Kaunas University of Technology

Faculty of Mechanical Engineering and Design

Development of Knee Exoskeleton for Physical Work

Master's Final Degree Project

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Project author

Prof. Egidijus Dragašius

Supervisor

Kaunas, 2023

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Mechatronics (6211EX017)

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3. I have not paid anyone any monetary funds for the final degree project or the parts thereof unless required by the law;

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Task of the Master's Final Degree Project

Given to the student – Martynas Zaleckis

1. Title of the Project

Development of Knee Exoskeleton for Physical Work

(In English)

Kelių egzoskeleto fiziniam darbui kūrimas

(In Lithuanian)

2. Aim and Tasks of the Project

Aim: to develop knee exoskeleton suitable to assist a person in physical work.

Tasks:

1. to compare existing different types of knee exoskeletons;
2. to design a knee exoskeleton frame to assist in physical work;
3. to select an actuator assisting the work of the muscles of the lower limbs;
4. to compare different types of materials in manufacturing of knee exoskeleton frame;
5. to select sensors for the exoskeleton that will count human body steps and squats;
6. to evaluate the cost of the knee exoskeleton, the influence in environment and sociality.

3. Main Requirements and Conditions

Von Mises Stress, safety factor, displacement, cost of 1kg filament of selected materials. The height and weight of an average Lithuanian. For an actuator of the required torque and speed. A drawing of the assembly is required. Maximum bending angles for the lower limb of the human body. Mounting the actuator in the exoskeleton frame so that it only works from 50 degrees of flexion. Electronic devices that will count a person's steps and squats. Battery working time for the microcontroller. Cost of knee exoskeleton.

4. Additional Requirements for the Project, Report and its Annexes

Not applicable.

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	(Name, Surname)	*(Signature)*	*(Date)*
Supervisor	Egidijus Dragašius		2023 03 03
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Martynas Zaleckis. Development of Knee Exoskeleton for Physical Work. Master's Final Degree Project, supervisor prof. Egidijus Dragašius; Faculty of Mechanical Engineering and Design, Kaunas University of Technology.

Study field and area (study field group): Production and Manufacturing Engineering (E10), Engineering Sciences (E).

Keywords: knee exoskeleton; calf support; thigh support; polyethylene terephthalate glycol; safety factor.

Kaunas, 2023. 66 p.

Summary

The purpose of the knee exoskeleton is to assist humans in physical work that requires leg muscle work, such as correctly lifting an object off the ground. The purpose of this study is to develop a knee exoskeleton. In order to produce this, it was decided to 3D print the exoskeleton of the knee, which means that the exoskeleton frame will be made of PETG plastic, since after research it was found that this plastic had the best ratio between durability and cost. A gas spring was chosen as the device that provides additional force to a person during squatting and standing, because the analysis revealed that there are no such electronic devices that correspond to speed, distance and force, only using a gas spring it was possible to give up the speed, and the other parameters coincided. The lower attachment of the gas spring will be in the slider in the guide, since only from an angle of 50 degrees the gas spring could do its work, in which case the exoskeleton will not interfere the person while walking. Electronic components have been selected such as a micro switch that will count the steps taken by the person, and a micro photoelectric sensor that will count the squats taken by the person, based on which it will be possible to decide when exactly the gas spring needs to be replaced, as “Suspa” manufacturers say that wear can occur between 10,000 and 100,000 thousand contractions and relaxations. Based on the measurements of steps, it will be possible to decide how many individual steps a person takes during work. A microcontroller that will be able to send signals to a computer via Wi-Fi and process them there will be used. The selected lithium power source will allow the electronic components to work non-stop for about 10 hours. In order to reduce the environmental pollution of PETG plastic, solutions have been proposed, such as the use of recycling options and printing methods, such as would allow reducing the amount of waste. After calculating the cost of the components, it was found that the amount will not exceed 300 euro. The sociality of the knee exoskeleton is such that it will be able to be worn in everyday life, like by a pensioner with weakened leg muscles.

Martynas Zaleckis. Kelio egzoskeleto fiziniam darbui kūrimas. Magistro baigiamasis projektas, vadovas prof. Egidijus Dragašius; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.

Studijų kryptis ir sritis (studijų krypčių grupė): Gamybos inžinerija (E10), Inžinerijos mokslai (E).

Reikšminiai žodžiai: kelio egzoskeletas; blauzdos apsauga, šlaunies apsauga; polietileno tereftalato glikolis; atsargos koeficientas.

Kaunas, 2023. 66 p.

Santrauka

Kelio egzoskeleto paskirtis padėti žmonėms fiziniame darbe, kuriame reikalaujama kojų raumenų darbas, kaip taisyklingas daikto kėlimas nuo žemės. Šio tyrimo tikslas yra kelio egzoskeleto sukūrimas. Norint tai pagaminti, buvo nuspręsta kelio egzoskeletą gaminti 3D spausdinimo būdų, o tai reiškia, kad pats egzoskeleto rėmas bus pagamintas iš PETG plastmasės, kadangi atlikus tyrimą buvo išsiaiškinta, kad šios plastmasės santykis tarp patvarumo ir kainos buvo pats geriausias. Prietaisas suteikiantis papildomos jėgos žmogui tūpiant ir stojantis buvo pasirinkta dujinė spyruoklė, dėl to, kad atlikus analizę buvo išsiaiškinta, kad nėra tokių elektroninių prietaisų, kurie atitiktų greitį, eigą ir jėga, tik naudojant dujinę spyruoklę buvo galima atsisakyti greičio, o kiti parametrai sutapo. Apatinis dujinės spyruoklės įtvirtinimas bus kreipiančiojoje esančiame šliaužiklyje, dėl to, kad tik nuo 50 laipsnių kampo dujinė spyruoklė galėtų atlikti savo darbą, tokiu atveju egzoskeletas netrukdys žmogui eiti. Elektroniniai komponentai buvo parinkti kaip mikro jungiklis, kuris skaičiuos žmogaus atliktus žingsnius, mikro fotoelektrinis jutiklis, kuris skaičiuos žmogaus atliktus pritūpimus, pagal tai bus galima nuspręsti, kada tiksliai reikia pakeisti dujinę spyruoklę, kadangi „Suspa“ gamintojai teigia, kad susidėvėjimas gali atsirasti tarp 10,000 ir 100,000 tūkstančių susitraukimų ir atsileidimų. Pagal atliktus žingsnių matavimus, bus galima nuspręsti kiek individualiai žmogus atlieka žingsnių darbo metu. Mikro kontroleris, kuris Wi-Fi būdu galės siųsti signalus į kompiuterį, o ten juos apdoroti, bus naudojamas. Pasirinktas ličio energijos šaltinis leis elektroniniams komponentams veikti be sustojimo apie 10 valandų. Norint sumažinti PETG plastmasės taršą aplinkai, buvo pasiūlyti sprendimai, kaip perdirbimo galimybių naudojimas ir spausdinimo būdai, tokie, kurie leistų sumažinti atliekų kiekį. Apskaičiavus komponentų savikainą išsiaiškinta, kad suma neviršys 300 eurų. Kelio egzoskeleto socialumas yra toks, kad jį bus galima dėvėti kasdieniame gyvenime, kaip pensijinio amžiaus asmenims, kurių kojų raumenys yra nusilpę.

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Introduction

Many different careers in modern life need physical exercise, but not everyone can work in such a position. Jobs such as pickers, couriers, construction workers, furniture makers and countless others require strong legs that can handle a full day's work. People who have leg muscle pain or weakness may find it difficult to do work that requires them to squat to pick up an object. Because of these conditions, it is possible to harm yourself even more, simply because weakening leg muscles allow you to raise items from the ground unevenly, which will create back discomfort. To avoid this, it is best to wear a knee exoskeleton intended to make physical labour easier. Numerous studies have shown that when wearing an exoskeleton, the muscles of the human body contract much less during work than when not wearing it. As civilization evolves, so do mechatronic systems; among the developments are exoskeletons; before, they were all immobile and weighed hundreds of kilos, but now there is a wide range of low-weight exoskeletons. Exoskeletons are classified into two types: passive, which contain no electronic equipment and as actuators usually springs and rubber bands are used, and active, which feature sensors and electrical, pneumatic, or hydraulic actuators. However, because the knee exoskeleton must be mobile, the chosen actuator must be as light as possible and not require an excessive amount of energy. The knee exoskeleton must be built of a light and sturdy material, such as plastic, in which case 3D printers will be used to produce the exoskeleton itself. In terms of the polymers that can be created using 3D printers, study will be required employing various plastics, taking into account their durability and cost. To carry out the research, it will be required to determine the average weight of human body components as well as the forces imposed on the exoskeleton. The environmental degradation caused by the use of plastic in printing must also be considered. It must be determined how pollution to nature can be reduced or eliminated entirely. The exoskeleton must be as comfortable as feasible and restrict motions as little as possible, otherwise, it will have a detrimental impact on a person's movements. When walking and squatting, the bending angles of the lower part of the human body must be determined. The exoskeleton must be able to flex to the resultant angles as well. To determine how many steps and squats will be completed while wearing the exoskeleton, electrical components such as sensors, a microprocessor, and a battery will be required. This knee exoskeleton project should be beneficial not only for those who undertake manual labour but also in their daily lives. For example, when people reach retirement age and have torn leg muscles, they will be able to wear this exoskeleton and aid their leg motions. Exoskeletons are very important in modern life in order to help people live fulfilling lives.

Aim: to develop knee exoskeleton suitable to assist a person in physical work.

Tasks:

1. to compare existing different types of knee exoskeletons;
2. to design a knee exoskeleton frame to assist in physical work;
3. to select an actuator to assist the work of the muscles of the lower limbs;
4. to compare different types of materials in manufacturing of knee exoskeleton frame;
5. to select sensors for the exoskeleton that will count human body steps and squats;
6. to evaluate the cost of the knee exoskeleton, the influence in environment and sociality.

Hypothesis: Knee exoskeleton will provide additional strength during squatting and standing.

1. Applicability of Exoskeleton in Physical Work

Exoskeletons are not very popular in the modern world, due to their complexity, price and lack of versatility. The knee exoskeleton helps a person to do physical work. It provides:

- Additional power to make a movement.
- Movement with less pain if there is an injury.
- To facilitate the work of human body muscles.
- Reduced muscle fatigue after a working day.
- Comfortable work.
- Ability to work in physically demanding work with muscles or injury.

In order for the exoskeleton to perform its work positively, it is need:

- Strong and comfortable constructions.
- Easy to use access. Working principle.
- Properly secured actuators and sensors.
- Understand the possible angles of bending the human knee.
- Understand the anatomy of the human leg.

In order to create a suitable exoskeleton to wear, it is necessary to first examine the different exoskeletons that have already been created and take some of their inputs.

1.1. Relevance of Exoskeleton in Physical Work

Exoskeletons are relevant these days because they make human life easier. They can be used in rehabilitation, physical work, or without any human limb as an electronic or artificial replacement. Any type of physical work can cause a muscle pain. Overhead labour produces hand muscle and bone discomfort, which is a significant concern in today's workplace. Physical work as attaching parts to the automobile base, drilling to secure screws, and inserting fasteners into the frame are all commonplace in particular sectors. Such effort results in complicated and concurrent tissue stressors such as contraction and reduced blood flow. It is necessary to have an exoskeleton here on hands to lessen this, but experimental investigations are required to ensure that the exoskeleton would truly avoid hand discomfort and that the outcome will be visible. To fulfil the requirement for hand exoskeleton, this is required to investigate the power and periodicity of human muscular tension during specific task with and without exoskeleton, see Fig. 1.

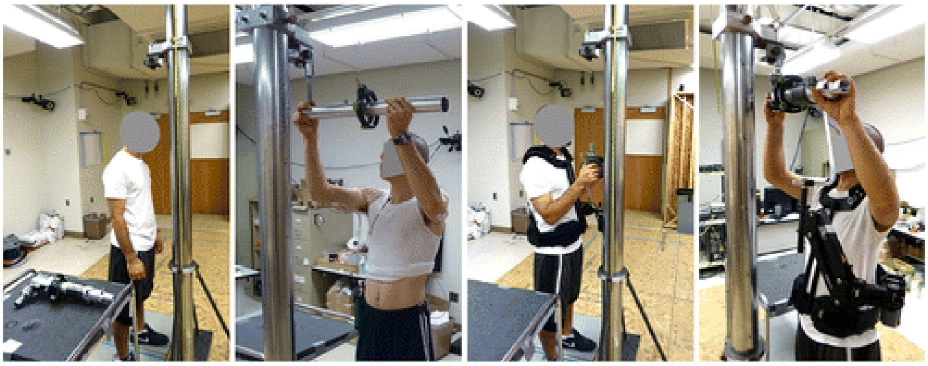

Fig. 1. Overhead tasks performed without and with exoskeleton [1]

Sensors that can detect the work of a muscles must be linked to them while the human, for example, drills through the ceiling [1]. In certain cases, the exoskeleton should tighten the muscles greater than they would be without it. Because the stress communicated to the back whenever the arms are elevated, an experiment on the spinal column is also required [2]. The experiment is carried out by holding the wrists above the head, as if drilling a hole into the ceiling, at a different height and at an interval of time using the "Ekso Vest "exoskeleton. To assess the level of muscle contraction, however, a sensor must be placed to the bottom, top, and corners of the back. The findings revealed that even after wearing an exoskeleton twice, muscular fatigue is minimized in certain hand postures. Because the legs are exposed to stresses from the arm and back exoskeletons, an armour of the feet is necessary to shorten rest time. The exoskeleton, on the other hand, must be pleasant for the user, as the pain and roughness of the legs into the framework of the exoskeleton might be as exhausting as without it. In order to create motion, input data that represents the system's motion as a human move is required [3]. This experiment was carried out utilizing "Contemplas" technology, which examines the leg motions and the rotational angle of each joint in a walking person, such as the hips, knees, and ankles, just like in the Fig. 2.

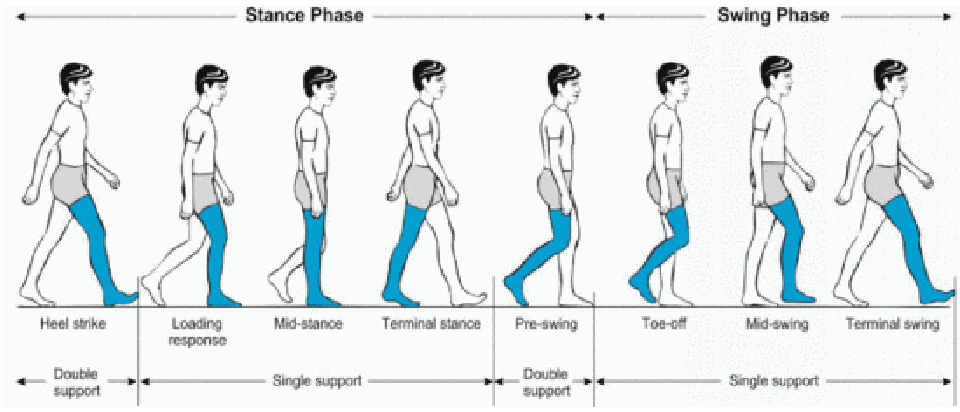

Fig. 2. Human gait stages when walking [3]

The basic idea behind the test is that camera-based sensors were used to track body motions, and the data was uploaded to software dubbed "Templo motion software," where it was examined. The test can be used to calculate the degrees of freedom and angle of each armour joint. Based on this information, an exoskeleton is built in the legs, allowing an individual to move freely while using fewer leg muscles. As the end, the individual is far more effective. In conclusion, there are countless studies done with and without exoskeletons while doing some kind of physical work and it has worked with results where we see that wearing an exoskeleton reduces muscle tension and makes physical work easier.

