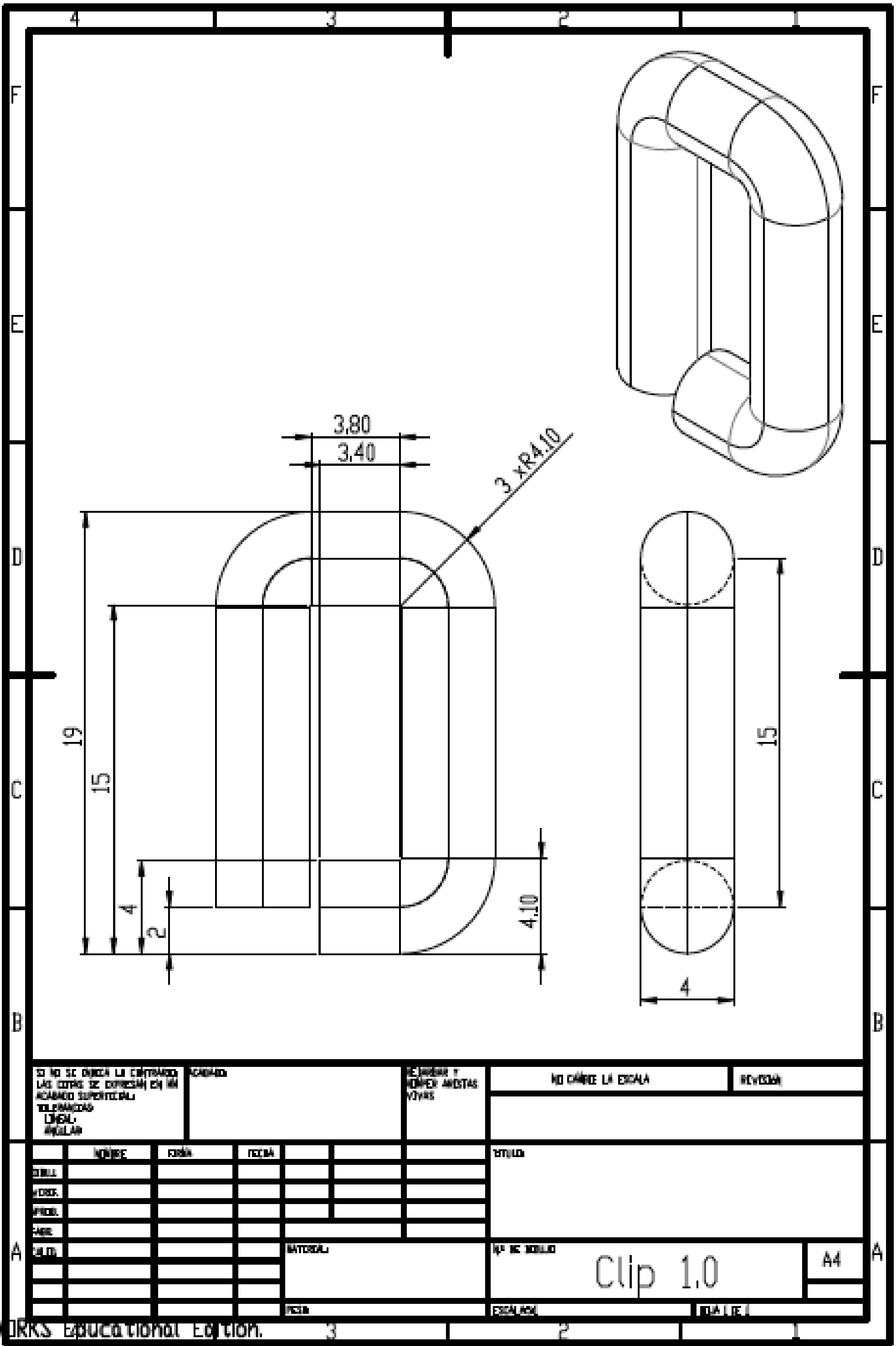

ø 8
2 x M6
15
356
341
SI NO SE INDICA LO CONTRARIO: LAS COTAS SE EXPRESAN EN MM ACABADO SUPERFICIAL: TOLERANCIAS: LINEAL: ANGULAR:
ACABADO:
REBARBAR Y ROMPER ARISTAS VIVAS
NO CAMBIE LA ESCALA
REVISIÓN
NOMBRE
FIRMA
FECHA
DIBUJ.
VERIF.
APROB.
FABR.
CALID.
TÍTULO:
MATERIAL:
N.º DE DIBUJO
Bar to connect case heads
A4
PESO:
ESCALA:
HOJA 1 DE 1

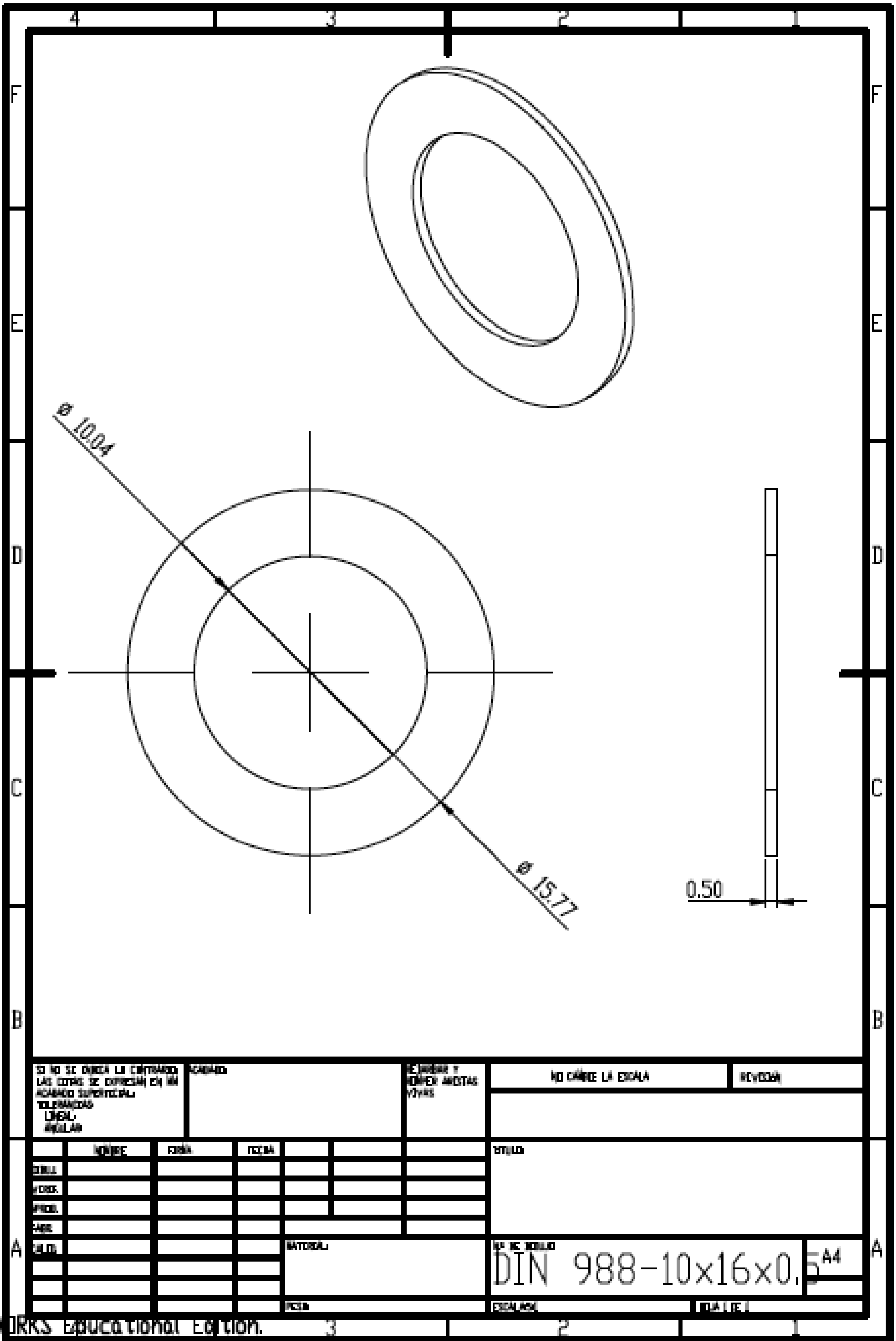

3.50
1.75
5
10
R5
ø 5
13.50
11
NO CAMBIE LA ESCALA
Buffer for middle joint
A4

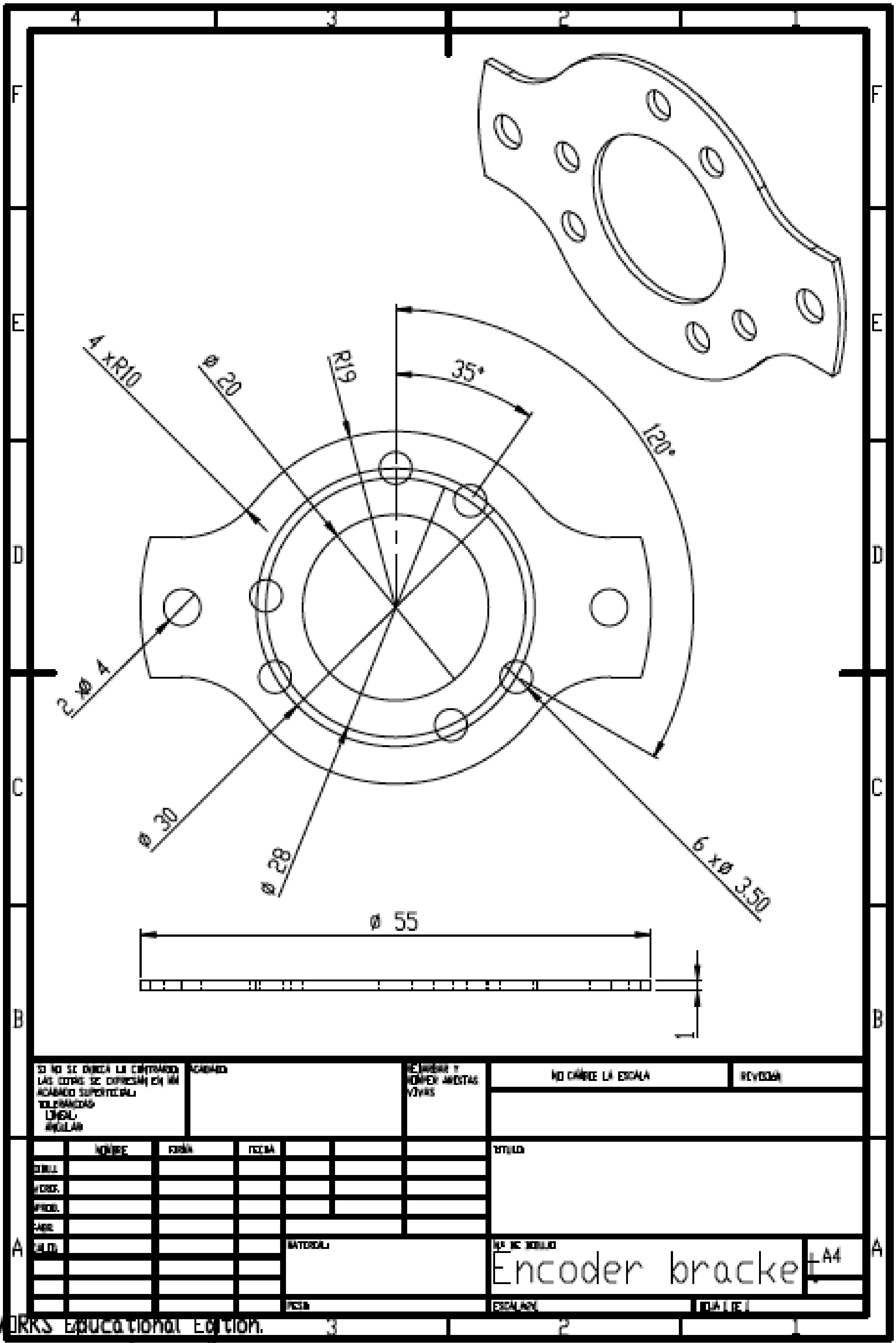

11 x M2
10 x 32 (= 320)
340
10
28.80
55.80
R28.80
A
113.60
56
113.60
4.10
2.60
1.10
0.80
0.90
1
1
2 xR0.90
DETALLE A
ESCALA 5 : 1
NO CAMBIE LA ESCALA
NOMBRE
FIRMA
FECHA
TÍTULO:
MATERIAL:
Case 2x2 1.0
A4