1.2. Passive and Active Exoskeletons

Without the requirement for case-by-case robot instruction programming, exoskeleton technology has the ability to combine people to make and robot power enhancement. Engineers have been working tirelessly to build novel exoskeletons for military, rehabilitative and industrial uses in order to capitalize on this critical benefit. These exoskeletons are classed as active or passive actuation. Active exoskeletons continue to suffer from a lack of agility, dexterity, dependability, and energy economy. Because of these limitations, they are not suited for use in real industrial processes, even though they offer the ability to give more reactive and accurate help from feedback of Rom sensors. As illustrated in Fig. 3, the unique multi-linkage passive mechanism is designed and proposed to provide appropriate assistive torque released by spring energy based on the angle of the upper arm exoskeletal [4].

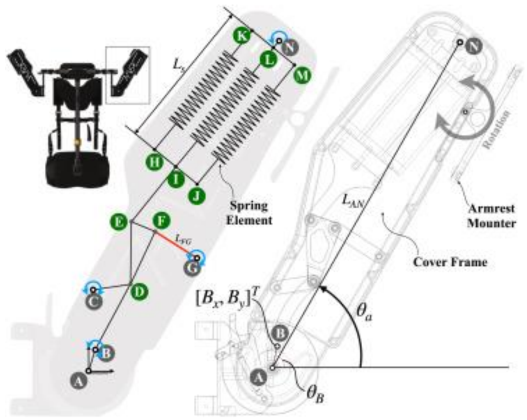

Fig. 3. Exoskeletal upper arm with multi-linkage spring-energy dissipation mechanism [4]

Its lightweight mechanism is composed of components joined at joints connected to the covering framework and other floating joints inside the cover frame, enabling the mechanism to be concealed within the thin cover frame. Another force material, such as bandages, might be used in a passive exoskeleton. The Ergo-Vest is a passive exoskeleton with elastic elements that function in concert with the erector spinal muscle to transmit force from the spine to the shoulders, hips, and upper legs [5]. These elastic pieces are placed on top of the user's garments on the body's surface. When doing lifts, they are strained and tensile energy is stored. This stored energy is released during the up portion of lifting to reduce the energy demands on the involved muscles. The Ergo-Vest is well-known for its light, adaptable fabric and flexibility, inexpensive cost, and suitable for long working hours. The following are critical Ergo-Vest components. Shoulder belts, which resemble backpack straps, are made of soft, wide foam to relieve local pressure. The back elastic band is positioned on the sleeves to hold the straps in place and prevent them from slipping outward, assuring Ergo performance. Vest's Lumbar elastic bands connect the top border of the lumbar cushions to the trailing edge of the straps in the upper area of the back. Elastic bands run parallel to the armature spinal musculature and are in charge of storing and releasing energy during lifting actions. The spinal cushions were designed to prolong the torque arms of bands, minimizing the force applied to the spine while increasing the weight. A waist belt was attached to the waist for proper Ergo-Vest installation. The pelvic support is made of a large, soft, waterproof, and quasi-fabric to improve the force distribution surface and thereby ease the local strain on the pelvis. The leg elastic band runs parallel to the thigh and connects to the back of the thigh strapping from the pelvic support's bottom border. To avoid local stress in the front of the thigh, the leg strap is comprised of a soft, wide, and flexible pad. Active exoskeletons are much more expensive, although they are capable of that passive exoskeletons could not do. Powered exoskeleton robotics for improving physical capabilities and recovery therapy has garnered a lot of interest during the last two decades. Exoskeletons with different actuators, including hydraulic actuators, electrical motors, series elastic actuators, and pneumatic muscle actuators, are being created for a wide range of use situations. The hydraulically operated exoskeletons Berkeley and Sarcos are iconic [6]. Figure 4 displays a fluid knee exoskeleton concept. A hydraulic cylinder with a piston rod is fitted between both the knee and the shaft of the exoskeleton robotic leg to actuate the knee joint. The cylinder is guided by high-pressure hydraulic fluid, which is regulated by the valve, as well as the orifice opening is regulated by the input voltage of the valve.

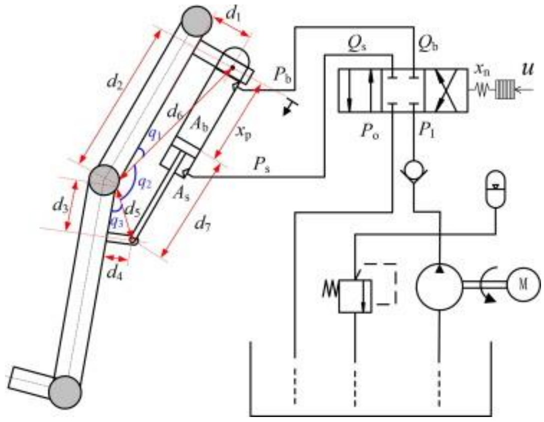

Fig. 4. Knee exoskeleton powered by hydraulic piston [6]

A hydraulic cylinder can handle a lot of weight, but this design requires a pump to carry the oil to and from the cylinder. This exoskeleton is for rehab only, as you won't be able to go anywhere with it far from all the rest of the equipment like the pump and power source which are stationary. If these components are assembled into the exoskeleton itself, the mechanism would be too heavy and it would only complicate the wearer's movements. Many lower-limb exoskeletons are now in development, and the possibilities for these technologies are considerable. They've been used to reduce both ordinary and load-carrying walking's metabolic expenditure. They may be useful in the treatment of people with gait disorders and in enhancing the balance of the elderly [7]. Imagine rescue professionals employing exoskeletons to carry individuals to safety from disaster areas, or disabled persons using exoskeletons for complex locomotor activities like traveling over rocky terrain in the future. End-effector for the knee exoskeleton and an emulator system, see Fig. 5.

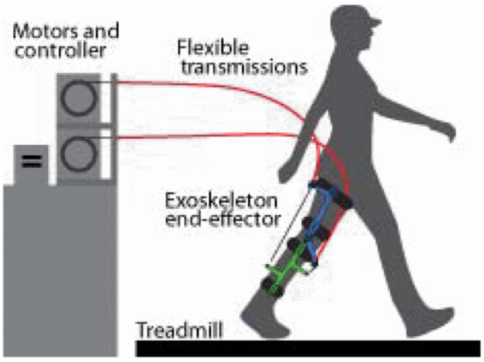

Fig. 5. Exoskeleton usage scheme [7]

Mechanical power is transferred to the end-effector by flexible Barlow cable transmissions from strong off-board motors (red). The end-effector is separated into two primary sections: the thigh (blue) region and the calf’s section (green). These are linked by an aluminium rotary joint that is roughly collocated with the human knee's centre of rotation. The gadget is secured to the user's thigh by four cushioned bands positioned at the top of the leg, just above the knee, under the knee, and over the ankle. Two strong off-board servo motors and a true controller drive the knee exoskeleton end-effector, with mechanical power delivered through flexible Bowden wire tethers. This system's controller and tether are detailed in depth. This exoskeleton propulsion device is a servo motor that tightens or loosens the ropes, but as in the previous review, this exoskeleton is only for rehabilitation and most of the components like the motor and the control board are stationary. This device could be used if physical work would be stationary. In conclusion, exoskeletons are of two types passive and active. Passive exoskeletons have no additional electrical, pneumatic, or hydraulic propulsion. The rescue force is developed from springs, elastic materials, or a simple pneumatic device such as a gas spring. Active exoskeletons have sensors, and electrical, hydraulic, or pneumatic propulsion devices.

1.3. Different Types of Actuators Used in Exoskeletons

As technologies advancing, actuators became much smaller and especially stronger, thanks mostly to advances in motor and cell technologies, making it easier to build exoskeletons with higher weight-bearing capacity and range enabling long-distance usage. Even the elements used to build the exoskeleton's structure have progressed; by employing aluminium and carbon fibre, the bodysuit has become significantly lighter, and complex designs can be easily constructed [8]. The management system, too, has grown into a compact computer with great system control. It is now possible to make an anthropomorphic exoskeleton using small actuators and the ease of manufacturing the body. These advancements must be understood in order to advance in the sector. Figure 6 depicts a comparison of the technology of actuators used in exoskeleton systems.

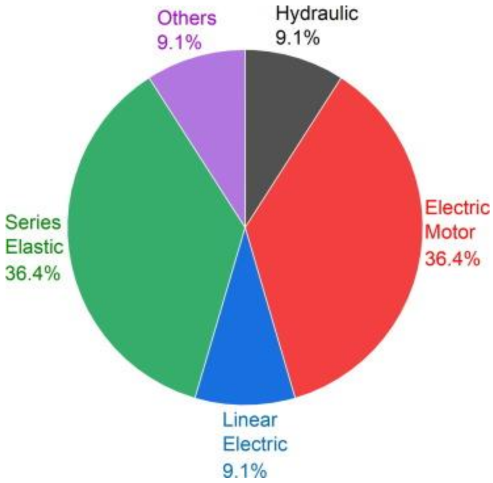

Fig. 6. Exoskeletons usage of actuator technology [8]

Because augmentation exoskeletons need high force value systems to lift heavy objects, hydraulic actuators are used; however, due to the need for valves and pumps for actuation, they are also very heavy; instead, sequential servos are a great choice as they may also provide high force, are easily manipulated, and do not need any extra equipment [9]. Since precise ranges of motion with optimal and adjustable speed and torque are necessary for the field of assistive exoskeletons, servo engine actuators are highly preferred because they are easily controlled and the duration can be monitored. Some have also used elastic actuators, that are light in weight and have a fixed range, eliminating the need for extra sensors to stop at a set range.

1.3.1. Floating Spring Type Actuator

The bidirectional antagonism variable stiffness and floating spring joint types were combined to create an actuator design, as shown in Fig. 7. Both VIACTORS consortium versions have quite diverse features, particularly in terms of motor size [10]. The rotating spring joint is equipped with two motors of varying sizes, one for establishing the joint's location and the other for changing the rigidity present at the joint. The bidirectional antagonistic variable stiffness, in contrast, hand, consists of two identical motors that total their torques via variable stiffness mechanisms in the output, with stiffness being modified by the motion relative between each.

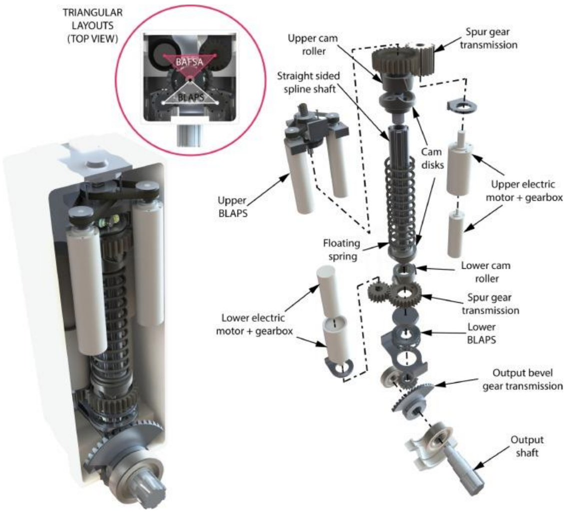

Fig. 7. Bidirectional antagonistic variable stiffness actuator mechanism and components [10]

Combining the hanging spring joint and bidirectional adversarial variable stiffness models presented in this work resulted in the design of an actuator with a convenient slender structure suitable for attachment along the thigh segment of an exoskeleton, as well as its cam form and other variables to make the output conform with the previously established design specifications. It was not possible to scale any of the four models, or any of the variable resistivity motors known so far, to create an actuator aimed at the knee joint. The output ranges would not have fit in a readily correlated fashion; especially, the torque-stiffness connection is particularly sensitive to design factors, and those devices were created for distinct uses. Furthermore, for the same reasons indicated above, merely scaling conventional variable impedance actuators would have resulted in power-to-mass, power-to-volume, maximum torque-to-mass, and maximum torque-to-volume ratios improper for the knee joint. The bidirectional oppositional variable stiffness actuator has a triangle configuration for compactness: one vertex has a straight-sided spline shaft, and the other two have one electric motor each, all axially aligned as shown in Fig. 7. A cam disk attached through the simple splines is attached to either side of the shaft, as is a cam roller linked to a single motor via a spur gearbox. The shaft extends out on one of the ends, securing a bevel gear whose crown is attached to the actuator's output shaft.

1.3.2. AC Motor Type Actuator

When the foot connection makes contact with the surface, it transmits the weight of the human or exoskeleton to the ground. Four force sensors are also included in the foot link to monitor ground response forces. The efficacy of the robust outputs feedback assistance control approach is examined in this study in a unique type of motion known as VSwing motion when the foot does not make contact with the floor [11]. Also, the output data assistive control approach does not require ground reaction force feedback. As a result, the robot's foot link is unnecessary. A healthy user wears the FUM-KneeExo with its foot connection disconnected, and the knee stresses are measured in two pairs of aided and unassisted motions as shown in the Fig. 8.

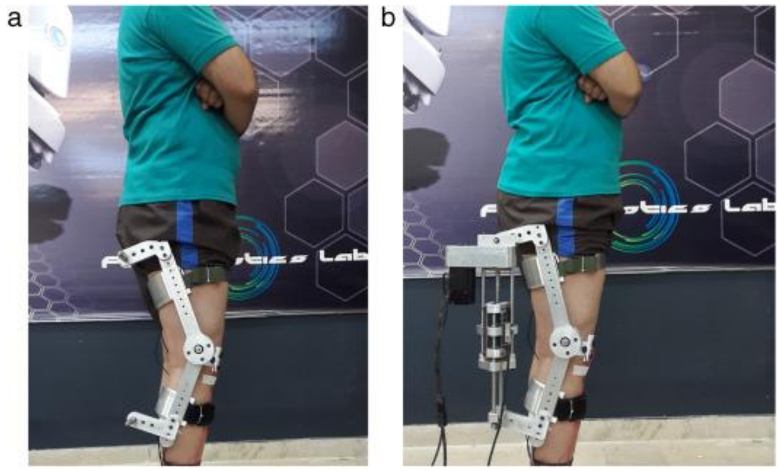

Fig. 8. FUM-KneeExo (a): No operator, (b): Effected by FUM-LSEA [11]

FUM-KneeExo is powered by actuation by elasticity "FUM-LSEA", which was developed at the robotics department at Ferdowsi University in Mashhad. The actuator is linked to the robot's thigh and backbone links to create assistive torques again for knee joint. The activation power of FUM-LSEA is produced by a delta electronics extended memory model 200 W AC motor with a maximum speed of 3000 rpm. A ball-screw mechanism converts the servo motor's rotating motion to the actuator's linear motion. To send motion from the servo to the rolling mechanism and to boost motor torque, a pulley and belt system with a 2:1 transmission ratio is utilized. To provide the requisite compliance for the actuator, two springs are wrapped all around the screw shafts of the ball-screw mechanism. The springs are connected in parallel and in parallel with the actuator and output connection. The deflection of springs is measured using a magnetic constant incremental encoder. The servo motor's built-in incremental encoder monitors motor rotation and, as a result, the movement of the ball-screw nut.

1.3.3. Pneumatic Cylinder Type Actuator

The compressor is a nonlinear actuator that will provide a large amount of force for a little quantity of air pressure. Because the cylinder's input is pressurized nitrogen, which is commonly available, the cost of running the actuator is lower than that of electric actuators [12]. Also, the air actuator has a better power-to-weight ratio, demonstrating its efficiency. Also, the output reaction, or piston extension, is substantially quicker. To generate sufficient force, it was chosen a piston with a piston diameter of 50 mm and a stroke length of 40 mm. This has a working pressure differential of 0.5 to 10 bar and a mean temperature range of 5 to 60. With frictional losses, the highest force it can create at 10 MPa pressure for expansion is 1767 N and 1484 N at retract. The cylinder is manufactured by Janatics in India and features rubber and padding at the tragic end to extend the life and efficiency of the piston. The cylinder chosen is a double-action single-end-rod pneumatic cylinder with an air input and an air exit port (see Fig. 9). This cylinder is half the diameter of the double-ended pneumatic cylinder, reducing the chunkiness of the actuator. The lengthy chain connecting the far side of the pistons from the knee joint to the sprocket [13] causes a large bending stiffness in the shaft that houses the pulley is placed, which accounts for the shaft's failure over repeated cycle reversal loads. This deformation can be minimized by shortening the wire in the suggested actuator.

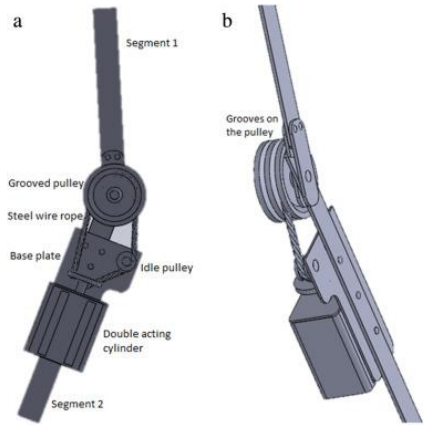

Fig. 9. (a) Pneumatic system actuator. (b) The pulley with two well-carved grooves [12]

The exoskeleton limbs can only be activated if the activator is rotating. The cylinder is a longitudinal actuator that must be converted to a rotational actuator by including a driving system. The drive train's main advantage is its ability to provide enough torque. This can be accomplished by replacing the pistons with a bigger bore diameter or raising the circle of the pulley while maintaining the supplied compressed air pressure constant.

1.3.4. Hydraulic Cylinder Type Actuator

The C-Brace® orthotropic transportation purpose is a robotic exoskeleton with passive knee-ankle joint orthosis for running support [14]. It can help paralyzed individuals recover by stretching the knee joint. The exoskeleton equipment has to be small and compact, but also lightweight. As a consequence, as shown in Fig. 10, the actuator utilizes an electronic hydraulic cylinder. Firstly, the hydraulic cylinder is a steady-speed actuator, which simplifies physical structure design by converting mechanical energy into human movement and assistance. Second, because it is little and travels fluidly, it makes the whole structure appear more compressed and natural. The hydraulic actuation structure's rod components were theoretically evaluated. The hydraulic cylinder's usual rated thrust is 600 N.

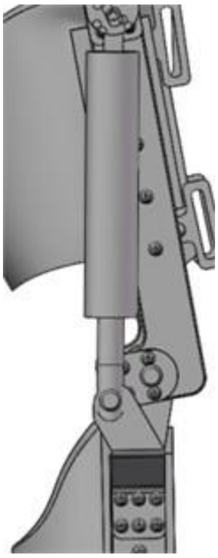

Fig. 10. Knee exoskeleton with a hydraulic cylinder as an actuator [14]

The knee exoskeleton uses a hydraulic cylinder as an actuator because it can provide more force than an air cylinder or electric motor. Strength is needed to support a person's weight. This device is fixed in the hinges of the exoskeleton frame because the hydraulic cylinder changes its position angle during human body movement.

1.4. Development of an Exoskeleton

The kind of actuation and material manufacturing procedures are critical in the creation of robot exoskeletons. The choice of a suitable manufacturing procedure guarantees that now the robot exoskeleton does have strength just at links and joints. The production procedures also assure the longevity of the robot bodysuit as well as the wearer's comfort level since these methods can supply the essential strength and functionality to these exoskeletons. Methods of manufacturing are often chosen after the material for the design of the robot exoskeleton has been completed, as these kinds of processes differ based on the material. Metal and non-metallic materials are manufactured using different ways.

1.4.1. Manufacturing of Metal Parts of the Exoskeleton

Lower limb exoskeletons are created using a variety of traditional manufacturing techniques such as extrusion, CNC machining, and metal casting. Extrusion is a powder metallurgy method wherein a metal or work item is pushed to flow thru a die to shrink its cross-sections or shape. This method is widely utilized in the production of pipes and steel rods. The force applied to the extrusion the work item is compressive. Metal forming is a modern process with ancient origins. Metal shapes are created in metal castings by pouring heated steel into a mould cavity, where it cools and therefore is later removed. The ATALANTE robot bodysuit was created using extruded and machining CNC technology. The ETH Knee perturbator is constructed by combining CNC machining with conventional drilling techniques. The LOPES exoskeleton was created by metal casting and CNC machining. The metal extrusion process was combined with CNC machining to build the SCUT robot exoskeleton.

Fig. 11. LOPES exoskeleton which is manufactured by metal casting and CNC machining [15]

Metals bonding technologies have also been used in conjunction with traditional machining procedures. Extrusion and welding of aluminium sheet components were used to make WPAL. The disadvantages of traditional fabrication techniques such as an extruder, metal casting, and CNC over contemporary fabrication methods such as 3d printers include a high cost per part, the cost of CNC machining, the difficulty of achieving uniform strength, the complexity of achieving constant wall thickness, and poor precision in the design and form of the finished part.

1.4.2. Types of Materials Used in Exoskeletons

There are endless materials in the world from which exoskeletons can be made. Figure 12 shows details of the various materials utilized in the development of robotic components [16]. Carbon fibre is the most commonly utilized material, accounting for 18.92% of the examined studies. It is the lightest and provides the best long-term performance. Aluminium is another material that is commonly used in the progress of exoskeleton components, accounting for 16.22% of the total. This material serves to protect from combustion and is widely used in the progress of prototypes; as a result, it is one of the most commonly used materials in the advancement of exoskeletons.

Material	Amount	
	Frequency	Percentage
Carbon Fiber	7	18.92%
Aluminum	6	16.22%
Steel-Aluminum	2	5.41%
Aluminum-Resin	1	2.70%
Nylon-Carbon Fiber	1	2.70%
Aluminum-Titanium	1	2.70%
Stainless steel 304	1	2.70%
Nylon	1	2.70%
Titanium	1	2.70%
N.E.	16	43.24%

Fig. 12. Percentages of the type of material used in exoskeletons [16]

Steel with aluminium in a ratio of 5.41%. Aluminium with resin, nylon with composite, aluminium with titanium, steel, nylon, and titanium are rarely used, only 2.7 % of each material was used. These materials are usually constructions comprised of solely one type of material at a low proportion. Lastly, 43.24% of the studies conducted did not indicate the substance utilized.

1.4.3. Exoskeleton Manufacturing Using 3D Printer

3D printing is being used in a variety of biological fields [17]. This method may be utilized to create metallic implants in hard tissues, organ-growing hard duplicates of mathematical models for surgical preparation, dental and orthoses [18] external fixators, and other applications. 3D printing includes multiple steps that must be completed step by step. Figure 2 depicts the 3D printing technique.

Fig. 13. 3D printing method [17]

3D printing is a relatively recent production process for medical rehabilitation items. 3D printed exoskeletons help impaired people to live normal lives while providing the benefits: cheap, mobilization, and customization for unique needs. 3D printing allows for the creation of robotic objects with unique anatomic forms and customized features. One of the biggest disadvantages of 3D printing is the likelihood of uneven shrinkage when printing. Despite the numerous advantages of 3D printing, there are significant obstacles associated with printing various materials, their qualities, and the cohesiveness between them. This 3D printing industry is still in its initial stages, and commercially available mech suits are still being developed. The majority of the studies were conducted in labs and discovered just for a few people locally, but demand for 3D printers will increase due to perks such as customizability. One of the challenges in constructing a lower extremity bodysuit is a lack of expertise, data, and a specific performance objective. The key parameter revealed during the experiment was based on data collected while using the bodysuit and without it [19].

1.4.4. Different 3D Printers Used in Manufacturing of Exoskeletons

In additive manufacturing, a computer-controlled transformation phase frequently converts a trend gear, like an ink-based print head or laser optics, to produce the needed goods in a layer-by-layer pattern. Patterned regions comprised of grains, pigments, or resins are cemented throughout the advanced manufacturing process to generate the essential 3D shapes [20]. 3D-printed things are actual manifestations of computer designs. Many essential additive manufacturing printing technologies were established with the introduction of 3D printing. Technology has advanced from creating basic prototypes to building finished products. The specific hardening and pattern process used by a certain method of additive manufacturing reveals the lowest feature size that can be achieved as well as the sorts of printable soft materials that can be used. The key variations in the various basic printing technologies are mostly connected to improving printing speed, improving printing resolution, reducing material consumption, and printing a desired 3D object with several materials [21]. 3D Printing methods utilized to manufacture soft robots are visible in the Fig. 14.

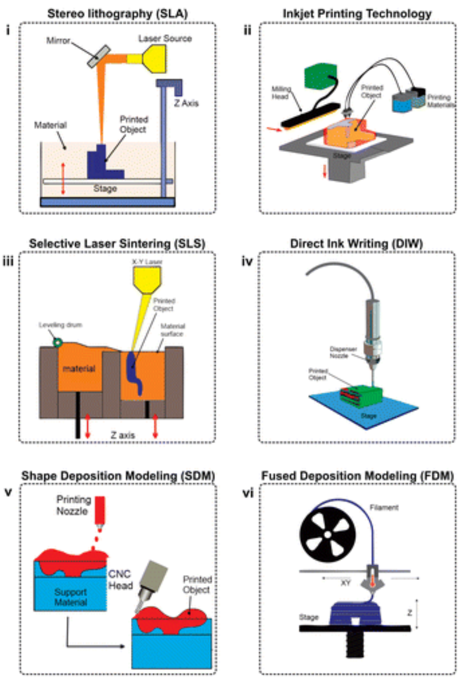

Fig. 14. 3D printing methods of manufacturing exoskeletons [20]

In the SLA technique (i), a laser selectively photopolymerizes a liquid resin. Inkjet printing (ii) is comparable to SLA in many aspects, with the exception that this approach uses a moving inkjet head to apply a photoresist that is triggered by a UV laser. Metal powder (iii) is rolled along a build platform, and a laser is focused into the powder, followed by spreading the powder so over top of the as-deposited layer, and this process is repeated until the desired 3D item is entirely created. DIW (iv) is indeed an alternate printing technology to FDM for the additional production of desired items under ambient circumstances, in which ink is regulated as it goes through a nozzle. The shape deposition modelling technique (v) is made up of numerous processes, one of which is deposition. In a heterogeneous deposition, the material is modified between deposition processes. With the FDM approach (vi), soft substances are printed as a continuous filament with a single layer added.

1.5. Similar Knee Exoskeleton Designs

Since the exoskeleton of several roads is desired, it is necessary to look at similar exoskeletons that already exist, so that it is certain to learn new ideas and not to make mistakes that someone can already do. The structure of the exoskeleton of the legs needs to be reviewed, pay attention to their attachment point, joints or the largest material of the structure. The principle of operation is also one of the most important factors that enable the exoskeleton to perform well.

1.5.1. C-Brace Exoskeleton

The microprocessor-controlled C-Brace elevates mobility to a whole new level, see Fig. 15. The C-Brace is the initial KAFO that allows the user to bend their leg underweight (for example, to sit down) as well as manage slopes, move on uneven ground, and descend stairs step by step. And there's much more to the C-Brace. It's smaller, so it can be worn under clothing, and it's lighter, so it doesn't require as much effort to walk. The use of advanced sensor technologies enhances the overall dynamism and responsiveness of the gait pattern [22]. A smartphone app allows the user to adjust parameters on their joint, such as switching to cycling mode.

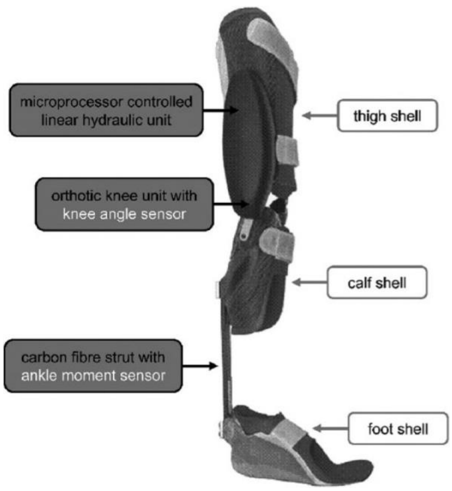

Fig. 15. C-Brace exoskeleton with components [22]

Main features of C-Brace exoskeleton:

- Microprocessor-based operation.
- Integrated battery.
- It is customizable.
- Lightweight weight- may be worn undergarments.
- The three-dimensional sensors that determine the real position.
- Composed of a fibre composite substance.
- May be difficult to utilize for those with cognitive impairments.
- For patients weighing little more than 125 kg.
- Not for persons who wear orthotics.

1.5.2. Hybrid Assistive Limb Exoskeleton

The single-joint hybrid supportive limb is a designed controlled neurologically therapeutic device that supports flexion and extension of the knee using bioelectrical impulses generated by the patient [23]. It was created as a single-joint variant of the hybrid assistive limb for the robot suit, as in the Fig. 16. In contrast to traditional exoskeletons, which are largely posture-controlled and hence give direct mobility aid, the hybrid supporting limb is controlled freely and physiologically by the patient's own electrophysiologic muscle impulses. It can be applied to the elbow or even the knee. It is a device used to apply additional force to a knee or ankle. This product falls between a consumer product and a medical assistance gadget.

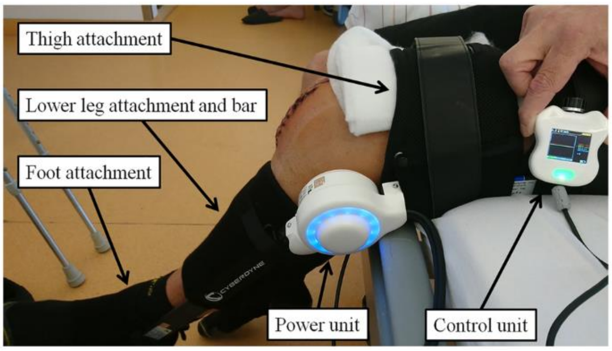

Fig. 16. Hybrid assistive limb exoskeleton with components [23]

Main features of hybrid assistive limb exoskeleton:

- There is only one motor.
- The weight is 1.5 kg.
- Hand operator that has been customized.
- Bioelectrical impulses are used to power the device.
- The angle of rotation is 120°.
- hours of battery life.

1.5.3. Archelis Exoskeleton

Because the healthcare business is more involved than ever in intricate operations that might take several hours to complete, the Archelis is a device developed to provide surgeons with leg support. The Archelis is a wearable chair created in partnership with Hiroaki Nishimura Engineering, the Chiba Institute Centre for Frontiers Medical Engineering, and Japan Polymer Technology [24]. When used on the knees, the Archelis provides enough support to allow the user to stand for long periods of time without being fatigued, see Fig. 17. To give a better entire experience for the surgeon, the leg assistance device works by relieving the pressure involved with sitting for such lengthy periods of time.

Fig. 17. Cloaked exoskeleton “Archelis” [24]

Main features of Archelis exoskeleton:

- Developed for surgeons during long-term procedures.
- Reduces pressure when standing and walking.
- There is no need for electricity.
- The wearer's maximum weight is 80 kg.
- Weight: 3.2 kg.
- The wearer's height ranges from 160 to 185 cm.
- There are three operational modes.