R6.08
R4.80
ø 12.16
NO CAMBIE LA ESCALA
REVISIÓN
Circlip DIN 471 - 10
A4

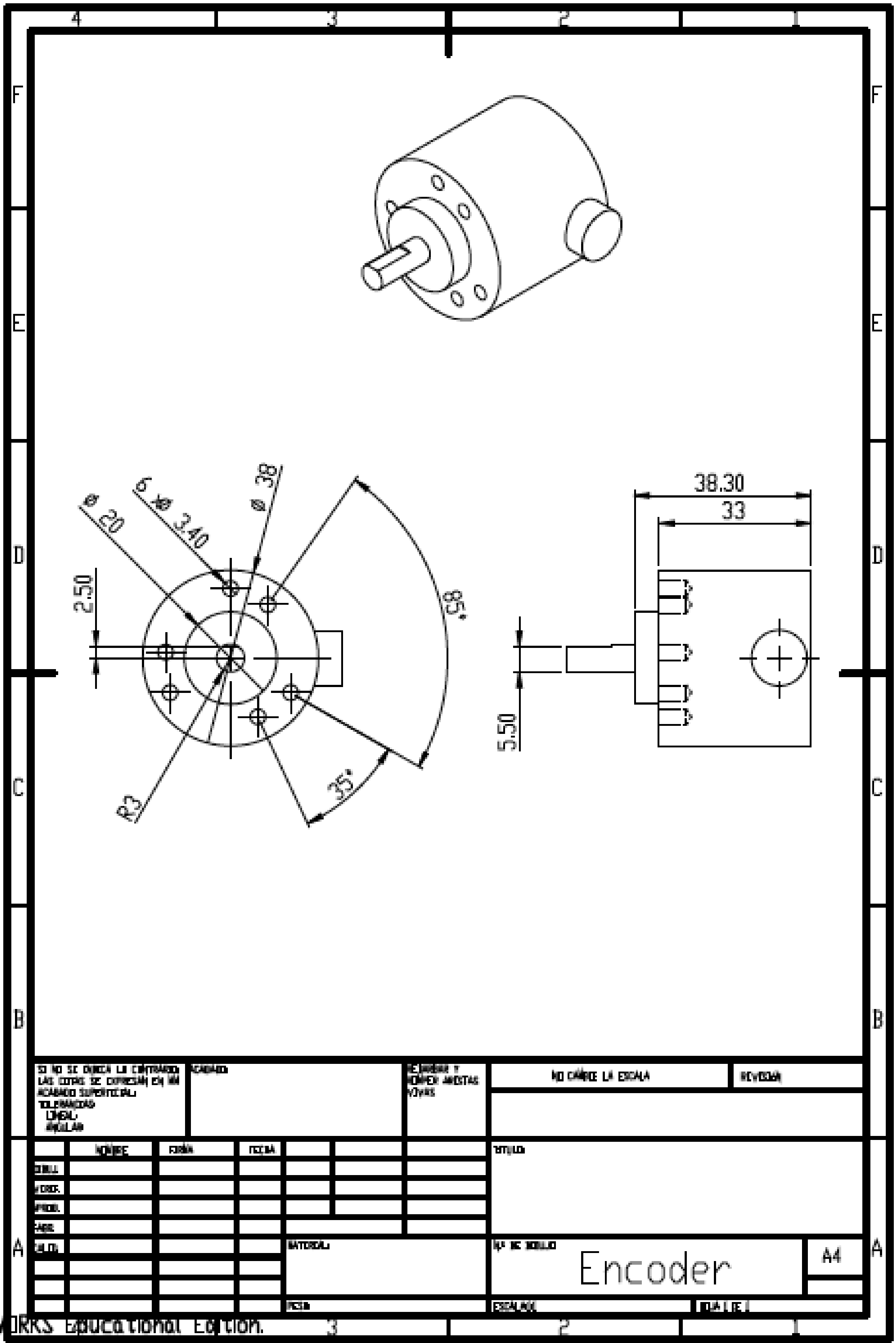


3,80
3,40
3 xR4,10
19
15
4
2
4,10
15
4
NOMBRE
FIRMA
FECHA
NO CAMBIE LA ESCALA
REVISIÓN
TÍTULO:
MATERIAL:
Clip 1.0
A4

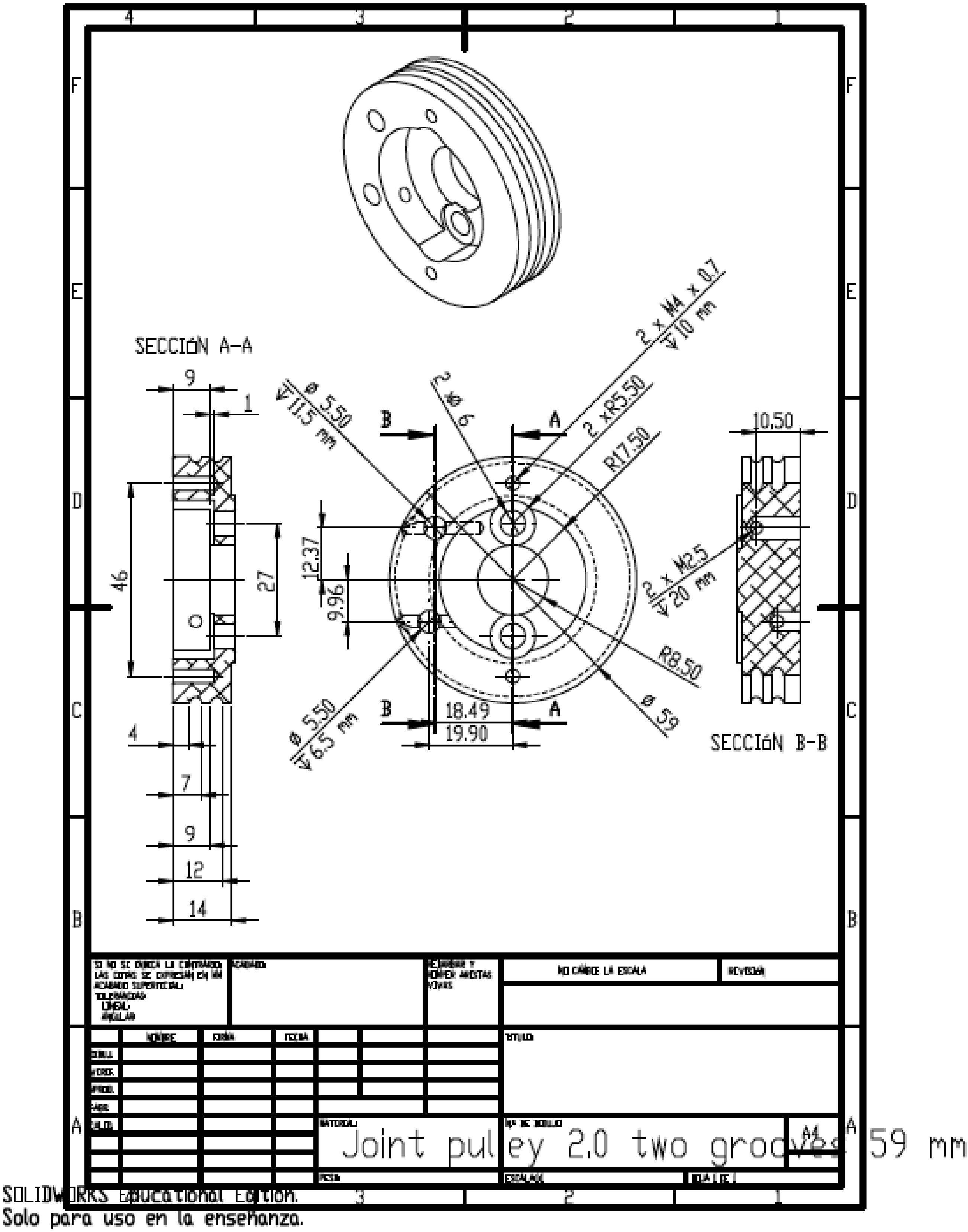

Ø 10.04
Ø 15.77
0.50
NO CAMBIE LA ESCALA
REVISIÓN
TÍTULO:
DIN 988-10x16x0,5
A4
MATERIAL:
PESO:
ESCALA:
NOMBRE
FIRMA
FECHA