1.5.4. Honda Leg-Walk Assist Exoskeleton

The gadget is made up of a control module with a case specifically and a battery, assist power motors, and thigh frames, see Fig. 18. The user places on the control module and motors just at hip and thigh structures, as well as the thigh assist devices, on both thighs [25]. The angle of the hips and the throughput times of walking are measured by an encoder embedded into the motor, and the control CPU provides a signal to the actuators to provide help force in moving at an appropriate moment. It provides the leg of the outstretched leg with a kicking power that is almost twice as strong compared to the idle leg. It also allows the inactive limb to take a wider stride.

Fig. 18. Cloaked Honda exoskeleton [25]

Main features of the Honda Leg-Walk assist exoskeleton:

- The weight is 2.8 kg.
- Lithium-Ion battery.

- degrees of hip mobility.
- Intended to provide assistance to healthy people.
- Working time without recharging is 120 minutes.
- Only improves the hip joint.

1.6. Summary

The exoskeleton cannot be without a driving force, otherwise, it would simply be a prosthesis or a splint. As mentioned, power can be provided by various devices such as springs, electric motors, and air or hydro cylinders. Electric motors are mostly used because they can perform infinite actions depending on what is going to rotate, such as gears or helical gears. However, electric motors cannot provide much power without the use of gears, and the use of gears will also reduce rotational speed. Pneumatic and hydro cylinders are used when high power is required, but they can only provide linear displacement. Some of the best cases where it is needing just support, rather than doing all the task for are passive devices like springs, ropes, and flexible belts. They are much lighter than electric, air, or liquid devices. The principle of their operation is simple and their production is also simple. Depending on the construction of the exoskeleton, its control components, and its purpose, certain materials are chosen from which the exoskeleton will be made. If the exoskeleton has to perform a full movement that a human cannot perform, it will need a more powerful and heavier actuator. For this reason, it is advisable to make such an exoskeleton out of metal. If the exoskeleton is only intended to provide some strength to the wearer to perform work, exoskeletons are usually made of composite materials or plastic. Metal parts are produced by extrusion, metal casting and later CNC machining or drilling. Plastic components are usually made by 3D printers, like shape deposition modelling, fused deposition modelling, selective laser sintering, direct ink writing, stereo lithography or inkjet printing technology. After reviewing similar exoskeleton designs of C-Brace, Hybrid assistive limb exoskeleton, Archelis and Honda leg-walk assist exoskeleton, it is possible to say that one of the purposes of making all exoskeletons are for rehabilitation, from treatments performed on the lower part of the body. One of the similarities between these exoskeletons is that they are made of similar materials, such as plastic and composite materials, but their construction itself differs greatly due to the different actuators used. Electric motors that have Honda leg-walk assist exoskeleton or mechanical components such as elastic materials that are in Archelis exoskeleton are used as actuators. The hinges in all the reviewed designs are based on the bearing and pin principle, as this greatly reduces friction.

2. Design of Knee Exoskeleton

To design a suitable knee exoskeleton, one must know the structure of a person's lower leg and its flexion angles during walking and squatting. The length of the thigh and calf is also important for an average Lithuanian, as the exoskeleton must be as universal as possible. Only after the results of length and flexion of thigh and calf it would be possible to design a frame for the exoskeleton, which must be as comfortable, light and sufficiently stable as possible. For the exoskeleton to provide the person with additional power when squatting and standing, a suitable actuator has to be chosen, which needs to be fast enough and strong enough when the person only wants to move without being restricted from moving.

2.1. Research of Human Lower Body Part

Normally, all physically working people have to lift a heavy object from the floor, and this should be accomplished without any injury to human legs or back. Lifting a large object incorrectly can result in acute muscle or tendon strains that may persist for a short time or be prolonged. These strains are small tears in the muscles of the lower back. As it is expected, pain relief is beneficial. To avoid back injuries when carrying large objects, there is a specific technique for lifting heavy objects by squatting with your back straight and holding the object as close as possible between your knees, see Fig. 19.

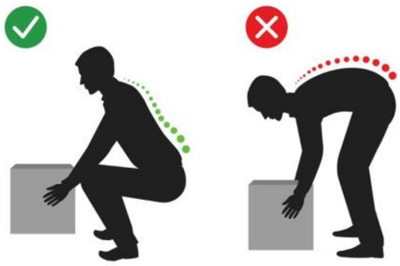

Fig. 19. Lifting objects from the ground correctly [26]

The dynamic deep squat is a popular exercise to increase the strength of the lumbar flexors, achieve the following strength and strengthen the leg muscles, as well as prevent injuries and improve athletic performance. The dynamic deep squat involves kneeling in a posture where the knee is in 140-145° of flexion [27]. However, if the object is too heavy and the person's legs are too weak, the object is lifted in a stooped posture because it is not possible to lift it with the legs and straight back alone. Muscle aches or injuries in the legs and back may occur. A knee exoskeleton can prevent this because it gives the legs additional lifting power. To design a knee exoskeleton, it is necessary to know what the maximum flexion angle of the human lower limbs is, the weight of the lower limbs, and also the height of the calf and thigh.

2.1.1. Walking and Squatting Down

The knee joint consists of a synovial hinge that has an ellipsoidal shape. It is divided into two sections: the femoral-patellar joints and the femoral-tibial joints [28]. It moves in several basic reference lines that pass through the joint centre and gives it two degrees of freedom: Flexion-Extension and Medial-Lateral Rotation. As with the hip joint, flexion-extension is the most important joint motion in the frontal plane that allows humans to walk stably (see Fig. 20).

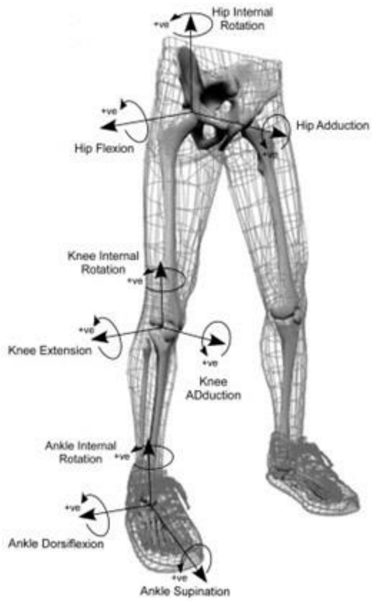

Fig. 20. Human lower limb kinematic [28]

The range of motion in flexion is up to 120° when the hip is extended, 140° when the pelvis is flexed, and 160° when the knee is passively flexed. The rotation (internal) that occurs in the last phase of extension is called medial-lateral rotation. It helps bring the knee into a locked position for optimal stability. It is limited to 10° of flexion with a flexion angle of 30° and 15° with the knee fully flexed. The lateral rotation occurs during the preliminary phase of flexion. It is required to unlock the joint, and the range of motion is limited to 30° at 30° of flexion and 50° at 120° of flexion [29].

Before designing a knee exoskeleton, it is necessary to analyse the degrees of motion of the human knee. The exoskeleton has to provide additional strength during landing and standing, and must not restrict movement during walking. In the bio mechatronics laboratory at KTU, an experiment was conducted using a protractor as a measuring instrument, see Fig. 21. With this measuring instrument, it was possible to determine the limiting angles of human knee motion.

Fig. 21. Protractor measurement tool.

When the exoskeleton is extended, it should be parallel to the leg at an angle of 180 degrees. A person's landing knee can form an angle of up to 45 degrees, as shown in Figure 22. The exoskeleton's thigh support and calf support must also keep pace with these angles.

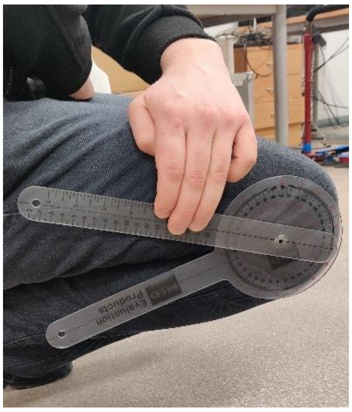

Fig. 22. Maximum degrees of squat knee landing

It is possible that the production of the exoskeleton may not be achieved by precisely bending to these degrees, but the difference should be as small as possible. There should be no external forces acting on a person as they walk. In this case, the exoskeleton would be uncomfortable and could even make the physical work performed by the person more difficult. After conducting the experiment, it was found that a walking person bends the knee up to 150 degrees, see Fig. 23.

Fig. 23. Maximum degrees of the knee while walking

Between 0 and 50 degrees, the exoskeleton cannot intervene with its auxiliary force. The actuator must be mounted in such a way that it would start to interact only from 50 degrees to 145 degrees.

2.1.2. Lower limb weight and height

Before making the knee exoskeleton, it is necessary to find out the weight and length of the lower part of the human body. In this case, the exoskeleton will be strong, which will not break, and will be comfortable, which will hold the leg firmly. First, it is necessary to find out which segments of the human body will participate in the operation of the knee exoskeleton, see Fig. 24.

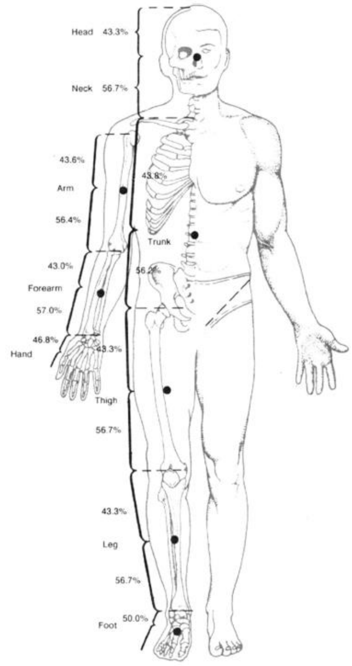

Fig. 24. Segmentation of the human body [30]

The knee exoskeleton will be attached to the thigh and calf, thus creating no extraneous influence on the movement of the knee [30]. Using the Dumpster study, we can determine the approximate weights and lengths of a person's thigh and calf, see Table 1.

Table 1. Segments of human body weight and height at precents according to Dempster

Segment	Percentage weight	Percentage height
Head and neck	8.10	10.75
Torso	49.70	30.00
Upper arms	2.80	17.20
Lower arms	1.60	15.70
Hand	0.60	5.75
Thigh	9.90	23.20
Calf	4.60	24.70
Foot	1.40	14.84

The average height of a Lithuanian resident is 180 cm and the 70 kg of weight. It will be based of calculations on this indicator, see Eq. 1 and Eq. 2.

Calculations of thigh and calf weight:

$$m_{segment} = \frac{m_{mean}}{100} \cdot m_{percent}, \quad (1)$$

where: $m_{segment}$ – a mass of the certain human body segment (kg); m_{mean} – mass of the average Lithuanian people (kg); $m_{percent}$ – percentage mass of the certain human body segment (%);

Calculations of thigh and calf height:

$$h_{segment} = \frac{h_{mean}}{100} \cdot h_{percent}, \qquad (2)$$

where: $h_{segment}$ – height of the certain human body segment (cm)t; h_{mean} – the height of the average Lithuanian people (cm); $h_{percent}$ – percentage height of the certain human body segment (%).
Calculation results are visible in the Table 2.

Table 2. Segments of human body weight and height according Dempster

Segment	Weight, kg	Height, cm
Head and neck	5.67	19.35
Torso	34.79	54.00
Upper arms	1.96	30.96
Lower arms	1.12	28.26
Hand	0.42	10.35
Thigh	6.93	41.76
Calf	3.22	44.46
Foot	0.98	26.71

The knee exoskeleton must withstand a mass of almost 10 kg and must be no longer than 86 cm. Since the exoskeleton will consist of two main parts, their lengths should be slightly longer than the centre length of the thigh or lower leg. In this case, it will fit comfortably and will not be too large. In this case, the length cannot be shorter than 43 cm.

2.2. Development of Knee Exoskeleton Frame

As discussed in the review, the frame of the exoskeleton itself cannot exceed 86 cm in length and it must also be able to bend up to about 45 degrees. In the Fig. 25 it is visible the length and bending degree that should be on the knee exoskeleton's frame.

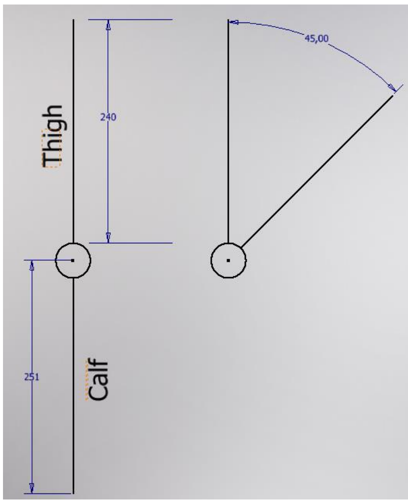

Fig. 25. Lengths and bending angle of knee exoskeleton frame

Between 240- and 251-mm dimensions there is a joint through which the exoskeleton frame will be able to flex. Based on this scheme, the exoskeleton must be designed.

2.2.1. Development of the Exoskeleton Part of the Thigh

The upper part of the exoskeleton will be the strongest, as the diameter of the thigh of the human body part going to be the largest compared to the lower part of the leg. This requires a two-part thigh support, as shown in Fig. 26.

Fig. 26. Part of the thigh exoskeleton’s frame

The thigh is held by two pieces reinforced by ISO 4762 M6x16 bolts and ISO 4035 M6 hex nuts. The size of the thigh band may differ from the diameter of a person's thigh, see Fig. 27. On the other side of the part in contact with the human body, it is advisable to add padding to provide less friction between the frame and the human body.

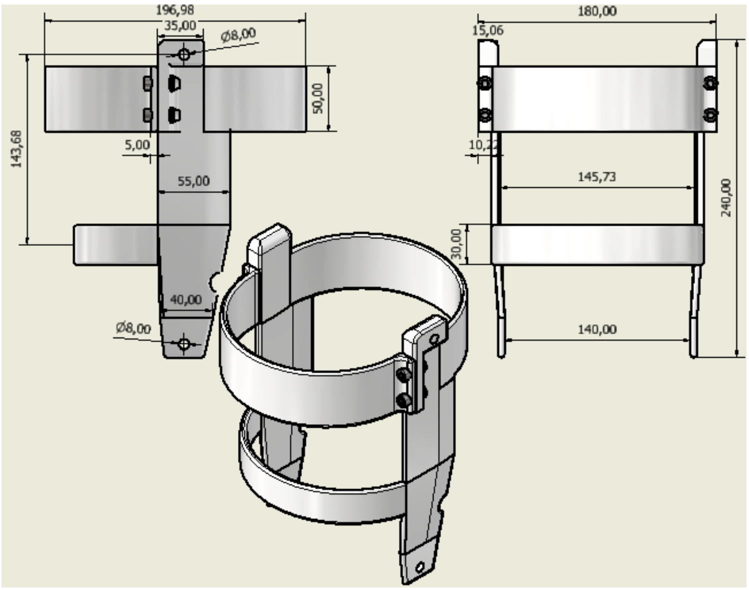

Fig. 27. Design of top knee exoskeleton

The width of the exoskeleton frame is 5 mm, because the maximum forces will only act on the anchors of the actuator. The frame is going to be made of plastic to avoid complicated manufacturing and additional weight. Except for the fasteners, which will be made of steel.