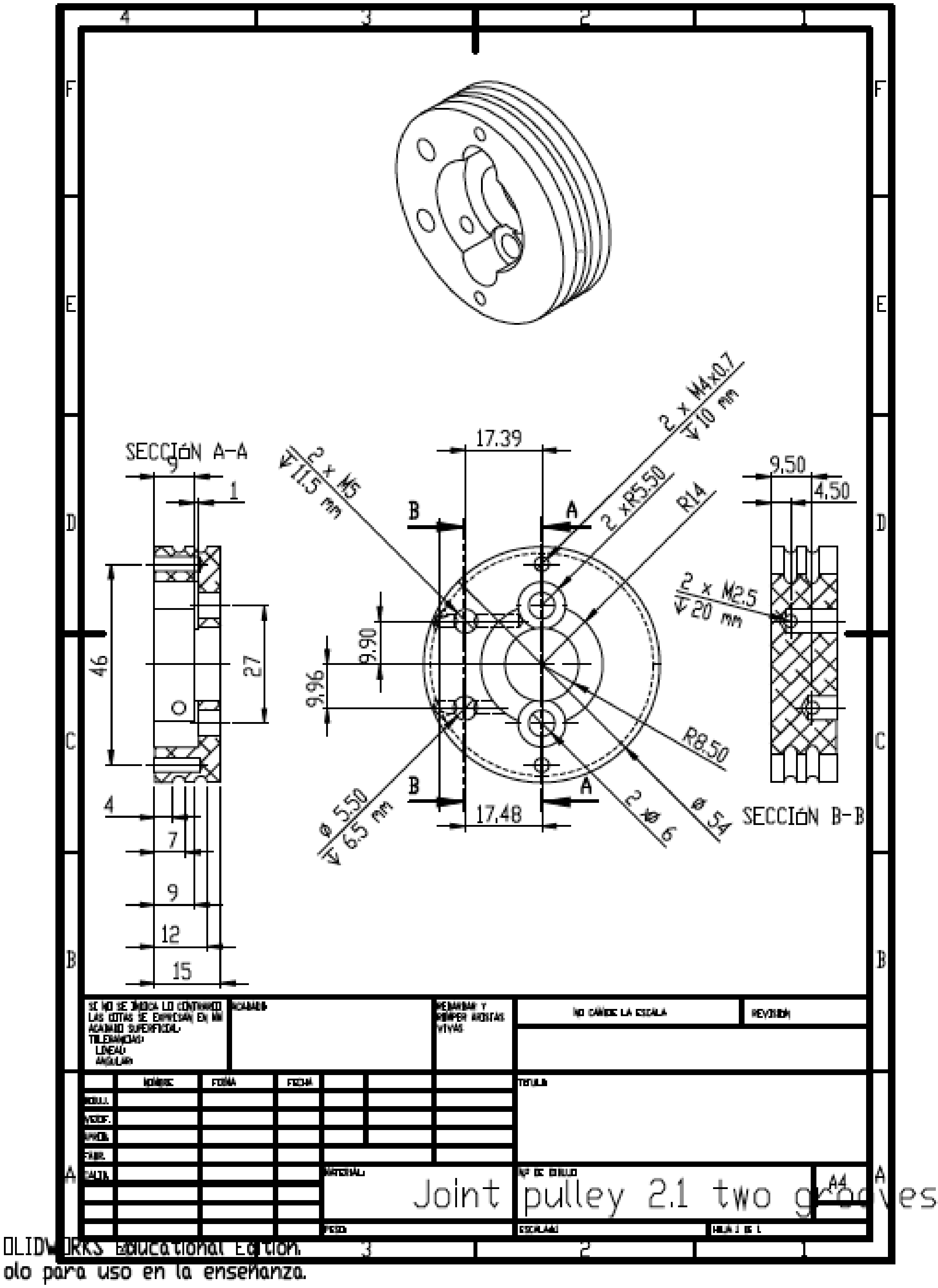


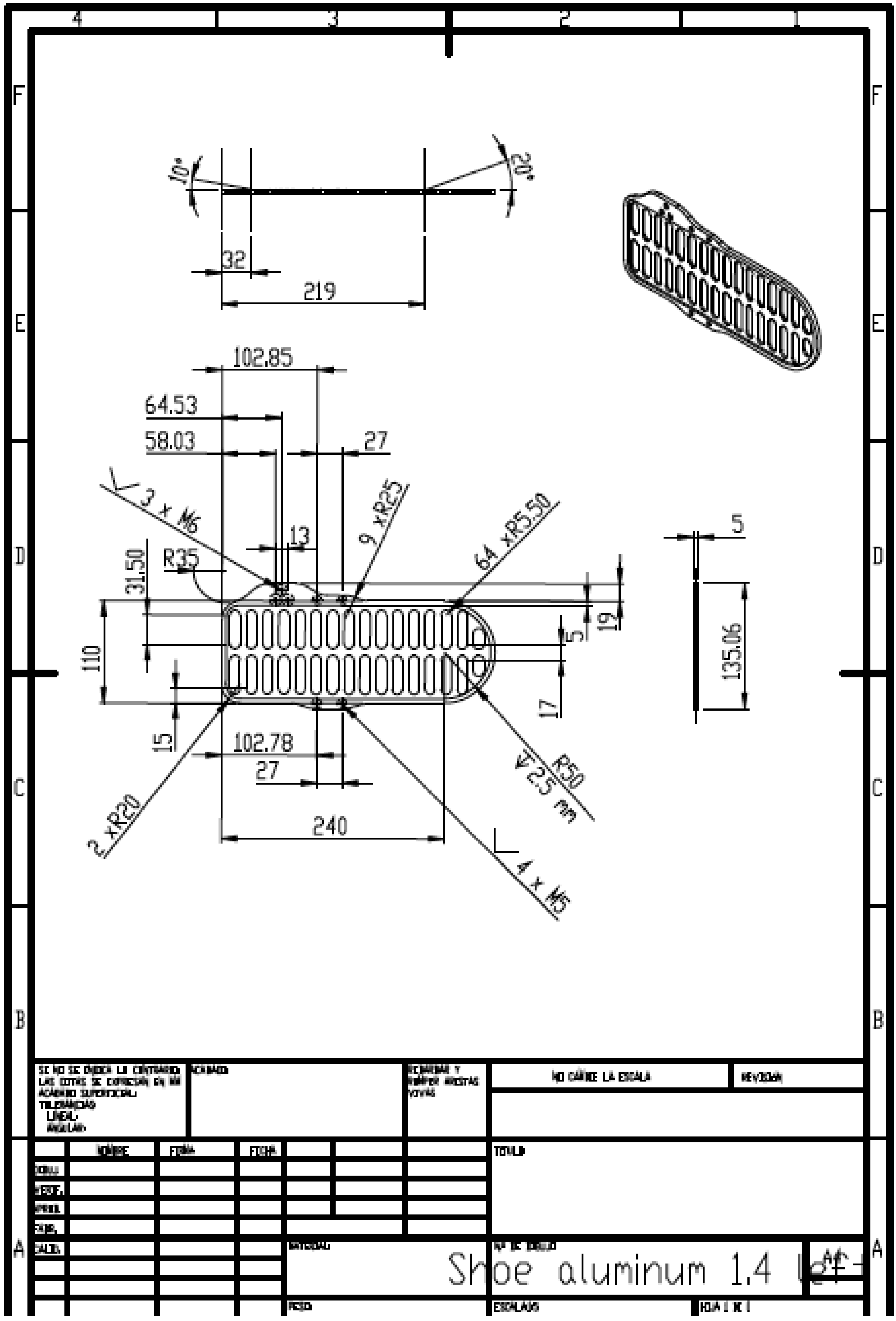
4 xR10
ø 20
R19
35°
120°
2 ø 4
ø 30
ø 28
6 xø 3.50
ø 55
1
SI NO SE INDICA LO CONTRARIO: LAS COTAS SE EXPRESAN EN MM ACABADO SUPERFICIAL: TOLERANCIAS: LINEAL: ANGULAR:
ACABADO:
REBARBAR Y ROMPER ARISTAS VIVAS
NO CAMBIE LA ESCALA
REVISION
NOMBRE
FIRMA
FECHA
DIBUJ.
VERIF.
APROB.
FABR.
CALID.
TITULO:
MATERIAL:
N.º DE DIBUJO
Encoder bracket
A4
PESO:
ESCALA:1:1
HOJA 1 DE 1

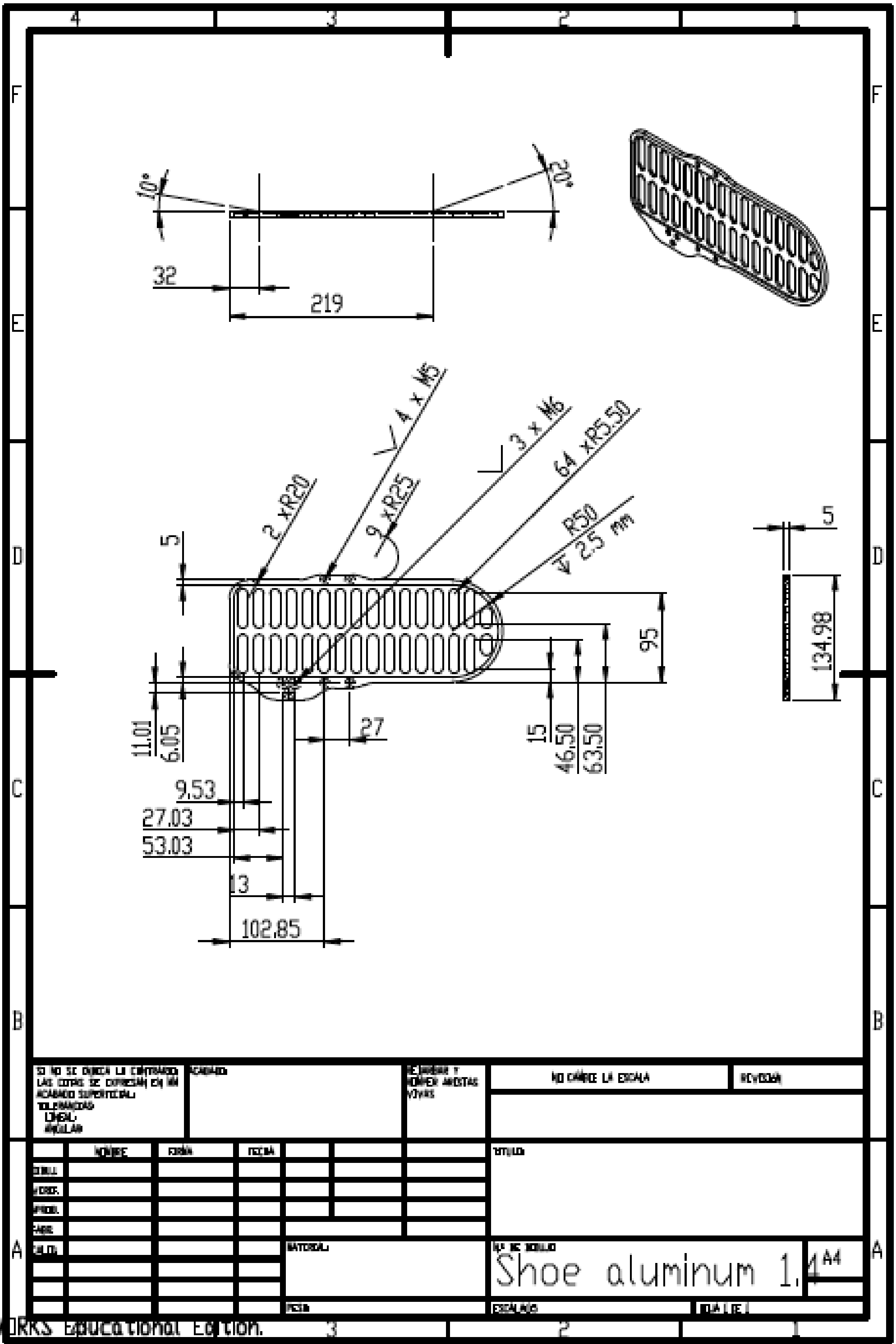


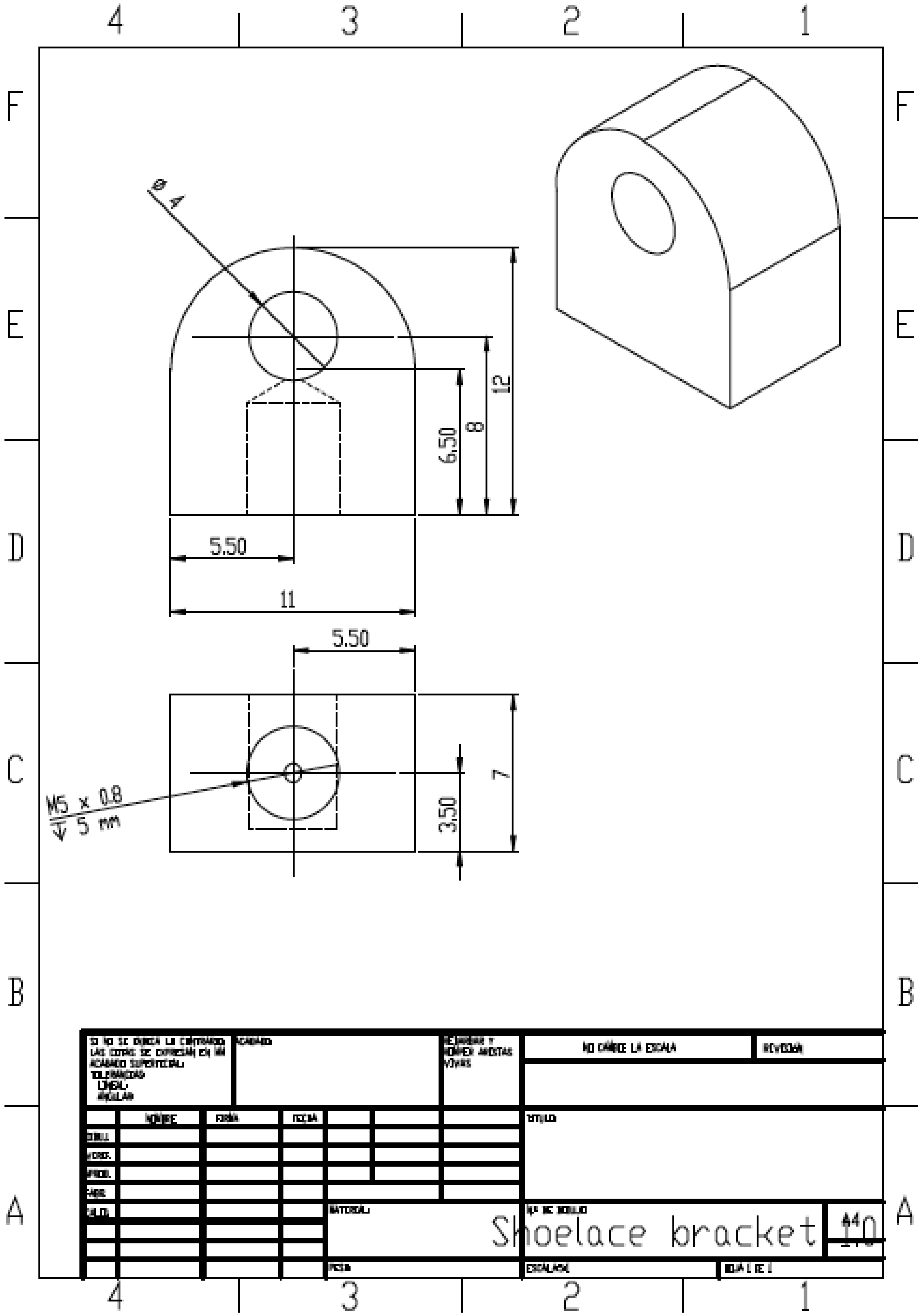
Ø 20
6 X Ø 3.40
Ø 38
2.50
R3
35°
58
38.30
33
5.50
SI NO SE INDICA LO CONTRARIO: LAS COTAS SE EXPRESAN EN MM ACABADO SUPERFICIAL: TOLERANCIAS: LINEAL: ANGULAR:
ACABADO:
REBARBAR Y ROMPER ARISTAS VIVAS
NO CAMBIE LA ESCALA
REVISIÓN
NOMBRE
FIRMA
FECHA
DIBUJ.
VERIF.
APROB.
FABR.
CALID.
TÍTULO:
MATERIAL:
N.º DE DIBUJO
Encoder
A4
PESO:
ESCALA:
HOJA 1 DE 1

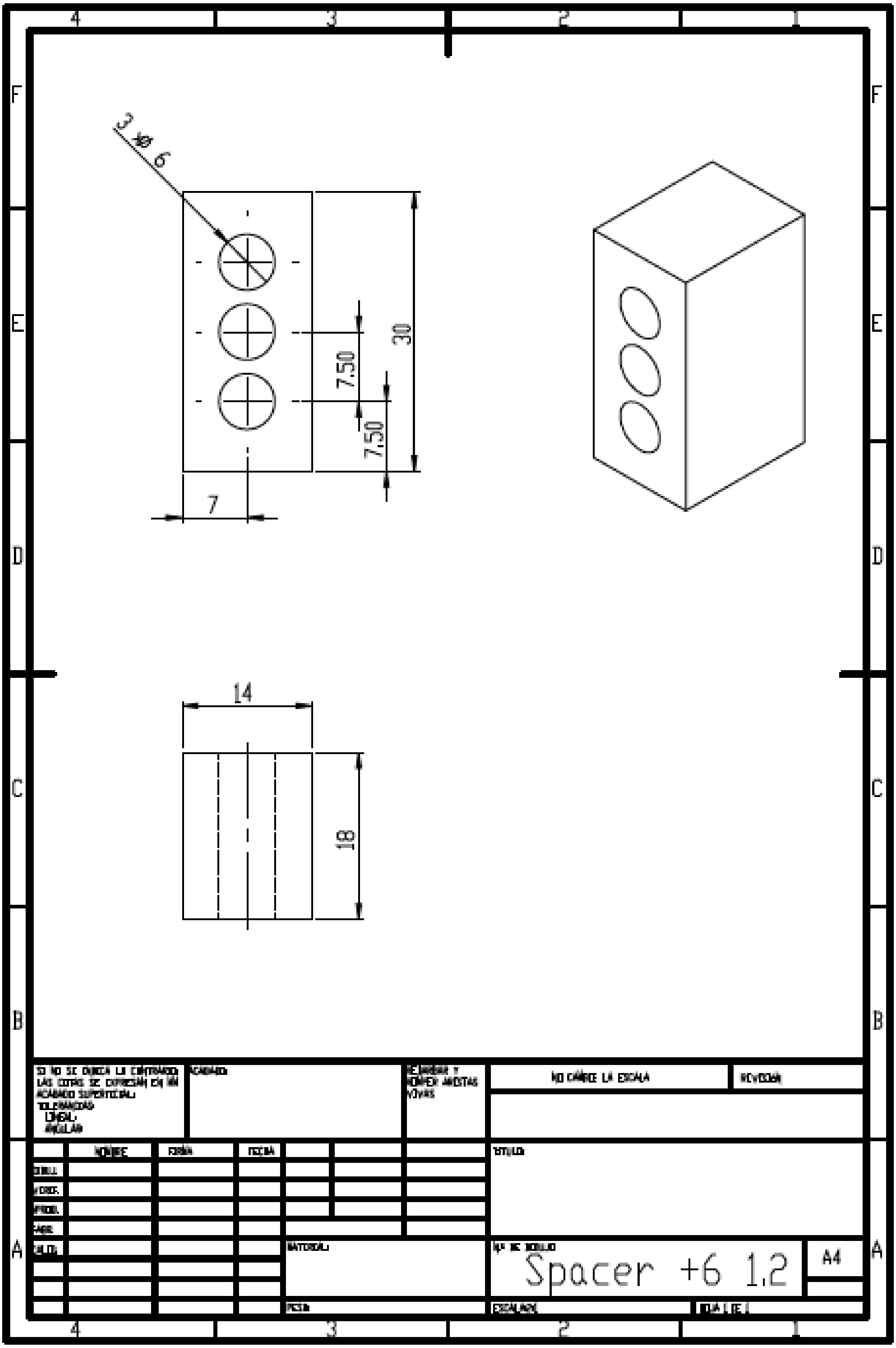

SECCIÓN A-A
SECCIÓN B-B
2 x M4 x 0.7
10 mm
2 xR5.50
R17.50
2 x ⌀ 6
⌀ 5.50
11.5 mm
⌀ 5.50
6.5 mm
2 x M2.5
20 mm
R8.50
⌀ 59
18.49
19.90
12.37
9.96
10.50
46
27
9
1
4
7
9
12
14
NO CAMBIE LA ESCALA
REVISIÓN
TÍTULO:
MATERIAL:
Nº DE DIBUJO
Joint pulley 2.0 two grooves 59 mm
A4
ESCALA:
HOJA 1 DE 1
SOLIDWORKS Educational Edition.
Solo para uso en la enseñanza.

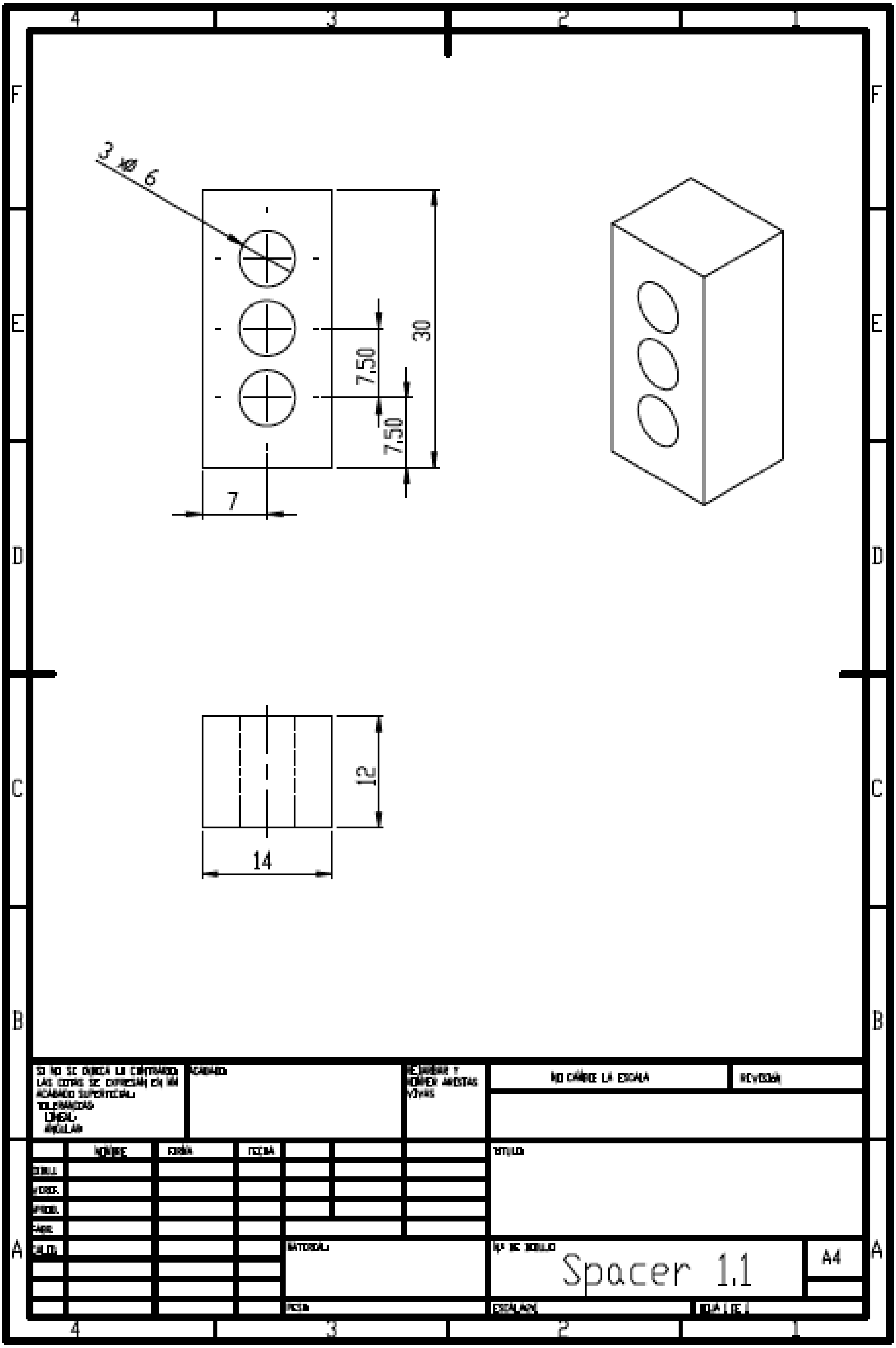

SECCIÓN A-A
SECCIÓN B-B
17.39
17.48
2 x M4x0.7
10 mm
2 x M5
11.5 mm
2 xR5.50
R14
R8.50
2 x M2.5
20 mm
9.50
4.50
9.90
9.96
46
27
ø 5.50
6.5 mm
2 x ø 6
ø 54
Joint pulley 2.1 two grooves
A4
SOLIDWORKS Educational Edition.
Solo para uso en la enseñanza.

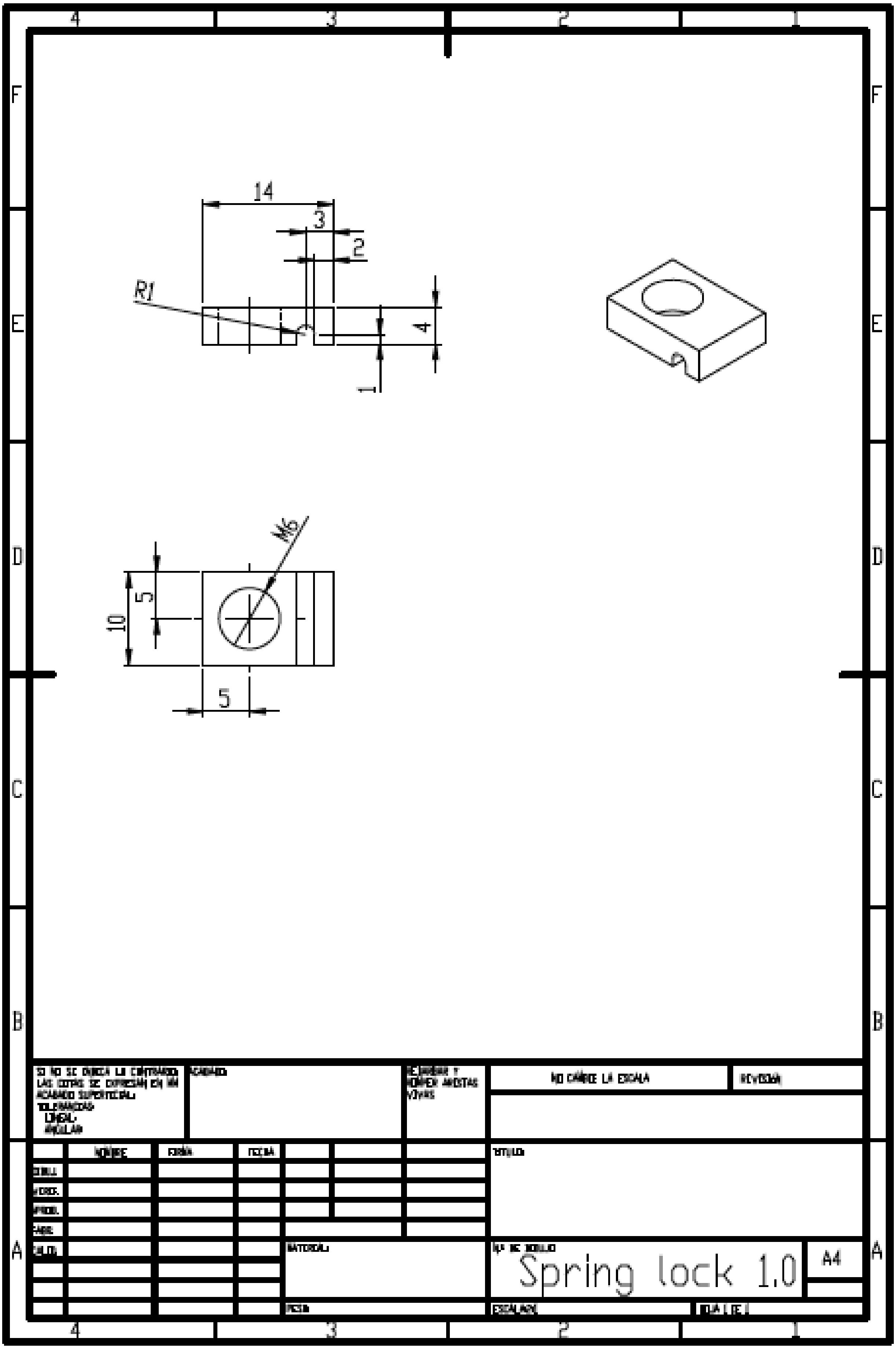

10°
20°
32
219
102.85
64.53
58.03
27
3 x M6
9 x R25
64 x R5.50
13
R35
31.50
110
19
5
17
15
102.78
27
240
2 x R20
R50
2.5 mm
4 x M5
5
135.06
NO CAMBIE LA ESCALA
Shoe aluminum 1,4