2.2.2. Development of the Exoskeleton Part of the Calf

When designing the lower part of the exoskeleton, a problem was faced that it could not be firmly anchored. The upper exoskeleton forms a full circle at the top and this forms the most rigid part of the frame. In the lower part of the exoskeleton, it is impossible to make a complete circle anywhere, as this will interfere with its bending angle. Therefore, it was decided to increase the width of its frame to 8 mm. The length of the bottom exoskeleton will be 255 mm, like in the Fig. 28.

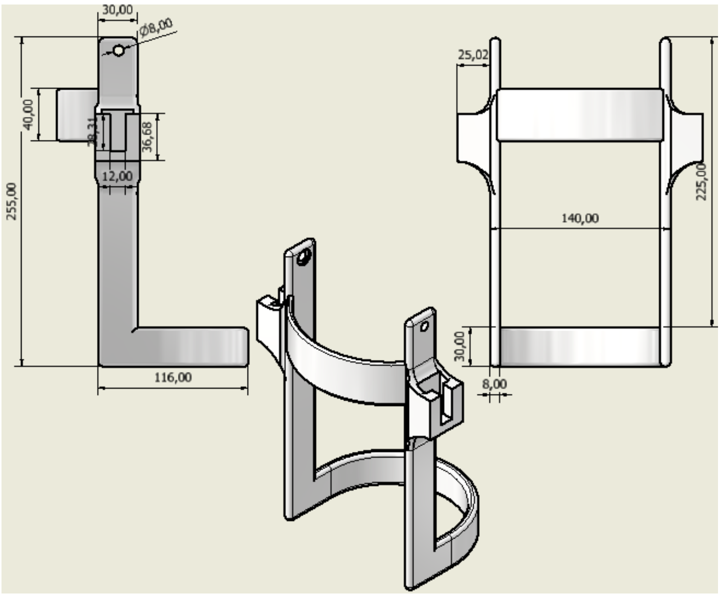

Fig. 28. Design of bottom knee exoskeleton

The lower part of the exoskeleton will be a solid plastic piece. This will not significantly affect the production if the 3D printing method is used. The upper and lower parts of the exoskeleton will be connected by a pin. This connection will work because the exoskeleton frame will not be able to expand and contract simply because the pin will hold it back. See Fig. 29.

Fig. 29. Connection of top and lower exoskeleton parts

Clevis pin connections ISO 2341 B 8 x 16 are used with drilled holes to put in the cotter pin AS 1236 2 x 16. In order not to damage the frame of the exoskeleton, and to hold it more firmly, a washer was used AS 1970 8. The pin cap is inserted 2 millimetres into the frame of the exoskeleton to make it more comfortable to wear.

2.2.3. Unsuitable Knee Exoskeleton Frames

Prototypes were created that were not suitable for the production and use of a knee exoskeleton. The biggest criterion was the weight of the exoskeleton frame. See Fig. 30.

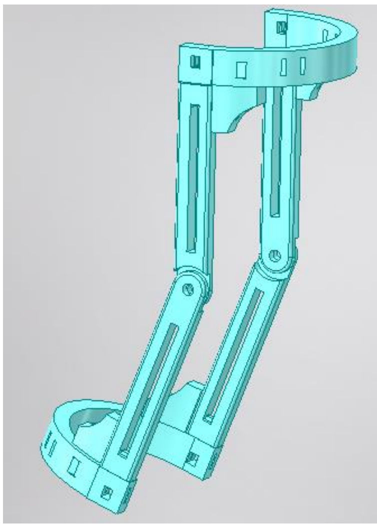

Fig. 30. First knee exoskeleton prototype

The first knee exoskeleton would be very uncomfortable, since the contact between the exoskeleton frame and the human body would only be in two places, the thigh and the lower leg. There would also be very poor anchorage and stability. The exoskeleton would be loose. The next exoskeleton is not much better than the first one. See Fig. 31.

Fig. 31. Second knee exoskeleton prototype

The second exoskeleton frame would be similar to the first one, but it would be even heavier than the first one because the exoskeleton frame lacks lightening points like holes. Also, this exoskeleton was designed with the idea that it would be metal for its strength. But here is the problem, it will be too massive and heavy, which can put an additional burden on the person wearing it. The last exoskeleton prototype is radically different from the first two, see Fig. 32.

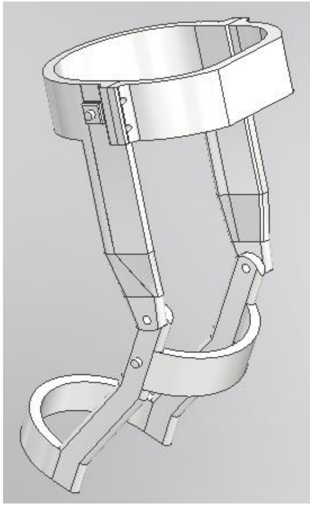

Fig. 32. Third knee exoskeleton prototype

The third knee exoskeleton is more comfortable than the first two discussed, but it is still missing one part that would help better anchor the wearer's leg. This prototype would be made of plastic. Although plastic is not a heavy material, its quantity is too high. The width of the knee exoskeleton frame is 10 mm. This construction is generally speaking, too strong. The actuators, sensors, control board will have to be fixed on the frame, which will add even more weight. In order to make an exoskeleton that is comfortable to wear, it is necessary to reduce the weight of the structure.

2.3. Actuator for Knee Exoskeleton

Since the exoskeleton of the knee is under development, a frame alone will not suffice. It is needing a means to give positive energy to the person. When a person squats, the device must provide sufficient relief to the calf and thigh muscles. A device that straightens up from a squat position must also compensate for a certain amount of the force a person uses when standing up. Because of the actuator, a person can work longer because he will not feel muscle pain due to strong muscle contraction and it will be less tired. The actuator in the exoskeleton frame must be fixed in such a way that the actuator would stop working when the legs are bent about 50 degrees, because then it becomes uncomfortable for the person to walk.

2.3.1. Rotary Motion as an Electrical Actuator for Knee Exoskeleton

The actuator in the exoskeleton must apply additional force to the legs when the person wants to squat or stand. In addition, it must not restrict the person's movements when a human only wants to walk. The first idea was to use a servo motor with a bevel gear. See Fig. 33.

Fig. 33. Servo motor with bevel gear transmission as an actuator

The servomotor will be anchored to the upper right side of the exoskeleton frame so that the servomotor would not rub against the person's other leg or have to walk splayed when the knee exoskeleton is also used on the other leg. One gear should be attached to the servomotor and another gear would be attached to the lower part of the exoskeleton, creating a 90-degree angle. To figure out which servo motor has to be needed, it was necessary to calculate the torque, see Eq.3.
Calculation of the required torque:

$$\tau = Fr, \ [31] \qquad (3)$$

where: τ – torque (Nm); F – linear force (N); r – distance measured from the axis of rotation to where the application of linear force takes place (mm).

To determine the value of F, the mass was converted into a force corresponding to the weight of a human without the part below the knees. See Fig. 34.

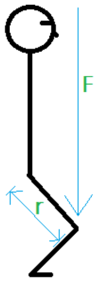

Fig. 34. Display of moment length and force values

The values can be found in Table No. 2. If the segments are added of the human body, the result of weight is 65.8 kg. If weight converted into the force, the result is 645 N. After the calculation a torque of 269.35 Nm is got. Normally, one person wears two knee exoskeletons, so the value should be divided by 2. The required servo motor has to be rated in torque of 134.68 Nm. After research, it was decided that servo motors usually have up to 10 Nm. Servo motors that have more than 10 Nm are too heavy for the structure of the exoskeleton. A servo motor and a bevel gear system for the knee exoskeleton is not suitable.

2.3.2. Linear Motion as an Electrical Actuator for Knee Exoskeleton

The rotary motion actuator did not work, so a review was conducted to find an actuator that would provide longitudinal motion. Pneumatic cylinders or hydro cylinders can provide this motion, but would require a pump or compressor. The entire construction is immobile, uncomfortable and inadequately expensive. One of the inserts was a linear actuator with a servo motor. The servo motor rotates the helical gear, giving it longitudinal movement. See Fig. 35.

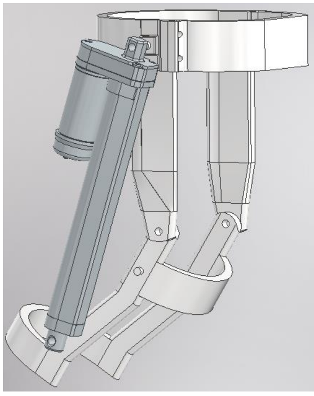

Fig. 35. Servo motor with the propeller transition as an actuator

As in the previous review, it is important to calculate the values according to which it will be possible to choose a linear actuator. It is need to find the speed of the linear motion. Since this helical gear can be self-locking, it does not need to be provided with all the force converted from the mass of the human body. It can only be used as an aid, providing a certain strength to a person when landing or standing, that is why it is not necessary to calculate the needed force. When calculating the required displacement speed of a linear actuator, we will use the simplest path, speed and time formula, see Eq. 4.

Calculation of the velocity:

$$v = \frac{s}{t}, \ [32] \qquad (4)$$

where: v – velocity, at what speed does a person squat (mm/s); s – displacement, what distance does a person squat (mm); t – time, in what time a person squats (s).

It possible to get an approximate squat distance by taking the lengths of the thigh and calf, which is 86.22 cm. Values obtained from Table 2. Using a timer and squatting 10 times, the average squat time is 2 seconds. After calculating the speed, result was obtained of 431.1 mm/s. Typically, a linear actuator that can contract and extend at approximately 400 mm/s would be required. After the analysis of linear actuators, it was found that the desired three parameters of the actuator do not coincide with each other. Or it will be fast but provide very little power and be too long for a knee exoskeleton design. The fastest actuator pull-out found is 230 mm/s, which will be almost half the required speed anyway. Such cases will make a linear actuator controlled by a servo motor unsuitable for the production of a knee exoskeleton.

2.3.3. Gas Spring as a Mechanical Actuator for Knee Exoskeleton

In the previous analyses of an electric linear actuator and bevel system with servo motor, it was found that three values, velocity, force, and length, must coincide. Since it was not possible to find a component that had these valid values, it was decided to omit one of the three values which is the velocity. A linear actuator for which the compression speed is irrelevant is a gas spring. The model of gas spring chosen is “Suspa” 16-1-131-104 with end pieces B246 and A246, see parameters in Table 3.

Table 3. Values of “Suspa” 16-1-131-104 gas spring

Product Attribute	Value
Size	16-1
Stroke (mm)	100
Force (N)	100
Rod diameter (mm)	6
Tube diameter (mm)	15
Extended length (mm)	235
Extended length + end fittings (mm)	273

The price of the “Suspa” gas spring is 58.94 euro [33]. A gas spring works on the same concept as a mechanical coil spring; it serves as a mechanism for storing energy. A gas spring, however, stores energy by compressing the nitrogen gas enclosed within it, rather than loading the substance that makes up the spring. While a gas spring is similar to a pneumatic or hydraulic cylinder, it differs in that it does not require an external energy source to produce motion (see Fig. 36). Because a gas spring is a completely closed system, no other gas is admitted to the system after it is built up and filled with inert nitrogen gas [34]. The pressure along either side of the piston in a gas spring remains constant whether the piston is fully extended or fully closed. This is different from a hydraulic or pneumatic cylinder, which requires differential pressure across the piston to move.

Fig. 36. Active pressures on a gas spring [34]

As the rod is pushed into the tube, the available volume decreases, the gas is compressed, and the pressure increases, resulting in the spring-like behaviour. A hole in the piston connected to the rod allows the gas to flow through the piston and regulate the extension speed. Since the gas spring is already supplied with a mounting consisting of a ball bearing and an M8 x 1.25 screw, self-tapping bushings must be attached to the exoskeleton in order to attach the gas spring to the knee exoskeleton, see Fig. 37.

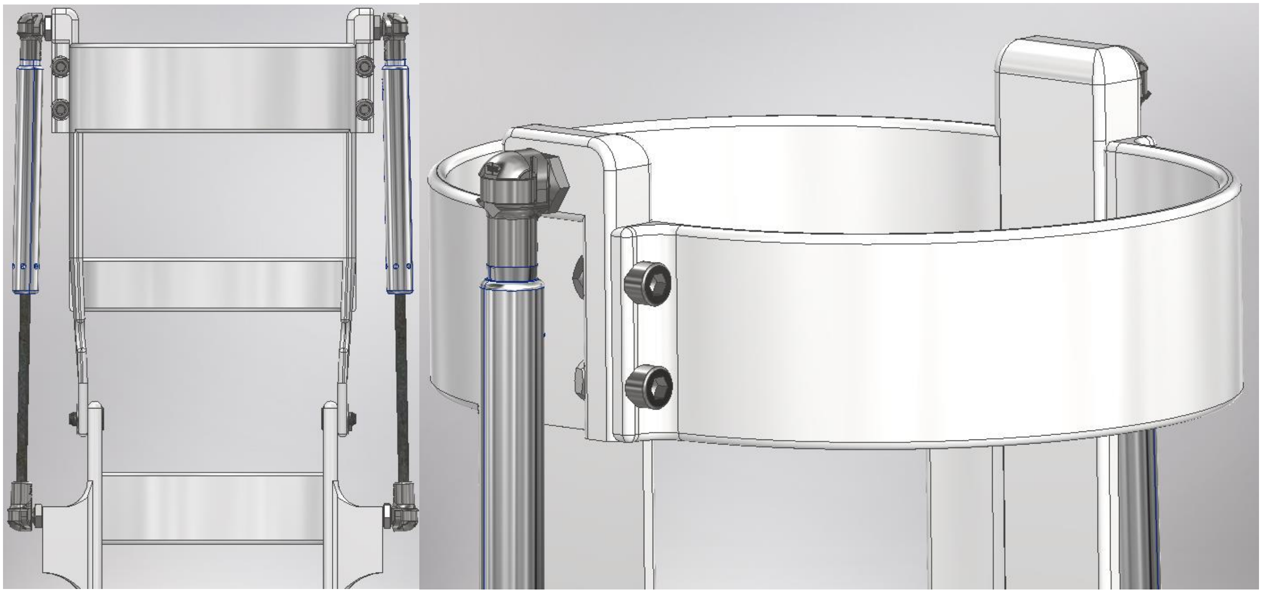

Fig. 37. Gas spring positioning places. Frontal view and side view

The upper part of the gas spring has to be immobile and well anchored, but the lower part of the gas spring must be movable so that the wearer does not have to apply additional forces when walking. For this case, a guide was designed with a slider that can slide up to 23 mm, see Fig. 38.