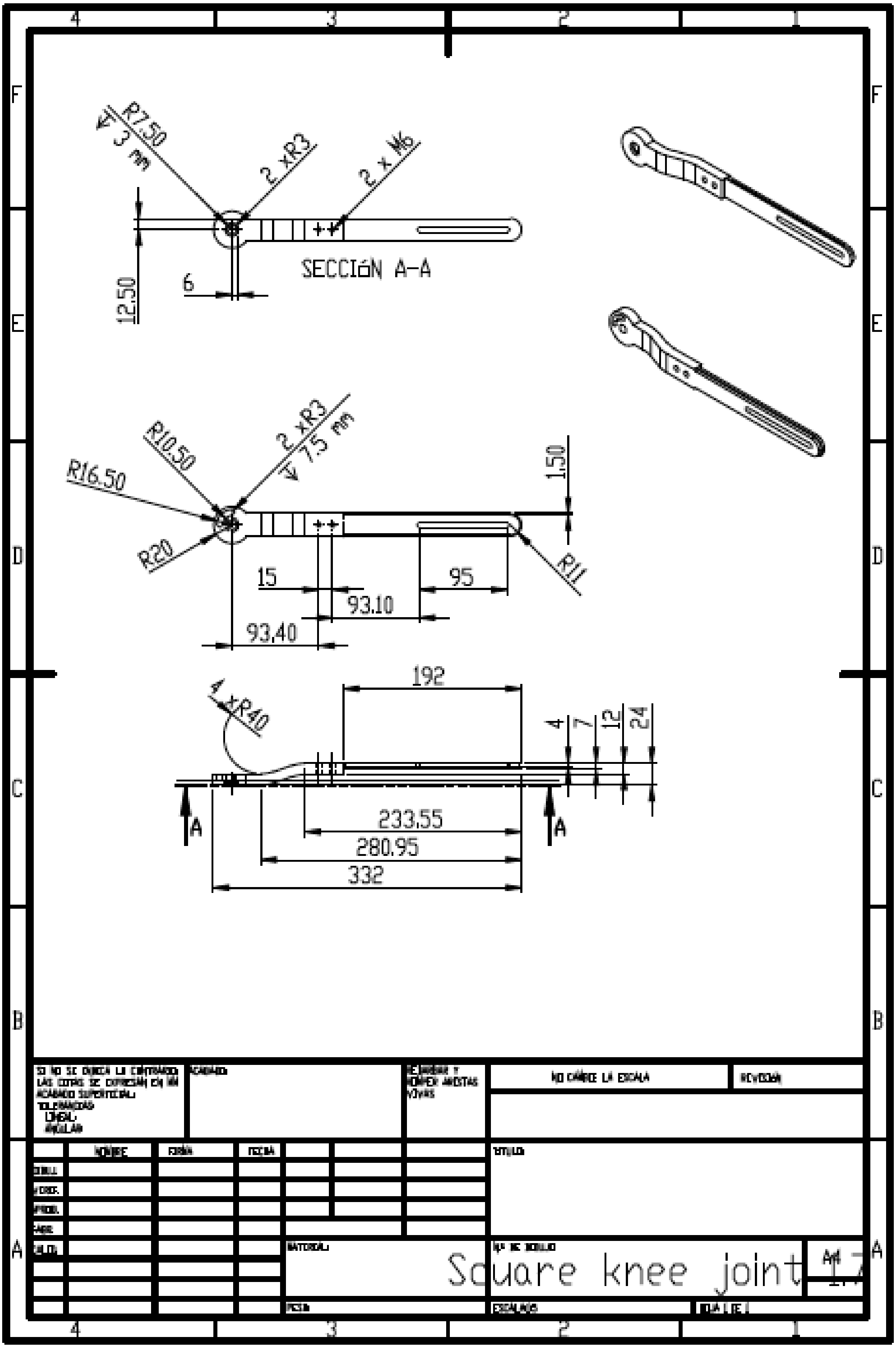

10°
20°
32
219
4 x M5
3 x M6
64 xR5.50
2 xR20
9 xR25
R50
2.5 mm
5
95
15
46.50
63.50
11.01
6.05
27
9.53
27.03
53.03
13
102.85
5
134.98
NO CAMBIE LA ESCALA
REVISIÓN
NOMBRE
FIRMA
FECHA
TÍTULO:
MATERIAL:
PESO:
ESCALA:1:5
HOJA 1 DE 1
Shoe aluminum 1.4
A4


ø 4
12
8
6.50
5.50
11
5.50
7
3.50
M5 x 0.8
5 mm
NO CAMBIE LA ESCALA
REVISIÓN
TITULO:
MATERIAL:
Nº DE DIBUJO
Shoelace bracket
A4
1:1
PESO:
ESCALA:
HOJA 1 DE 1

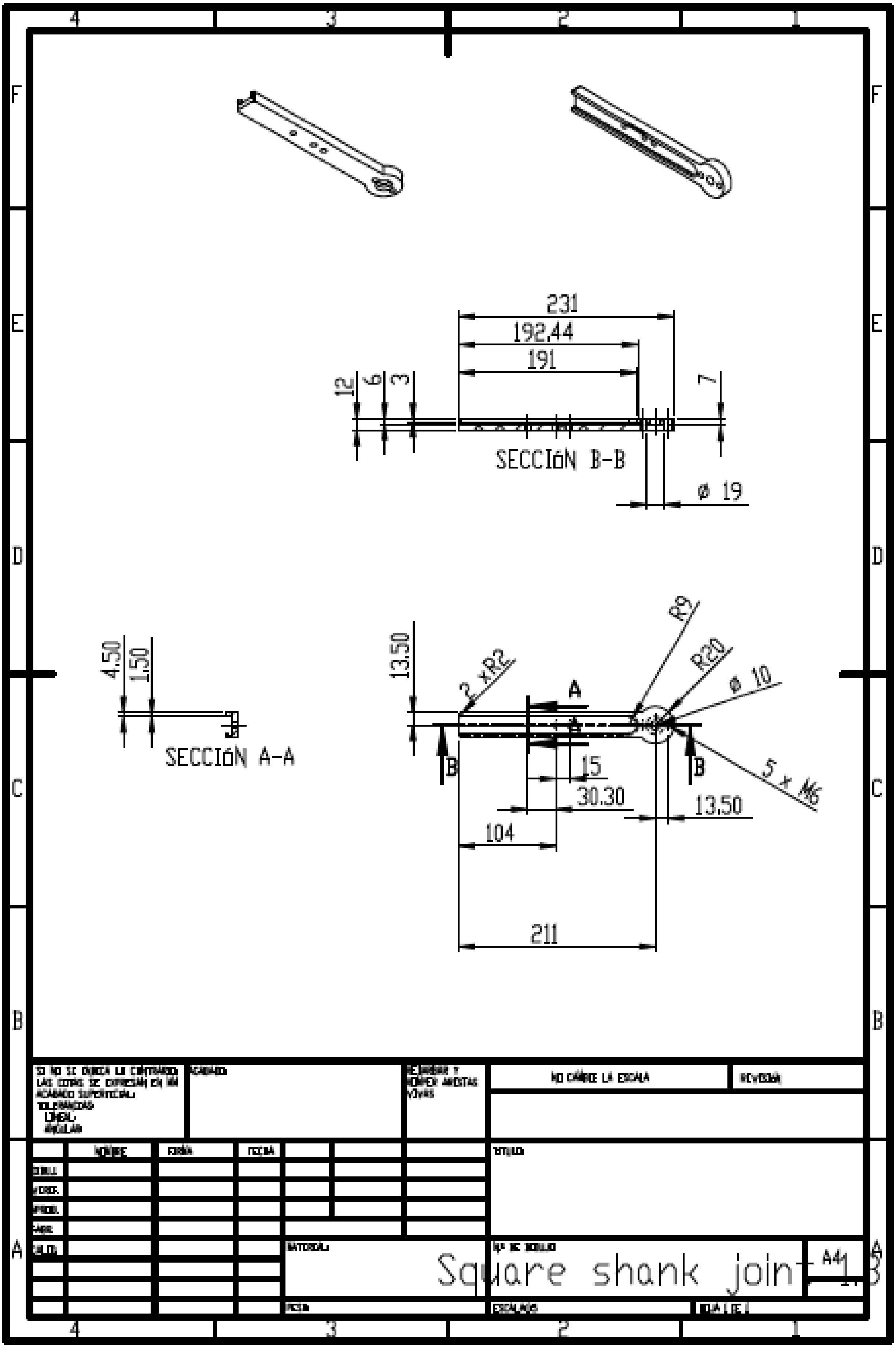

3 x ø 6
30
7,50
7,50
7
14
18
ACABADO:
NO CAMBIE LA ESCALA
REVISIÓN
NOMBRE
FIRMA
FECHA
TÍTULO:
MATERIAL:
Nº DE DIBUJO
Spacer +6 1,2
A4
PESO:
ESCALA:
HOJA 1 DE 1