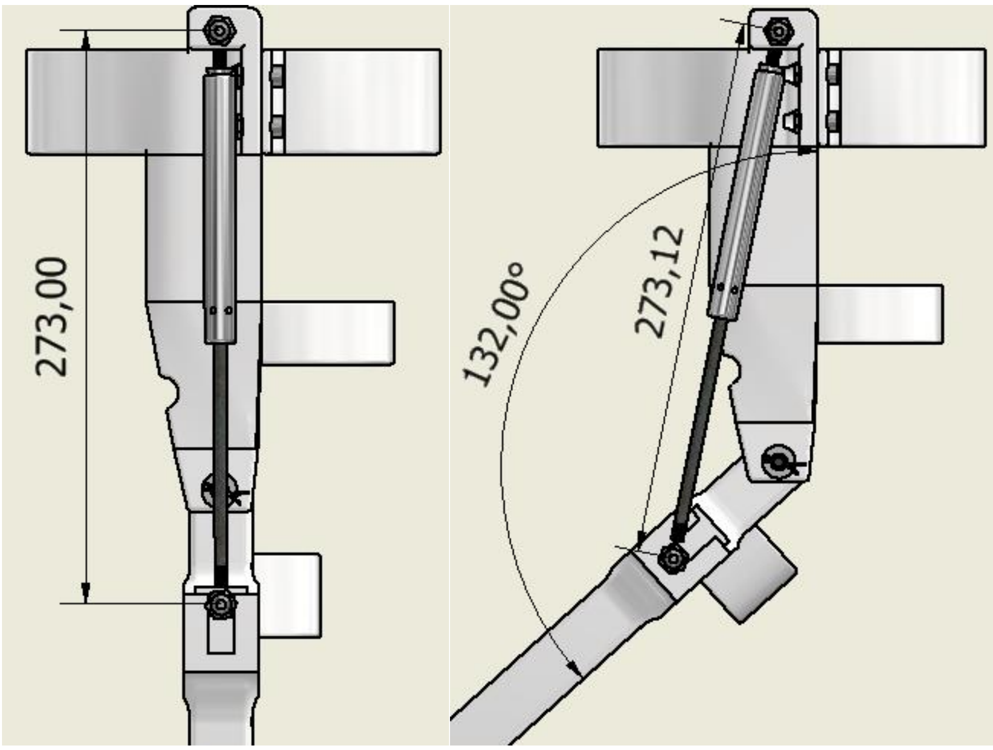

Fig. 38. The Lower part of gas spring fixation in the slider

Because of the sliding element, a person can bend his legs up to 48 degrees. In this case, the gas spring will not do its job. Only from 48 degrees, when a person squats, the gas spring starts to work.

2.4. Summary

To avoid back pain when lifting objects from the ground, it is necessary to wear a knee exoskeleton. It was found that a person can squat up to 45 degrees, so the exoskeleton should also be able to bend near 45 degrees. In order for the exoskeleton not to interfere human while walking, it is necessary to disengage the actuator from 150 to 180 degrees. The exoskeleton must withstand a weight of almost 10 kg, and its whole frame length cannot exceed 86 cm. The exoskeleton of the knee is made up of 4 parts. Thigh support and thig band holding the thigh part, calf support for holding the calve and slider which is going to be in the guide. These parts will be fastened with M6x16 screws and a B 8x16 clevis pin. The frame of the exoskeleton was manufactured in such a way that its frame material would be plastic, which would weigh less than metal, but would be strong enough. Two parts connected by braids will be able to form an angle from 180 to 45 degrees. After calculating the required parameters of various actuators, it finds out that the best actuator would be a gas spring. The most important thing was to find out its length and the force it would exert; the speed did not matter. The upper part of the gas spring is fixed immovably with M8 x 1.25 screws that are screwed into the bushing. The lower part of the gas spring is movably attached with the same screws, but to a T-shaped slider that can slide in the guide up to a bending angle of the exoskeleton of 48 degrees.

3. Manufacture of Knee Exoskeleton

A 3D printer is used to make the frame of the knee exoskeleton because the frame is designed to be easily printed, and it was considered that plastic would be used in the construction. In order to understand which plastic is the most durable and best for making the knee exoskeleton, a study should be done using Autodesk Inventor 2023 option stress analysis. The cost of the material is also important because the exoskeleton must be easy and inexpensive to manufacture.

3.1. Examination of a Knee Exoskeleton's Frame Material

There are many materials from which a knee exoskeleton can be made. However, it is necessary to do material research to achieve which material is durable, light and cheap. It is also necessary to make the knee exoskeleton as cheap and easy as possible. Using Autodesk Inventor 2023's stress analysis feature, the stresses, displacements are calculated and the safety factor (expresses how much stronger a system is than it needs to be for an intended load) of the knee exoskeleton frame is determined using different materials. The exoskeleton frame is maximally loaded by the gas springs when the wearer is fully squatting, at an angle of 135 degrees. There are two fixed points: one at the lower part of the exoskeleton, which rests on the human leg, and the upper part of the exoskeleton, which rests on the human thigh (see Fig. 39).

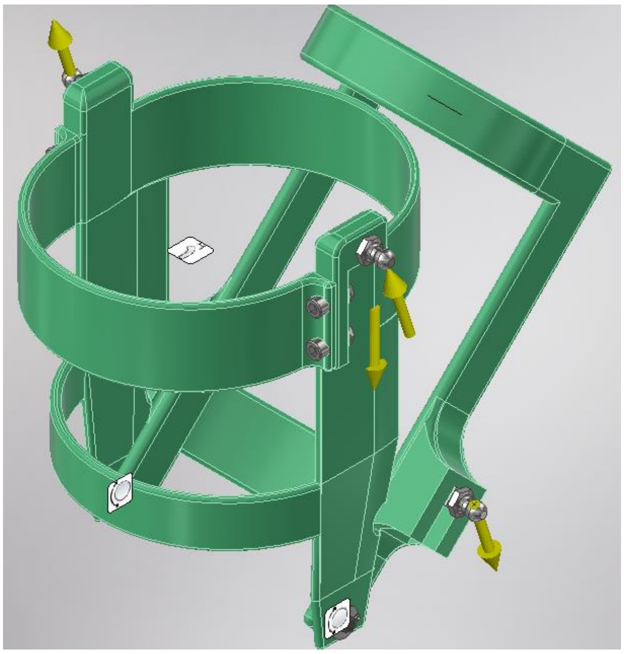

Fig. 39. Knee exoskeleton's places of fixation, pin constrain and forces

At the point where the thigh and calf supports are connected, the pin constraint is applied. Since gas springs are used, the compressive force is 100 N and is applied to all four attachment points of the gas springs. The rotational angle of knee is neglected due to the fact that this can affect the strength of the exoskeleton frame.

3.1.1. ABS Plastic as a Material for Knee Exoskeleton Frame

ABS (acrylonitrile butadiene styrene) is a popular thermoplastic polymer with the chemical formula $(C_8H_8)_x$ $(C_4H_6)_y$ $(C_3H_3N)_z$. It has a glass transition temperature of around 105 °C. ABS is amorphous; hence it has no actual melting point, is an amorphous polymer made up of non-uniform molecules [35]. ABS has advantageous mechanical qualities such as impact strength, hardness, and stiffness when compared with other popular polymers. To increase impact resistance, hardness, and heat resistance, several changes can be performed. Acrylonitrile butadiene styrene mechanical and strength parameters from Autodesk Inventor material library:

- Behaviour – isotropic.
- Young's modulus - 2240 MPa
- Shear modulus - 805.3 MPa
- Yield strength – 20.00 MPa
- Tensile strength - 29.60 MPa

Using ABS plastic as the frame material of the exoskeleton gives a maximum displacement of 0.954 mm, it is visible in the Fig. 40.

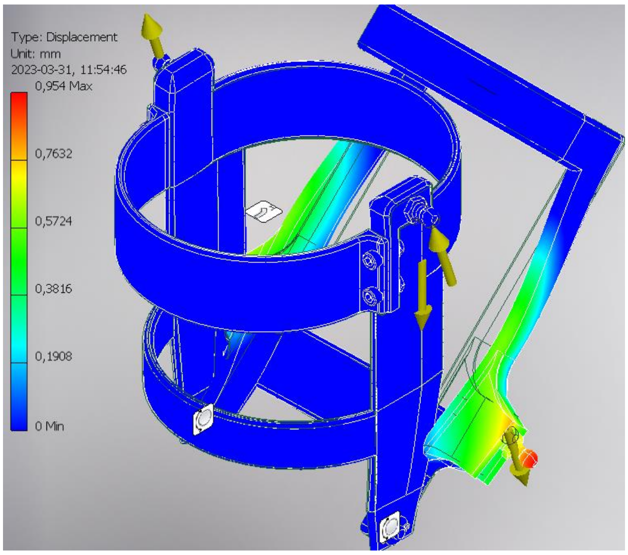

Fig. 40. Knee exoskeleton frame from ABS plastic displacement

The figure shows that the maximum displacement will be in the calf support, since it is not fully reinforced. However, it cannot be avoided, because otherwise the person will not be able to fully recline. Von Mises Stress is a value used to determine if a given material will yield or fracture, it can be visible in the Fig. 41.

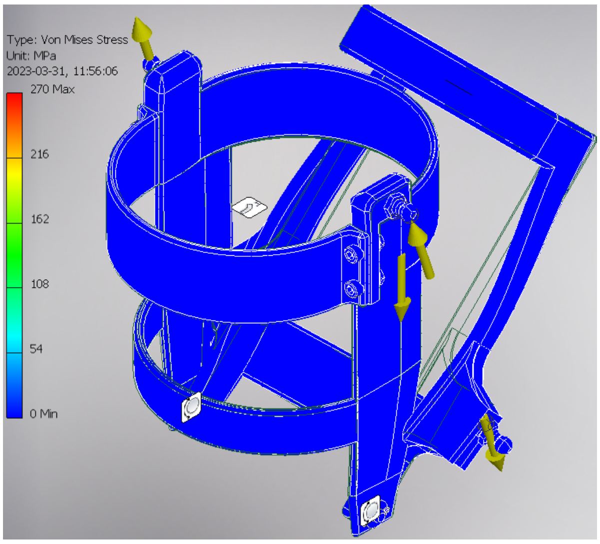

Fig. 41. Knee exoskeleton frame from ABS plastic Von Misses Stress

The Von Misses stress maximum result is 270 MPa. The safety factor is 0.93. The whole weight of construction with fittings and gas springs will be 1.118 kg. It is advisable not to use ABS plastic in the knee exoskeleton frame, as it is too weak a material. This structure will not withstand the load.

3.1.2. LCP Plastic as a Material for Knee Exoskeleton Frame

At both the melting and solids stages, liquid crystal polymers have a highly organized structure. Because of its exceptional strength at severe temperatures and resilience to practically all chemicals, weathering, radiation, and fire, LCP may replace materials such as ceramics, metals, composites, and other polymers. Polymer liquid crystals were composite material produced up of micron-sized liquid crystal droplets embedded in a polymer matrix. These composites have been employed in the production of flexible and transparent displays, as well as switchable windows. Significantly, by varying the concentrations of crystal and polymer, the electro-optical characteristics of PLC may be changed [36]. LCPs have high thermal stability up to 240 °C and short-term heat resistance up to 340 °C. Liquid crystal polymer mechanical and strength parameters from Autodesk Inventor material library:

- Behaviour – isotropic.
- Young's modulus - 1425 MPa
- Shear modulus - 5075 MPa
- Yield strength - 115.0 MPa
- Tensile strength – 130.0 MPa

Using LCP plastic as the frame material of the knee exoskeleton gives a maximum displacement of 0.155 mm, it is visible in the Fig. 42.

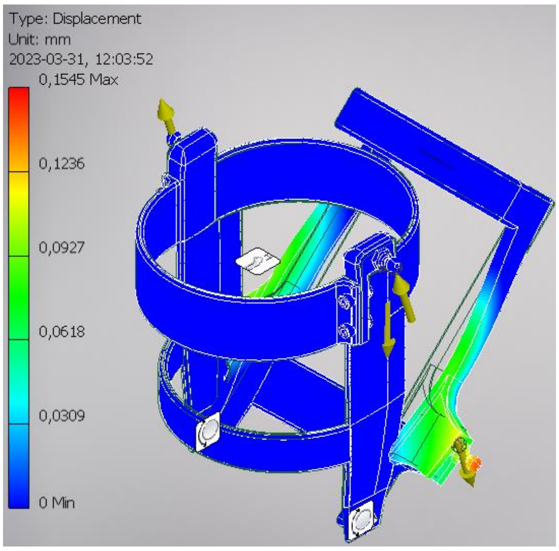

Fig. 42. Knee exoskeleton frame from LCP plastic displacement

The largest displacements can be seen in the lower part of the exoskeleton, where the attachment point is in the guide rail. This is due to the fact that the guide cannot be fully fixed. Compared to ABS plastics, LCP plastics are much stronger. Von Mises Stress is visible in the Fig. 43.

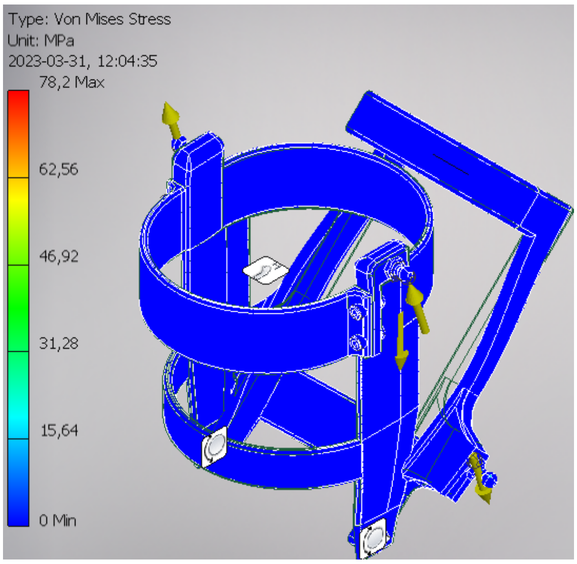

Fig. 43. Knee exoskeleton frame from LCP plastic Von Misses Stress

The maximum result of Von Mises Stress is 78.2 MPa. This result is also much lower than a frame with ABS plastic. The safety factor is 3.06. The whole weight of a construction with fittings and gas springs will be 1.418 kg, it is heavier by 300 grams than a frame from ABS plastic. It is possible to use this material for knee exoskeleton frame, because it can withstand the applied forces.

3.1.3. PETG Plastic as a Material for Knee Exoskeleton Frame

Polyethylene terephthalate glycol is the most prevalent thermoplastic polymeric material of the polyester family, and it is used in garment fibres, containers for beverages and foods, heat treating for manufacturing, and engineering resins in conjunction with glass fibre. PET uses the same monomers as the glycol modified PETG, but it has greater durability and strength. PETG is widely utilized in the packaging sector and has received substantial research. Because of their pervasive presence inside the environment for which polymers are utilized, H2O and O2 are considered to be the primary penetrants in polymers [37]. Polyethylene terephthalate glycol mechanical and strength parameters from Autodesk Inventor material library:

- Behaviour – isotropic.
- Young's modulus - 2757 MPa
- Shear modulus - 1239 MPa
- Yield strength - 54.40 MPa
- Tensile strength - 55.10 MPa

Using PETG plastic as the frame material of the exoskeleton gives us a maximum displacement of 0.082 mm, which is visible in the Fig. 44.

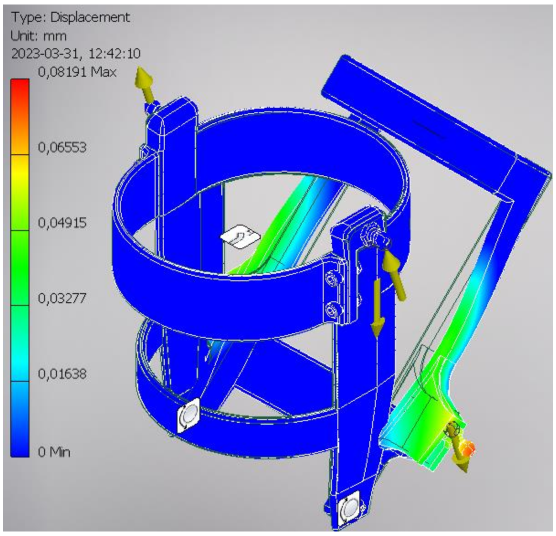

Fig. 44. Knee exoskeleton frame from PETG plastic displacement

Compared to past plastics, PETG plastics have the smallest displacement. It is almost invisible to see any displacements in the upper attachments of the gas springs, it is because that thigh band and thigh support are made more durable than calf support. Von Mises Stress is visible in the Fig. 45.