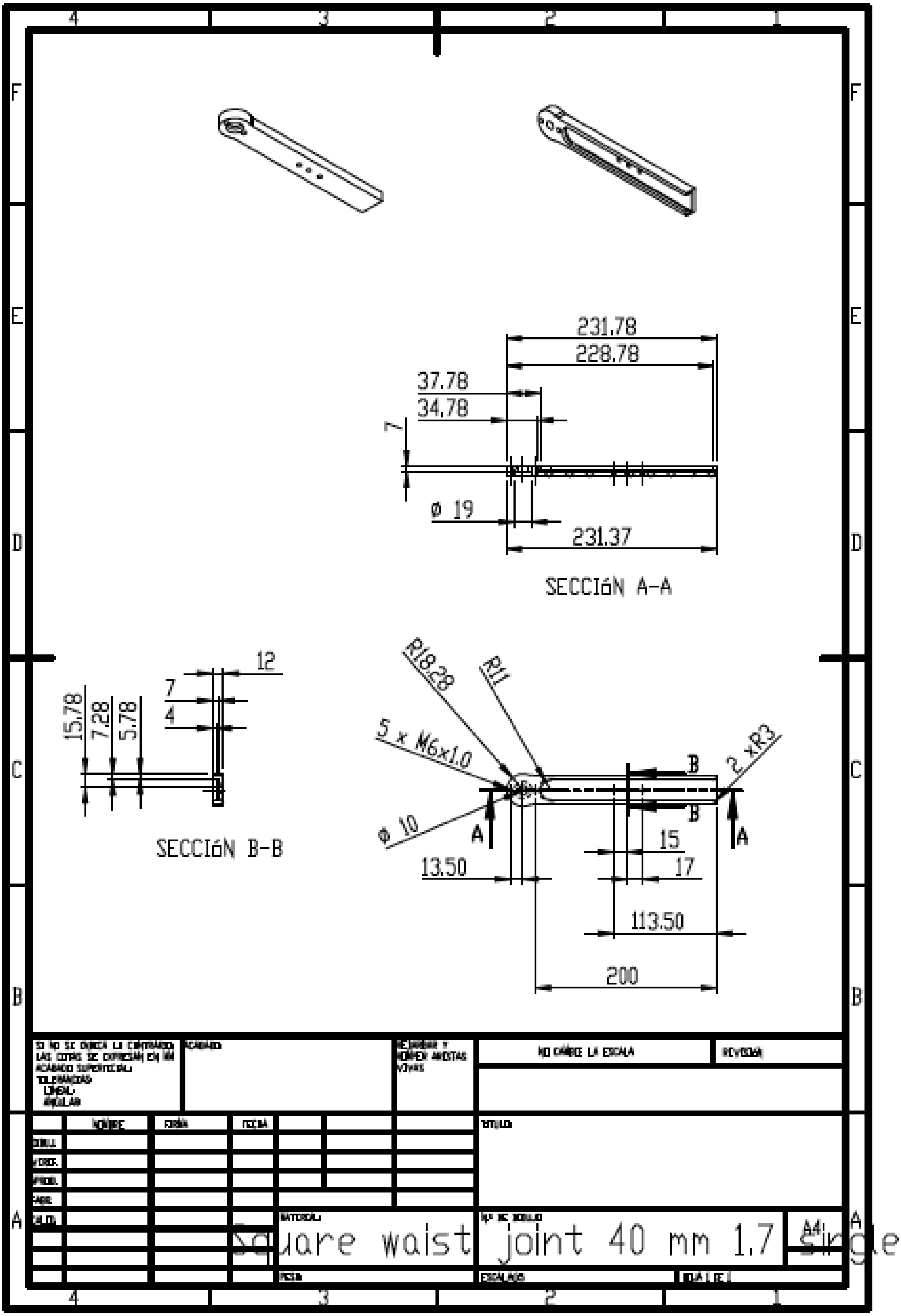

3 xØ 6
30
7,50
7,50
7
12
14
NO CAMBIE LA ESCALA
REVISIÓN
TÍTULO
MATERIAL
Spacer 1.1
A4

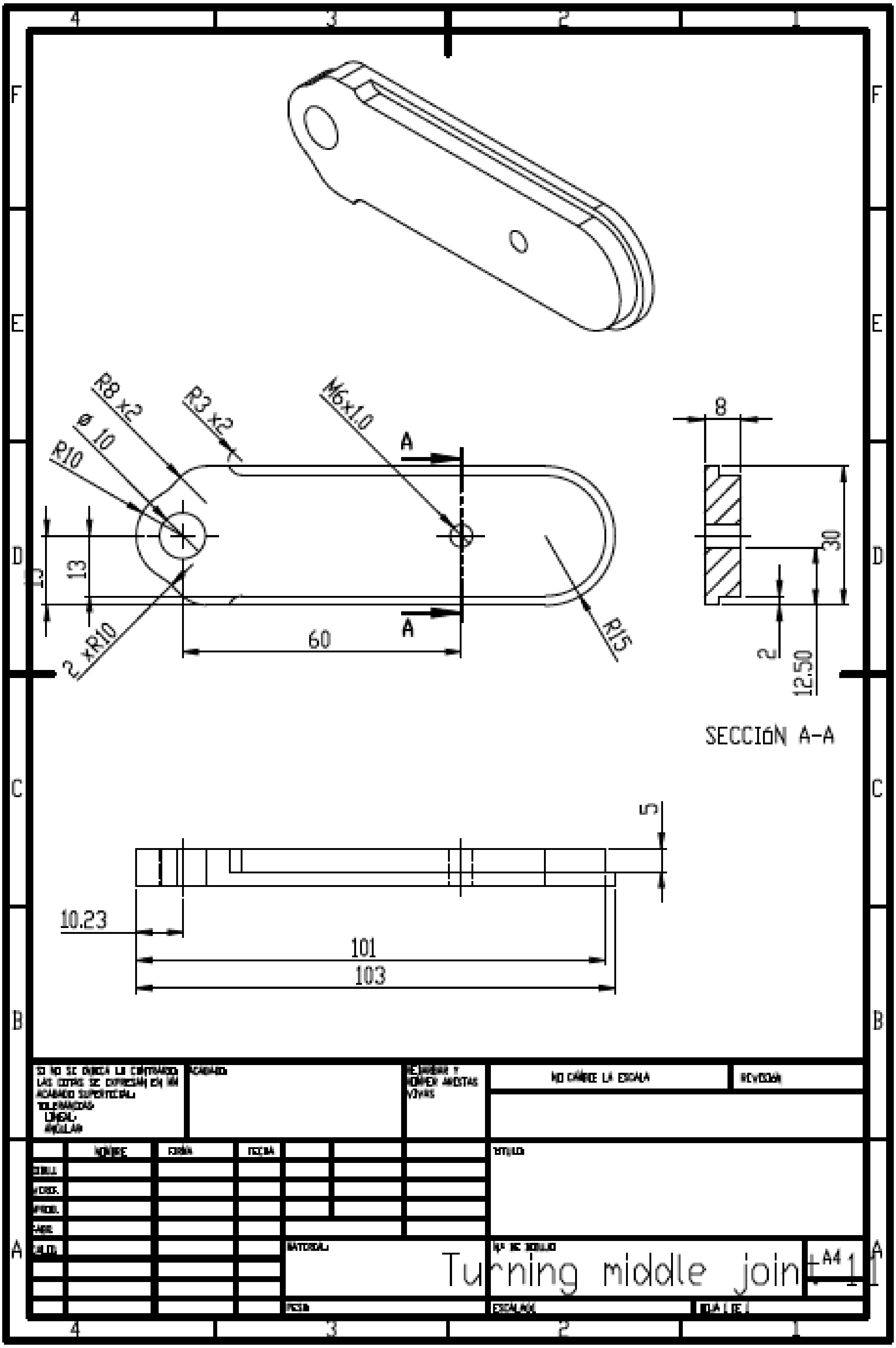

14
3
2
R1
4
1
M6
10
5
5
NO CAMBIE LA ESCALA
Spring lock 1.0
A4

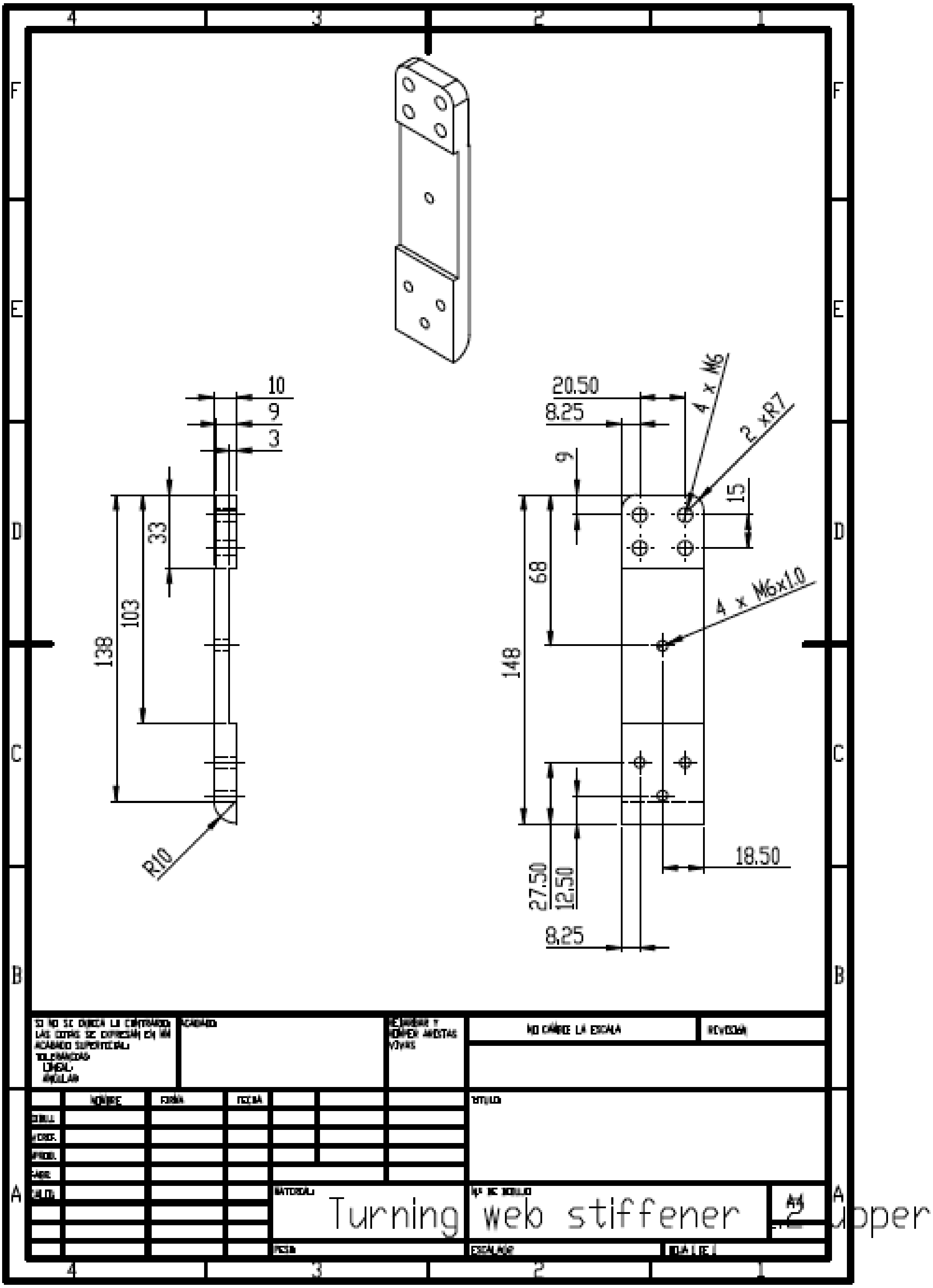


SECCIÓN A-A
R7.50
3 mm
2 x R3
2 x M6
12.50
6
R10.50
R16.50
R20
2 x R3
7.5 mm
150
R11
15
95
93.10
93.40
192
4 x R40
4
7
12
24
233.55
280.95
332
A
A
NO CAMBIE LA ESCALA
REVISIÓN
TÍTULO
MATERIAL
PESO
ESCALA
HOJA 1 DE 1
Square knee joint
A4

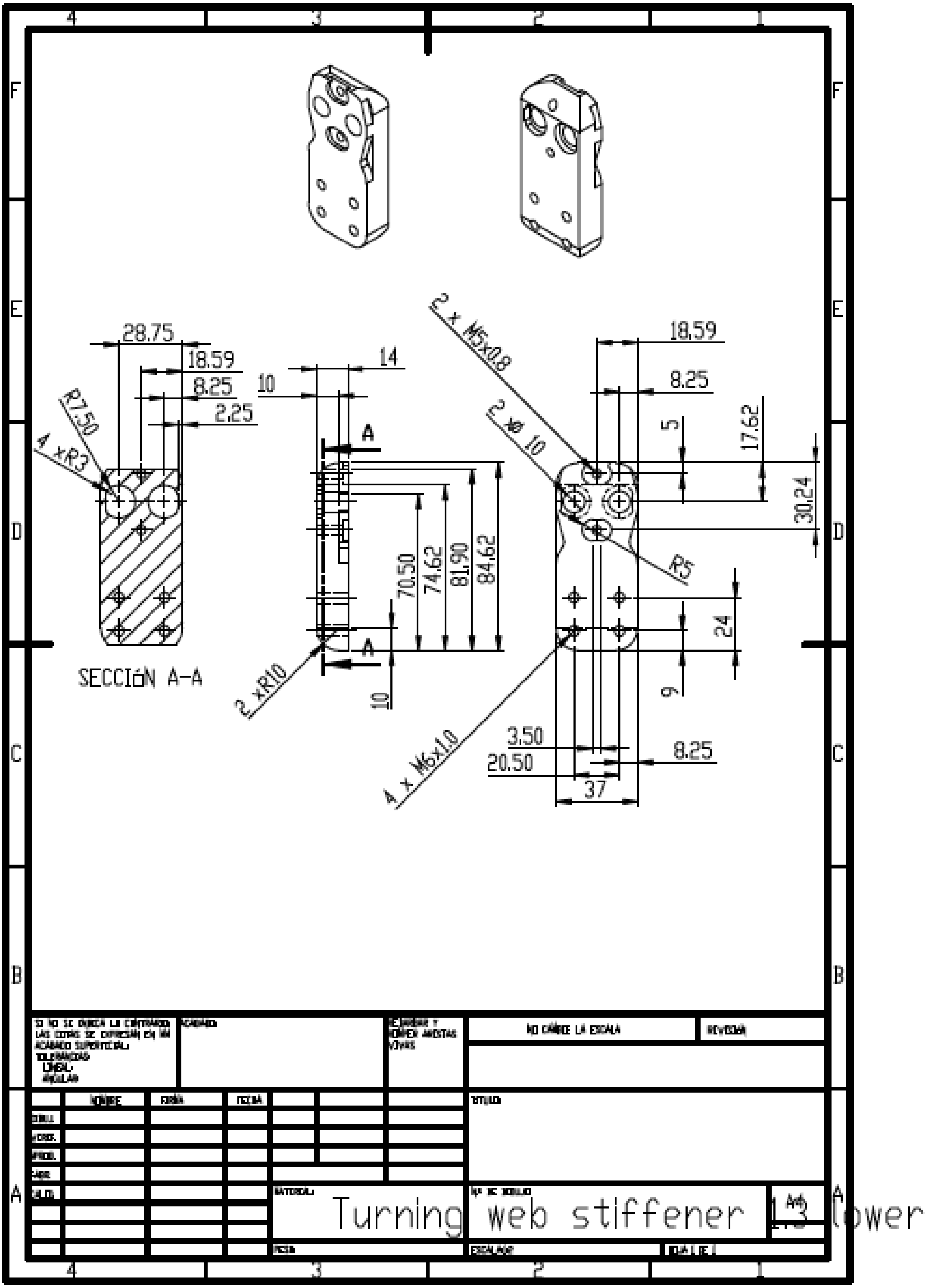

SECCIÓN B-B
231
192,44
191
12
6
3
7
ø 19
SECCIÓN A-A
4,50
1,50
13,50
2 xR2
A
B
R9
R20
ø 10
5 x M6
15
30,30
13,50
104
211
NO CAMBIE LA ESCALA
REVISIÓN
TÍTULO:
MATERIAL:
N.º DE DIBUJO
Square shank joint 1.3
A4
ESCALA:1:5
HOJA 1 DE 1