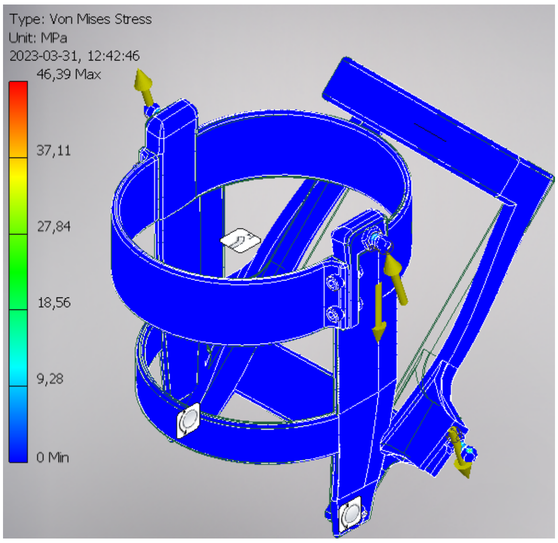

Fig. 45. Knee exoskeleton frame from PETG plastic Von Mises Stress

The maximum result of Von Mises Stress is 46.39 MPa. This result is almost twice as lower than a frame with LCP plastic. The safety factor is 4.2. The whole weight of construction with fittings and gas springs will be 1.373 kg, it is a little bit lighter than LCP plastic. It is possible to use this material for knee exoskeleton frame, because it can withstand the applied forces. Due to its strength and the value of the safety factor, this plastic can also be used in the production of the knee exoskeleton frame.

3.1.4. PBT Plastic as a Material for Knee Exoskeleton Frame

Because of its high toughness, strong stress-cracking resistance, resistance to fuels, oils, fats, and many solvents, minimal water absorption, and superior friction and wear properties, polybutylene terephthalate (PBT) is an essential commercial plastic. Additionally, due to its quick crystallization and ease of processing, PBT is preferable to its equivalent, polyethylene terephthalate [38]. This is a flexible engineering polymer that is utilized in the electronic and electrical sectors as an insulator. PBT may be shaped into numerous functional components and structural elements normally constructed from metals or thermosets, such as electrical, automotive, communications, machine components, food, and medical applications. Its chemical formula is (C12H12O4)n. Polybutylene terephthalate mechanical and strength parameters from Autodesk Inventor material library:

- Behaviour – isotropic.
- Young's modulus - 8997 MPa
- Shear modulus - 1867 MPa
- Yield strength - 55.10 MPa
- Tensile strength - 109.9 MPa

Using PBT plastic as the frame material of the exoskeleton gives us a maximum displacement of 0.243 mm, it is visible in the Fig. 46.

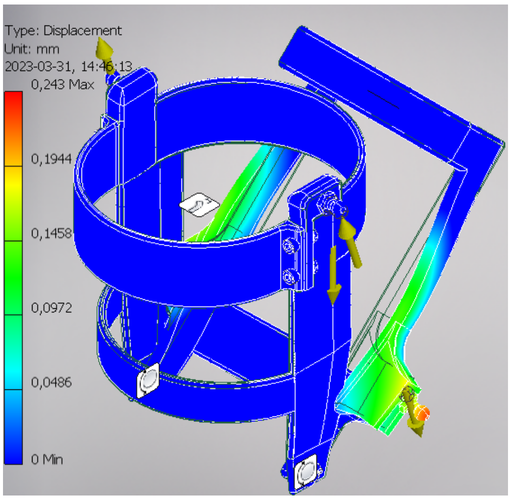

Fig. 46. Knee exoskeleton frame from PBT plastic displacement

The maximum displacements are in calf support, where the attachment point is in the guide rail. Displacement is bigger than PETG and LCP plastics. Von Mises Stress is visible in the Fig. 47.

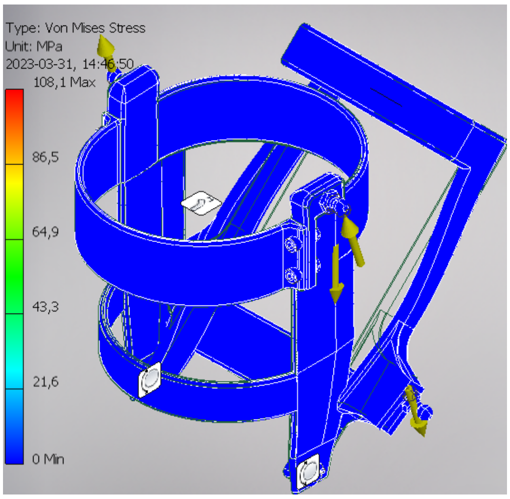

Fig. 47. Knee exoskeleton frame from PBT plastic Von Mises Stress

The maximum result of Von Mises Stress is 108.1 MPa. Stresses are bigger than PETG and LCP plastics, but lower than ABS plastic. PBT plastic gives the result of a safety factor of 2.24. The knee exoskeleton frame from PBT plastic is heavier than ABS plastic, although it is lighter than PETG and LCP plastic. Frame made from PBT weights 1.250 kg. PBT plastic is suitable for knee exoskeleton frame.

3.1.5. PMMA Plastic as a Material for Knee Exoskeleton Frame

One of the polymer compounds with high mechanical qualities is polymethyl methacrylate (PMMA). It is a translucent thermoplastic engineering plastic. The extreme wear and friction of pure PMMA, on the other hand, limit its use as a friction material for machine systems [39]. Because it is not optimal for most uses, pure poly (methyl methacrylate) is rarely sold as just an end product. Rather, customized formulations with various proportions of additional being together, additives, and filler are developed for applications requiring specific qualities. PMMA chemical formula is (C5O2H8)n. Polymethyl methacrylate mechanical and strength parameters from Autodesk Inventor material library:

- Behaviour – isotropic.
- Young's modulus - 2739 MPa
- Shear modulus - 1700 MPa
- Yield strength - 48.90 MPa
- Tensile strength - 79.77 MPa

Using PMMA plastic as the frame material of the exoskeleton gives a maximum displacement of 0.781 mm, it is visible in the Fig. 48.

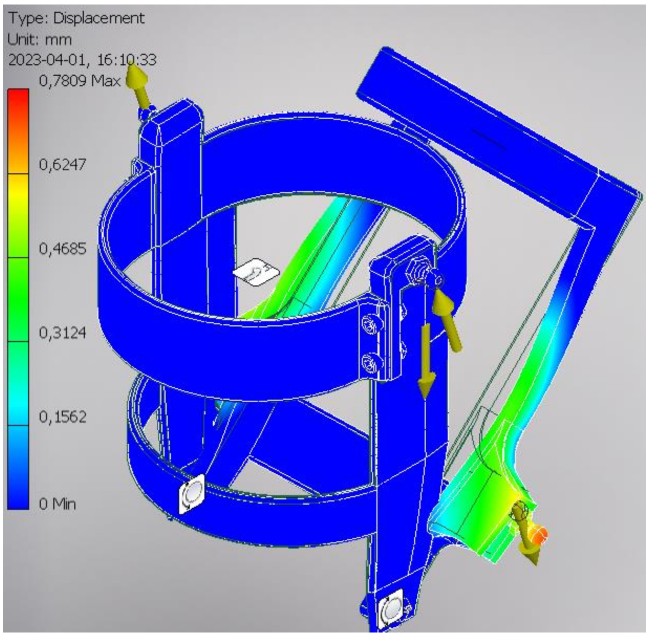

Fig. 48. Knee exoskeleton frame from PMMA plastic displacement

The maximum displacements are in the lower part of the exoskeleton. Displacement is bigger than PBT, PETG and LCP plastics. Von Mises Stress is visible in the Fig. 49.

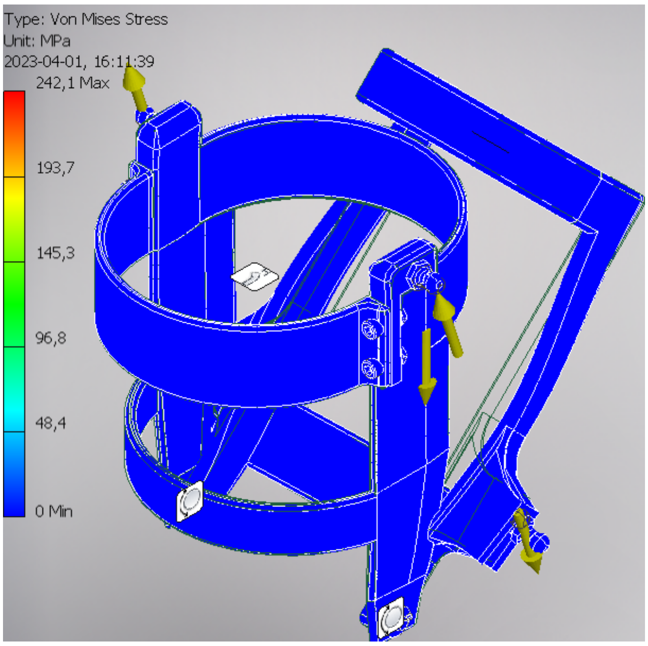

Fig. 49. Knee exoskeleton frame from PMMA plastic Von Mises Stress

The maximum result of Von Mises Stress is 242.1 MPa. Stresses are lower only than ABS plastic. PMMA plastic gives the result of a safety factor of 1.03. The knee exoskeleton frame from PMMA plastic is the lowest comparing ABS, PETG, LCP and PBT plastics. Frame made from PMMA weights 0.743 kg. The safety factor does not reach 1.5 in this case this material is not very suitable for knee exoskeleton frames construction.

3.1.6. Nylon Plastic as a Material for Knee Exoskeleton Frame

Nylon is a generic term for a class of synthetic polymers made up of polyamides. Nylon is indeed a silk-like thermoplastic that is often derived from petroleum and may be melted into fibres, films, or forms. Nylons have been utilized to make a variety of textiles and polymers due to their great strength, stiffness, flexibility, and chemical and heat resistance. Nylon-66 and nylon-6, in particular, account for about 90% of total nylon output globally (three to four million tons per year) [40]. It is possible to create compounds with diverse attributes by varying the acid and amine. Nylon mechanical and strength parameters from Autodesk Inventor material library:

- Behaviour – isotropic.
- Young's modulus - 2930 MPa
- Shear modulus - 999.7 MPa
- Yield strength - 82.74 MPa
- Tensile strength - 82.67 MPa

Using Nylon plastic as the frame material of the exoskeleton gives us a maximum displacement of 0.730 mm, it is visible in the Fig. 50.

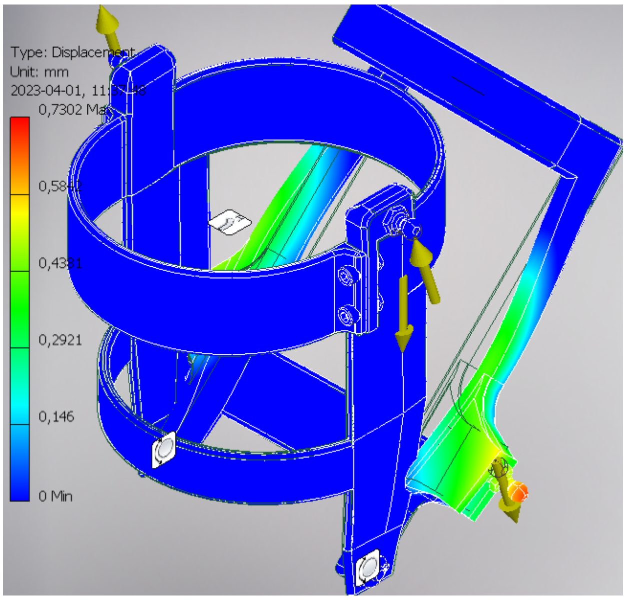

Fig. 50. Knee exoskeleton frame from nylon plastic displacement

The maximum displacements are visible in the lower part of the exoskeleton. Displacement is bigger are only lower than ABS plastics. Von Mises Stress is visible in the Fig. 51.

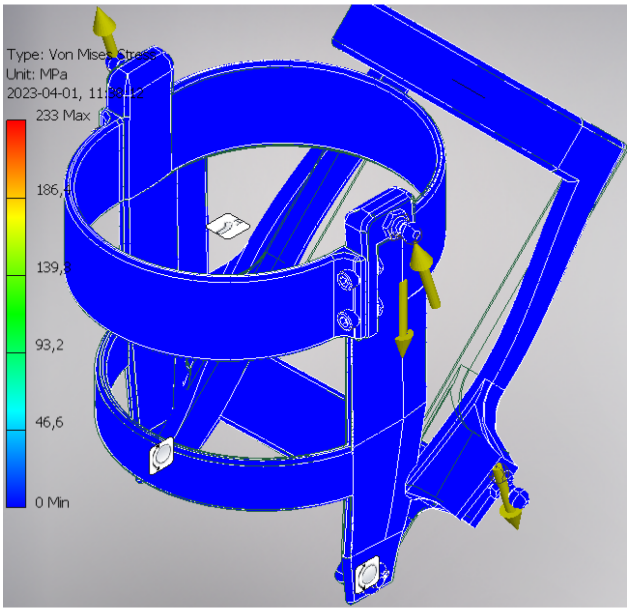

Fig. 51. Knee exoskeleton frame from nylon plastic Von Mises Stress

The maximum result of Von Mises Stress is 233 MPa. Stresses are lower only than ABS plastic. Nylon plastic gives the result of a safety factor of 1.07. The knee exoskeleton frame from Nylon plastic's whole construction weight is only 0.697 kg, this is the lightest material of all plastics that were used in research. This plastic cannot be suitable for the construction of the exoskeleton frame of the knee.

The obtained results need to be compared with each other to determine the appropriate material for the production of the knee exoskeleton. The first line chart is visible in the Fig. 52.

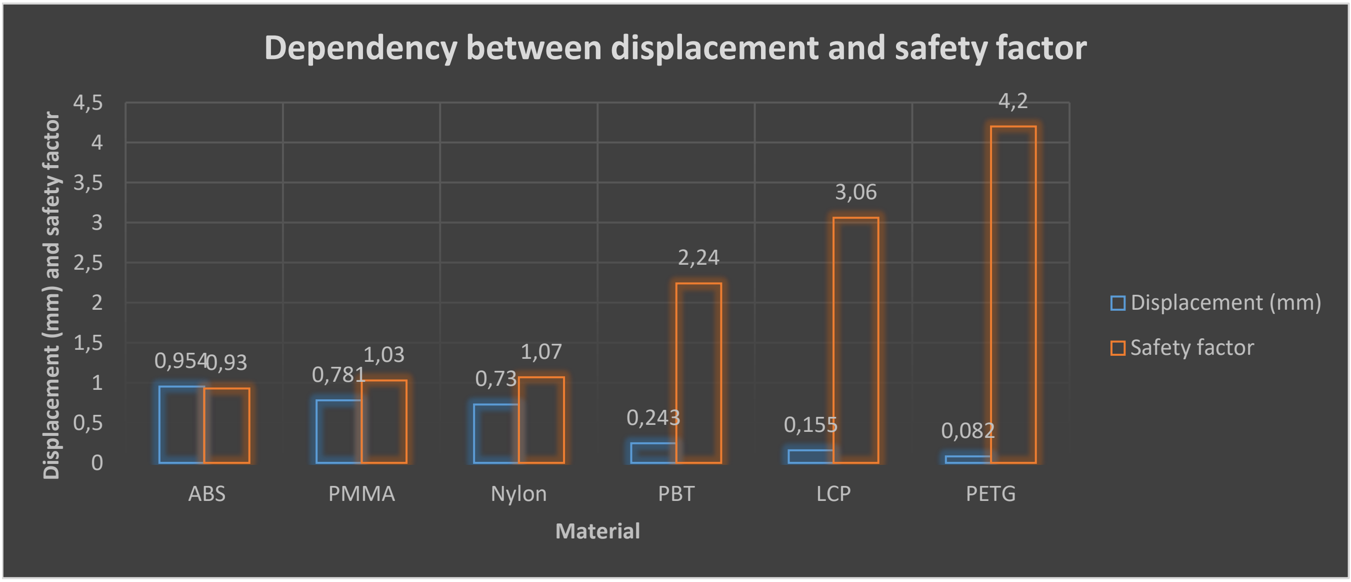

Fig. 52. Dependency between displacement and safety factor

In the clustered column chart, it is visible that three consecutive materials such as ABS, PMMA and Nylon do not differ much from each other. They have the lowest safety factors from 0.93 to 1.07 and the highest displacements of 0.730 to 0.954 mm. Materials such as PBT, LCP and PETG comply with the safety factor and displacements are not critical. From this chart, it is possible to conclude that materials that would be suitable for knee exoskeleton production are PBT, LCP and PETG. Also, it is possible to see the ratio of displacement and Von Misses stress that are visible in the Fig. 53.