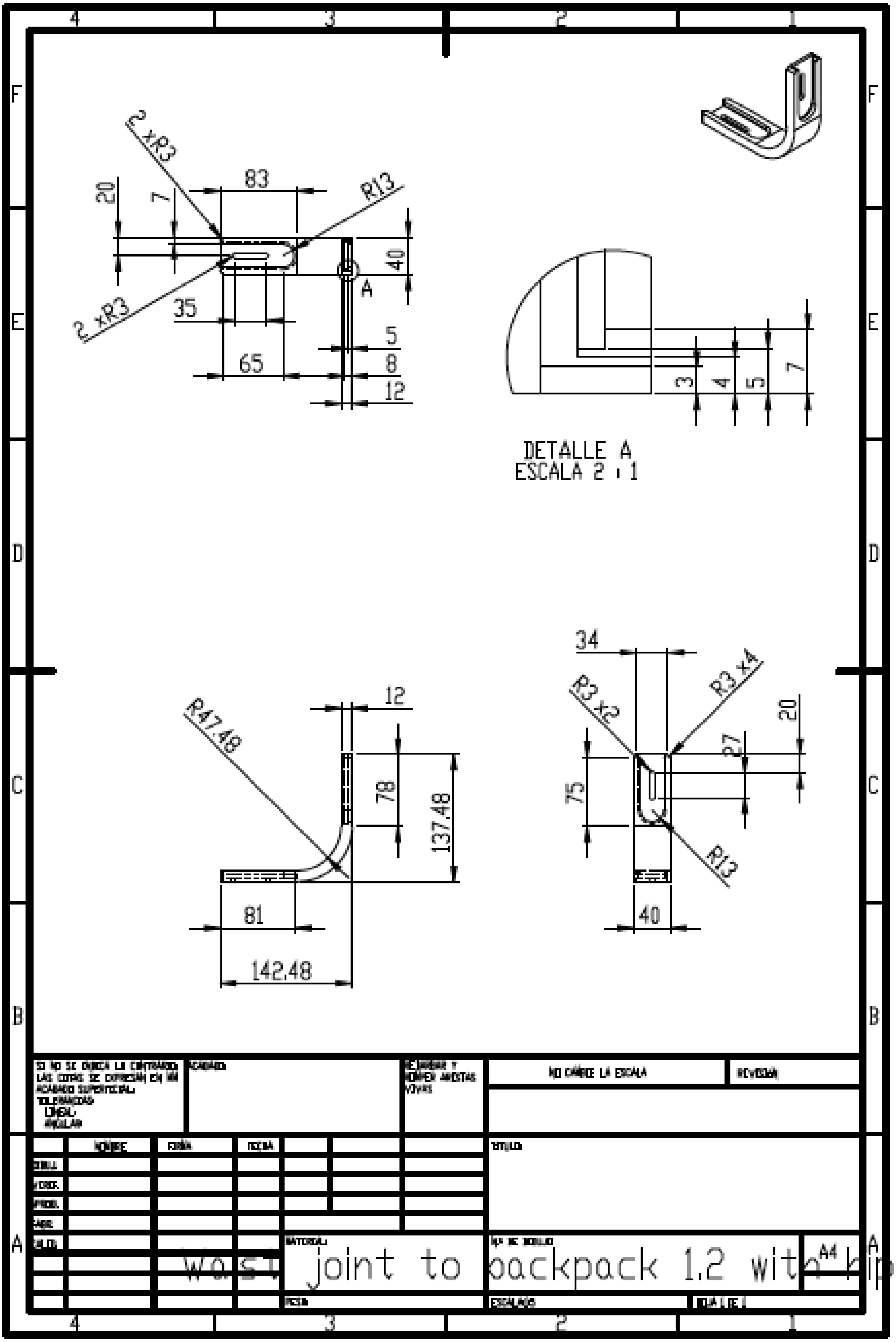

231.78
228.78
37.78
34.78
7
ø 19
231.37
SECCIÓN A-A
12
7
4
15.78
7.28
5.78
SECCIÓN B-B
R18.28
R11
5 x M6x1.0
2 xR3
B
B
ø 10
A
A
15
13.50
17
113.50
200
NO CAMBIE LA ESCALA
REVISIÓN
TÍTULO:
MATERIAL:
Nº DE DIBUJO
A4
Square waist joint 40 mm 1.7 Single
PESO:
ESCALA:1:5
HOJA 1 DE 1


R8 x2
ø 10
R10
R3 x2
M6x1.0
A
A
15
13
60
2 xR10
R15
8
30
2
12.50
SECCIÓN A-A
5
10.23
101
103
NO CAMBIE LA ESCALA
Turning middle joint
A4

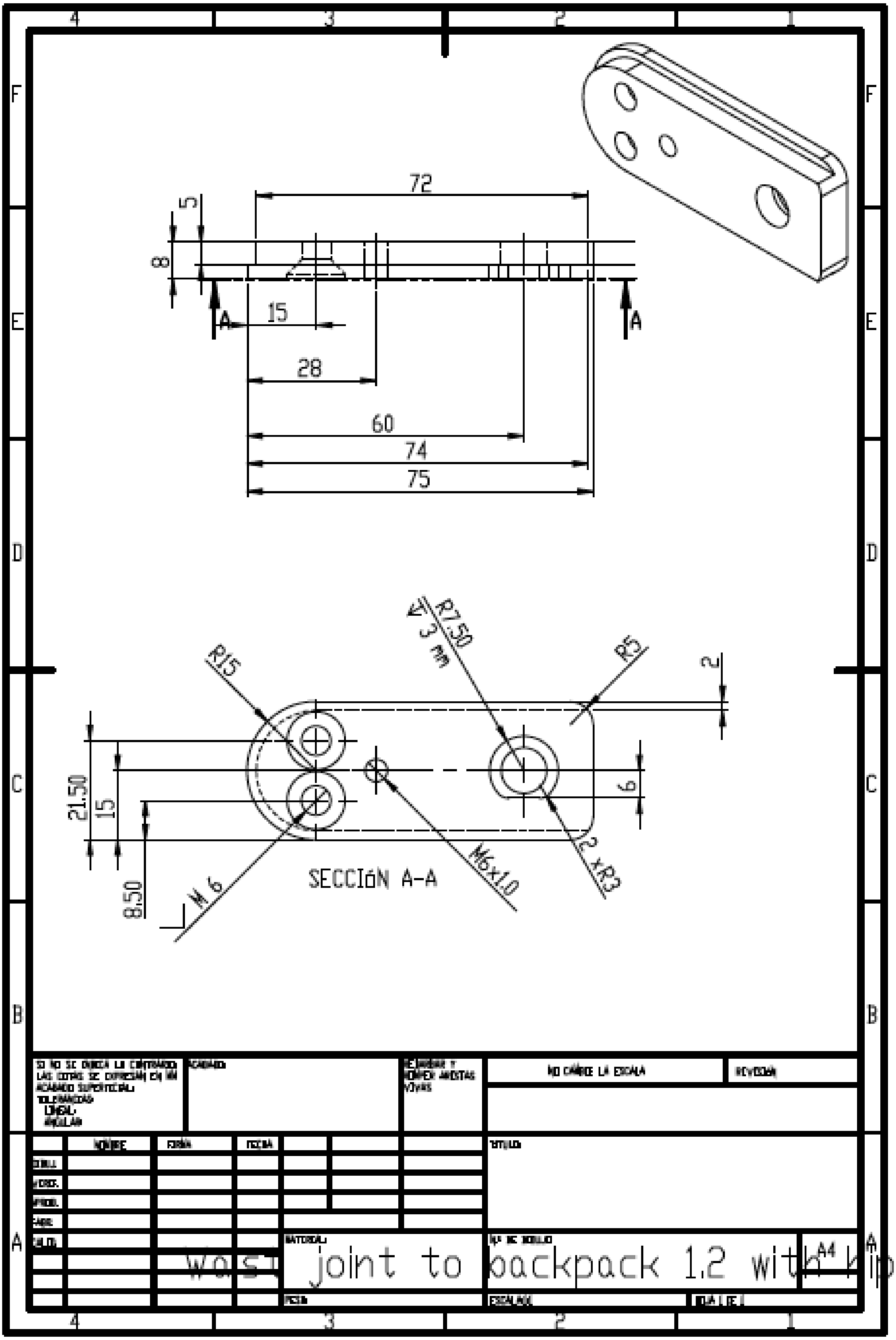


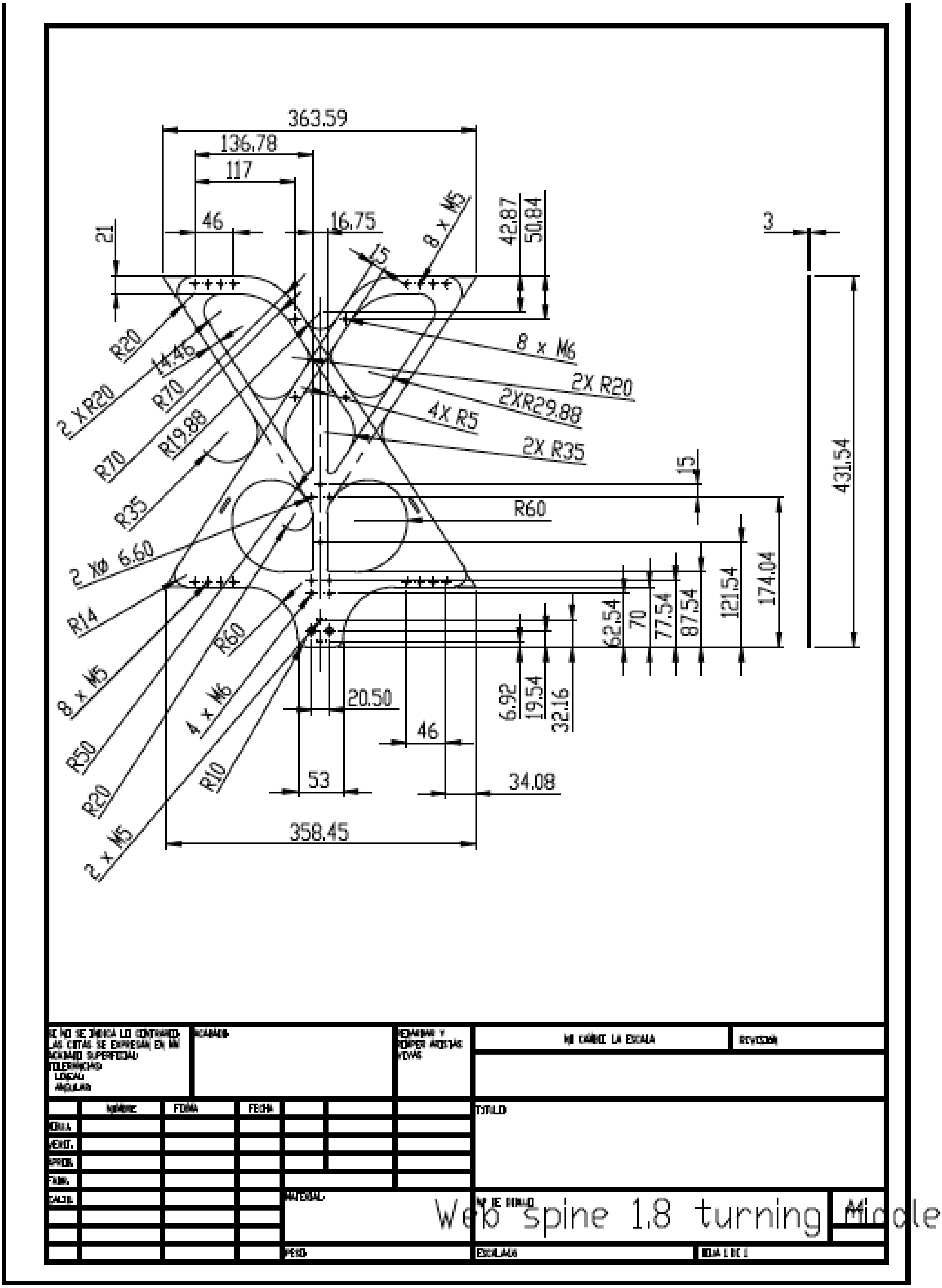
10
9
3
33
103
138
R10
20.50
8.25
4 x M6
2 x R7
9
15
68
148
4 x M6x1.0
18.50
27.50
12.50
8.25
NO CAMBIE LA ESCALA
A4
Turning web stiffener 2 upper

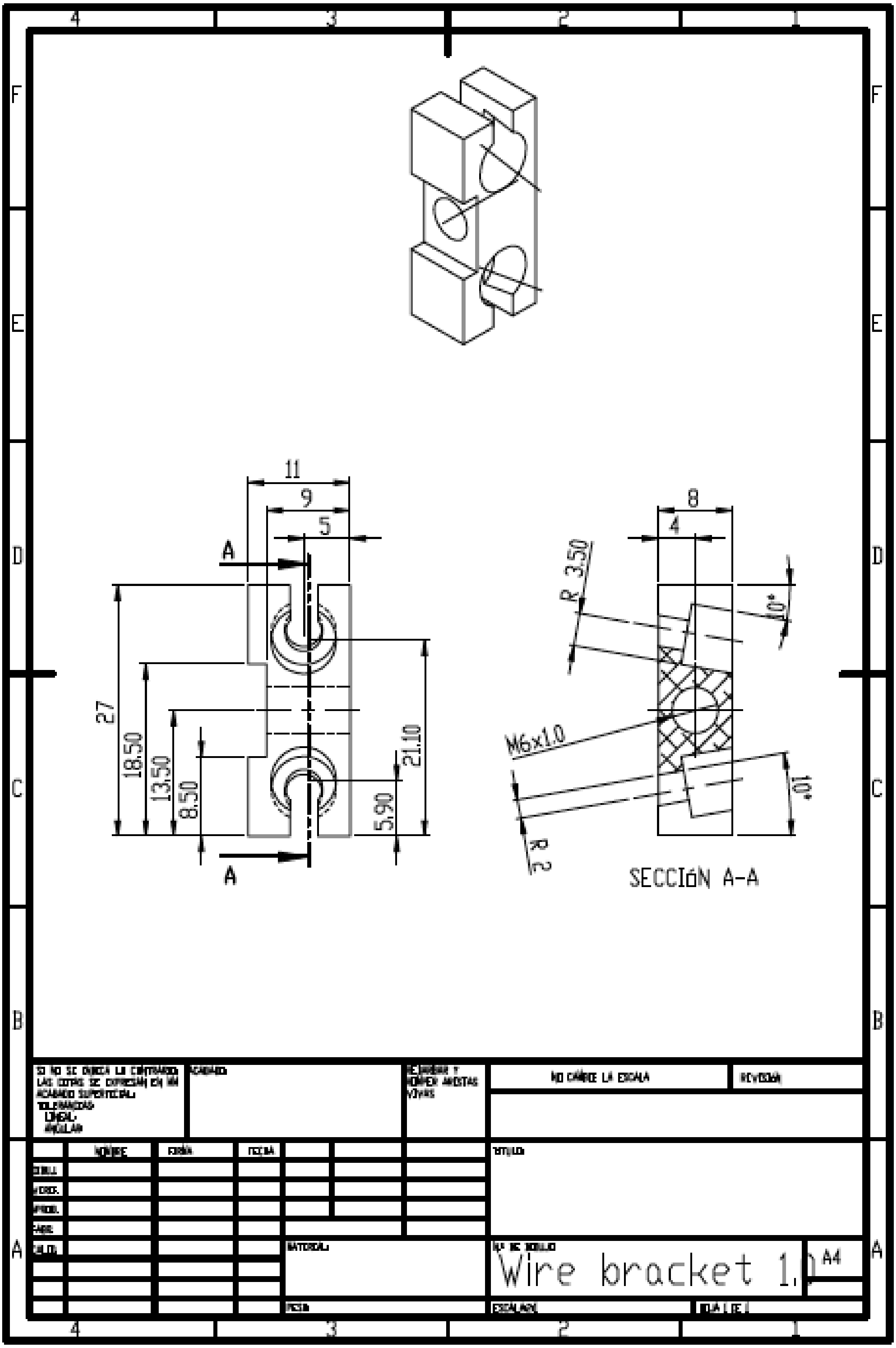

SECCIÓN A-A
28.75
18.59
8.25
2.25
R7.50
4 xR3
14
10
A
70.50
74.62
81.90
84.62
2 xR10
2 x M5x0.8
2 x Ø 10
R5
5
17.62
30.24
24
9
3.50
20.50
8.25
37
4 x M6x1.0
NO CAMBIE LA ESCALA
REVISIÓN
NOMBRE
FIRMA
FECHA
TITULO:
MATERIAL:
ESCALA:
Turning web stiffener 1.3 lower

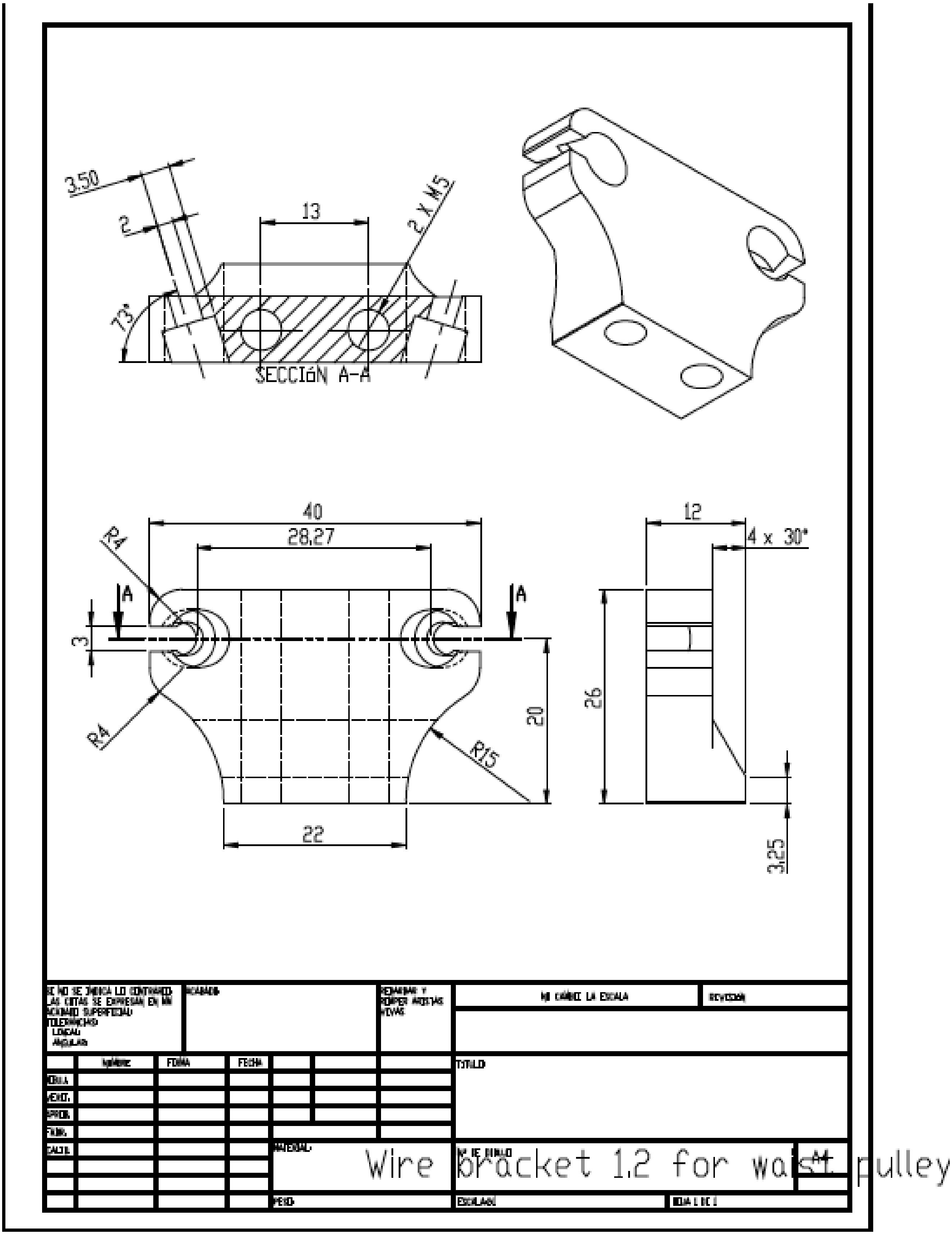


2 xR3
83
R13
20
7
40
A
2 xR3
35
5
65
8
12
DETALLE A
ESCALA 2 : 1
3
4
5
7
34
R3 x2
R3 x4
20
27
75
R13
40
12
R47.48
78
137.48
81
142.48
NO CAMBIE LA ESCALA
REVISIÓN
TÍTULO:
MATERIAL:
N.º DE DIBUJO
PESO:
ESCALA:
HOJA 1 DE 1
A4
Waist joint to backpack 1.2 with hip

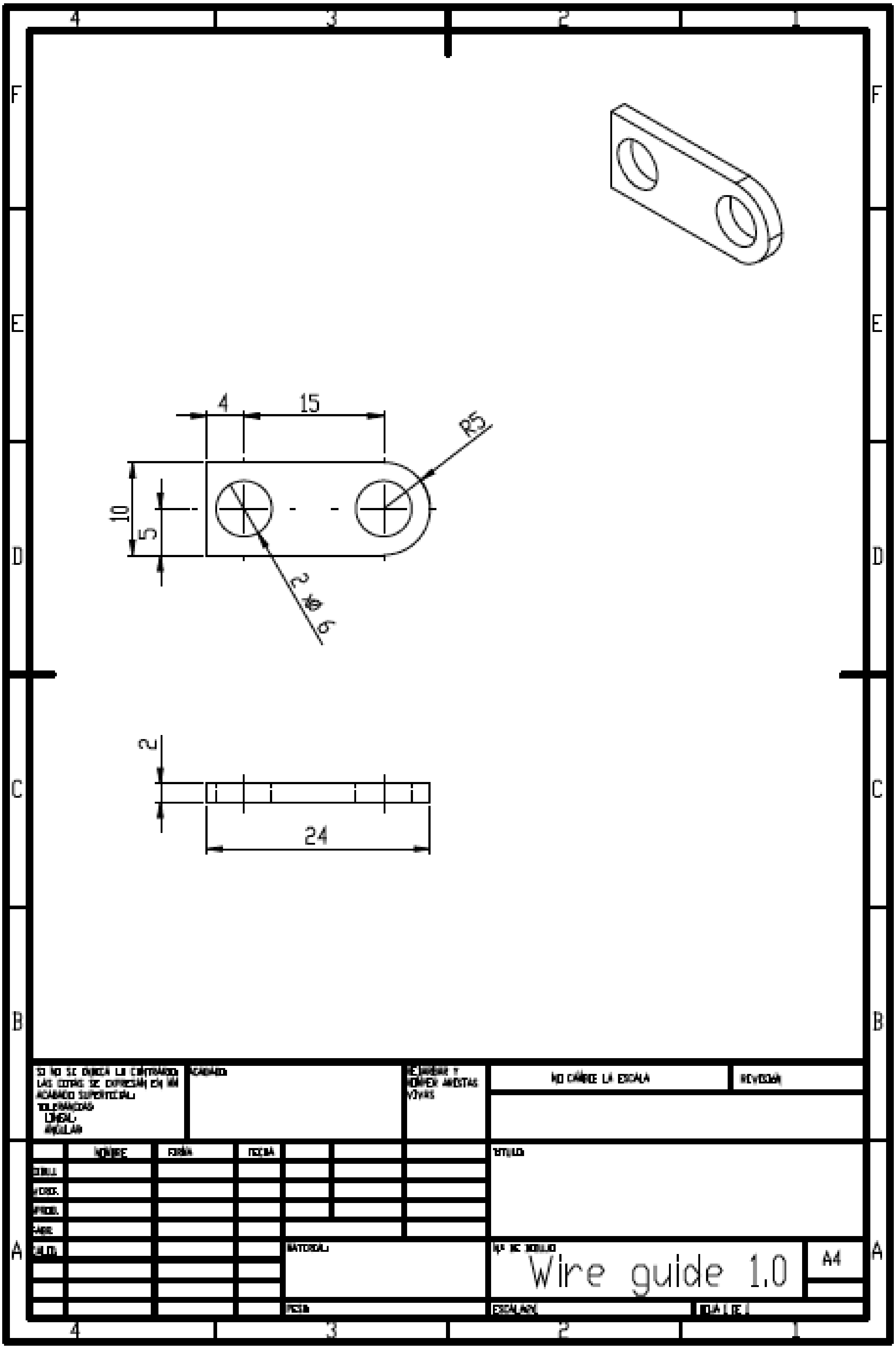

72
5
8
15
28
60
74
75
A
A
R7.50
3 mm
R15
R5
2
21.50
15
6
8.50
M 6
SECCIóN A-A
M6x1.0
2 xR3
NO CAMBIE LA ESCALA
REVISIÓN
TÍTULO:
MATERIAL:
Nº DE DIBUJO
A4
PESO:
ESCALA:1:1
HOJA 1 DE 1
waist joint to backpack 1.2 with hip


363.59
136.78
117
46
16.75
21
15
8 x M5
42.87
50.84
3
R20
14.46
2 X R20
R70
R70
R19.88
R35
8 x M6
2X R20
2XR29.88
4X R5
2X R35
15
R60
431.54
2 XØ 6.60
R14
174.04
121.54
87.54
77.54
70
62.54
8 x M5
R50
R60
4 x M6
R20
R10
2 x M5
20.50
6.92
19.54
32.16
46
53
34.08
358.45
Web spine 1.8 turning Middle
ACABADO
NO CAMBIE LA ESCALA
REVISION
NOMBRE
FIRMA
FECHA
TITULO
MATERIAL
PESO
ESCALA
HOJA 1 DE 1


11
9
5
A
A
27
18.50
13.50
8.50
21.10
5.90
8
4
R 3.50
10°
M6x1.0
10°
R 2
SECCIÓN A-A
NO CAMBIE LA ESCALA
Wire bracket 1.0
A4



3.50
2
13
2 X M5
73°
SECCIÓN A-A
40
28,27
R4
A
A
3
R4
R15
20
22
12
4 x 30°
26
3,25
NO CAMBIE LA ESCALA
REVISIÓN
TÍTULO
MATERIAL
PESO
ESCALA
HOJA 1 DE 1
A4
NOMBRE
FIRMA
FECHA
DIBUJ.
VERIF.
APROB.
FABR.
CALID.
ACABADO
REBARBAR Y ROMPER ARISTAS VIVAS
Wire bracket 1.2 for waist pulley


4
15
R5
10
5
2 x ⌀6
2
24
NO CAMBIE LA ESCALA
REVISIÓN
NOMBRE
FIRMA
FECHA
TÍTULO
MATERIAL
PESO
ESCALA
Wire guide 1.0
A4