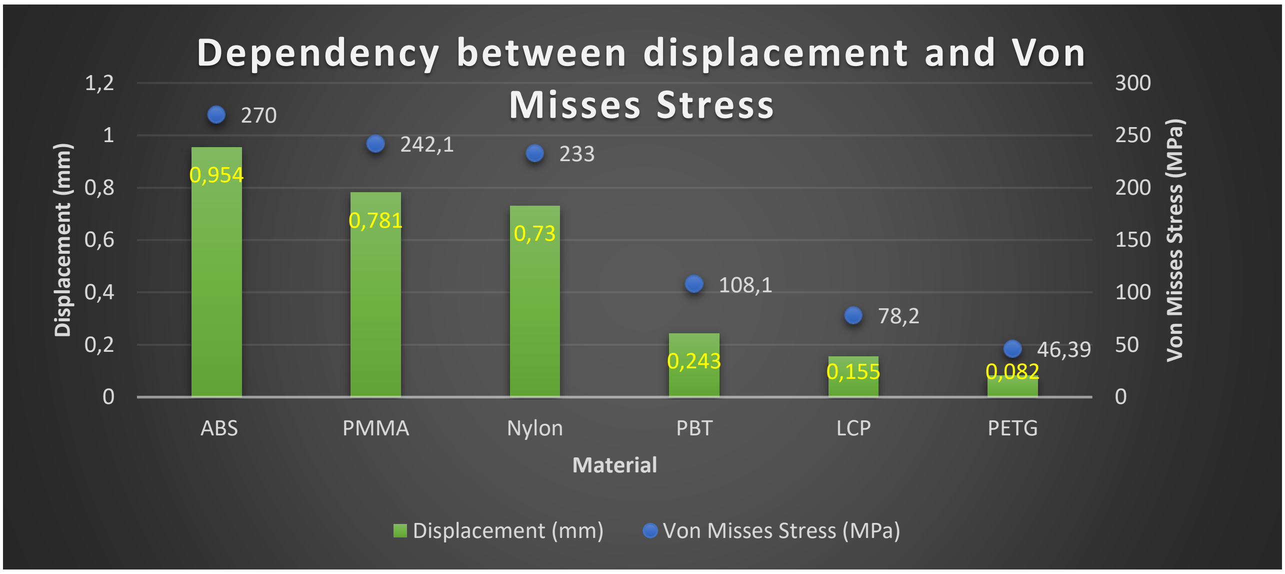

Fig. 53. Dependency between displacement and Von Misses Stress

In the dot-column chart, it is visible that the same three materials like ABS, PMMA and Nylon have the highest results of displacements and stresses of 233 to 270 MPa. PBT, LCP and PETG materials have low results like the stress of 46.39 to 108.1 MPa. The material which would be the most suitable for knee exoskeleton production is PETG because of the lowest displacement of 0.082 mm, lowest stress of 46.39 and biggest safety factor of 4.2.

3.2. Prices of the Materials for Knee Exoskeleton Frame

After analysing the forces exerted on different plastic materials, we found out that more than one plastic material is suitable for the exoskeleton frame, so it is necessary to find out if these plastics can be printed using a 3D printer and what their prices are. 3D printing characteristics and prices of materials:

- Acrylonitrile Butadiene Styrene (ABS) is a popular technical polymer and 3D printing filament. ABS has a high degree of durability and can endure quite high temperatures. ABS printing necessitates high temps for both the heating element and the printing bed. For excellent outcomes, heated building volumes are also necessary. Moreover, all forms of ABS warp while printing, resulting in poor dimensional accuracy. ABS offers a high resilience to general wear and tear. It is both tough and resistant to impact [41]. ABS is not water-soluble. Organic solvents such as acetone, methyl ethyl ketone, and esters, on the other hand, will dissolve ABS. It is also a food-grade plastic. The price of the 1 kg filament is 14.24 without VAT [41].
- PMMA filament is a thermoplastic transparent material in the shape of a fibre, sometimes known as plex or plexiglass. The material used in the FFF method of 3D printing. Filament coiled on a spool with a moisture absorber, vacuum sealed. 1kg of net materials is contained in the spool. It may be used in any FFF printer that is not restricted from foreign providers and open-source structures. PMMA has a high level of transparency and surface gloss. PMMA is designed for advanced users. The price of the 1 kg filament is 16.22 without VAT [42].
- Nylon, often known as polyamide, is a popular technical thermoplastic due to its high wear resistance as well as its strength. PA 6 is the most often used nylon grade for 3D printer filaments. Nylon is resistant to both impact and wear. Nylon, on the other hand, absorbs moisture quickly. It also necessitates rather high print temperatures that can reach up to 265 degrees Celsius. Because of the high temperatures required, nylon warps during printing. As a result, a warmed enclosure is advised [40]. Because of its hygroscopic nature, nylon stretches when exposed to water. Acetic and formic acids break down nylon. There are food-safe grades of nylon. The price of the 1 kg filament is 72.10 without VAT [42].
- PC/PBT is a polymer mix that provides excellent high thermal stability and durability at low temperatures (-20 C/-30 C). PolymakerTM PC-PBT is also chemically resistant. It is advised to utilize a heated chamber while printing with PolymakerTM PC-PBT. When not employing a heated chamber, it is suggested to sequence the printed item immediately after printing to remove residual internal tension. Price of the 1 kg filament is 53.18 without VAT [42].
- LCP uses of elevated raw materials result in a 3D printer filament that is very simple to produce. Very low production tolerances are obtained using a cutting-edge manufacturing method, resulting in convincing printing outputs with all FDM 3D printers. Each coil is individually wrapped in an elevated bag. LCPs offer good melt flowability, heat resistance, high-temperature dimensional stability, chemical resistance, low thermal expansion, and mechanical characteristics. Long-term heat resistance exceeds 190°C. weak bases and acids, alcohols, flavourings, chlorinated hydrocarbons, esters, ketones, and any compounds that might induce stress cracking in most other plastics are particularly resistant to LCPs. The price of the 1 kg filament is 518.53 without VAT [43].
- PETG (polyethylene terephthalate glycol) has the addition of glycol that reduces the melting temperature considerably to make PET more usable. PETG is not only easy to print, but it is also UV-resistant. Its main drawbacks are weak adhesion and the potential for strings to form

when the printhead traverses vacant space between features. PETG has outstanding mechanical qualities and is resistant to an extensive variety of chemicals and extreme heat. PETG is not very prone to warping [41]. Solvent and methyl ethyl ketones (MEK) are both soluble in PETG. This material is food safe. The price of the 1 kg filament is 11.72 without VAT [42].

After analysing the materials used in the study regarding their potential to be used in 3D printing production and price, it is possible to compare the prices of materials. Information is visible in the Fig. 54.

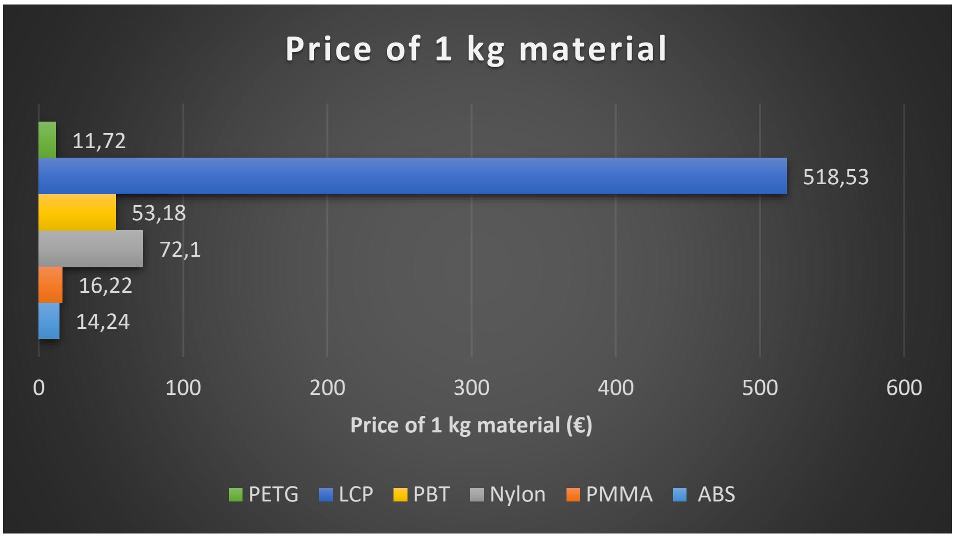

Fig. 54. Material price of 1 kg filament

Depending on given results in the clustered bar chart, it is visible that the most expensive material to use for knee exoskeleton production is LCP. Its price is completely different from other materials having 518.53 € for 1 kg. Nylon and PBT prices are not as high as LCP material although it is still higher than the three of left one's materials. ABS, PMMA and PETG have the lowest prices of 11.72 to 14.24 € of 1 kg. Paying attention to the cost of the material, these three materials would be the most suitable for the production of the knee exoskeleton.

3.3. Additional Electronic Functionality in the Knee Exoskeleton

The actuators used as gas springs in the knee exoskeleton are not permanent. They have their operating time and must be replaced with new ones after that time. Suspa manufacturers claim that the lifetime of the gas springs they supply is between 10,000- and 100,000 times compression and extension [44]. However, the actual service life of a gas spring in service is determined by a variety of circumstances. Therefore, gas springs should be evaluated in their individual applications under real-life conditions in order to make an accurate statement about the service life of the gas spring. If the gas spring has already begun to deflate, the person wearing the knee exoskeleton may not notice. The knee exoskeleton must have electronic components to detect the critical number of contractions and extensions and replace the gas spring before it fails. This saves labour time, and the person can avoid injury if the gas springs stop functioning fully without lifting a heavy object. In addition, the knee exoskeleton can be equipped with a sensor that measures not only the contractions and expansions of the gas spring but also the steps the person takes throughout the day. In this way, it is possible to determine how many steps a person takes per day, average them out, and monitor whether the employee is really working enough. All the information provided by the sensors must be forwarded to the computer, which contains the results of all the exoskeletons used.

3.3.1. Micro Switch Sensor

There are countless sensors that could read a human step, like a linear potentiometer, an inductive sensor, or an optical sensor. However, it should also be taken into account that the sensor must be properly attached to the knee exoskeleton frame, be as small as possible, and be cheap. All these criteria are best characterized by the micro switch. See Fig. 55.

Fig. 55. Micro switch sensor for measuring human steps [45]

This “RND Components” 210-00744 switch uses a mechanically powered lever to determine the location of a movable element and transmits an electrical signal whenever the moving portion has reached its final position. Because the switches require few components and consume very little energy. They locate the origins of the X, Y, and Z axes [45]. The limit switch may be operated with direct power of 5 V and includes two tiny bores for attachment to other components. The Max current is 30 mA. The size of the body is 12.8 x 5.8 x 6.5 mm. The actuation force is only 490 Nm. The price of this unit is only 0.96 euros without VAT.

3.3.2. Micro Photo Sensor

To receive a signal when a person squats to nearly 135 degrees requires a sensor that can read that the angle of the exoskeleton structure has changed. It would be logical to fix the sensor on the gas spring, but when changing the gas spring, the structure of the sensor should also be changed by exaggerating another gas spring. The most suitable sensor will be a micro photo sensor. See Fig. 56.

Fig. 56. Photo micro sensor for counting human squats [46]

“Omron” EE-SX674 photo micro sensor used to measure or detect things that travel across the uprights of the U-shaped detector. An IR receiver and transmitter pair face one another across a U-shaped enclosure of the module. The IR beam is broken when an item moves across these uprights.

Typically, these modules are used to count a thing as it goes through the uprights. This might be gears on a wheel counting rotations or RPM, or pellets descending via a funnel if it is part of a pellet stove or rabbit feeder [46]. Another application is as an optic limit switch to detect whether a device is open or closed or if an object moves into or out of a beam. Voltage can be from 5 to 24 V. Max current is 12 mA. Dimensions are 13.6 x 15.5 x 25.3 mm. The price of this unit is only 2.73 euros without VAT.

3.3.3. Microcontroller

In order to send the received signals from the sensors on the knee exoskeleton, a microcontroller with an additional Wi-Fi function is required. With the typical compact size of the UNO family, the Arduino Wi-Fi Rev.2 provides the simplest point of entry into basic IoT [47]. The Wi-Fi Module is an independent SoC including an inbuilt TCP/IP protocol that may give network connectivity or operate as an access point. 5 V is the operating voltage. Six analogue input pins are available. 50 mA DC Current per I/O Pin. The Max current that uses a micro board is 500 mA. It cost about 53.8 euros without VAT. The wiring diagram of the microcontroller is visible in the Fig. 57.

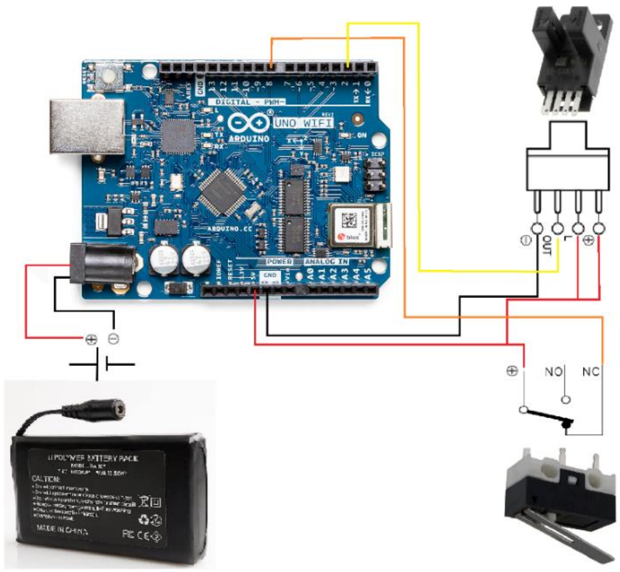

Fig. 57. Wiring scheme in to the Arduino Uno Wi-fi Rev.2

The battery should be connected to the power jack of the microcontroller, because this is the connection that can supply power from an external power source. The power jack allows the board to operate independently of a computer or USB connection. Micro switch will be connected to the 5 V source and digital out pin number 8. This sensor only has to sense when the lever is closed, so a connection called "normally closed" is only used. Micro photo sensor has 4 outputs. Positive is connected to the 5 V source, negative is connected to the ground, output is connected to the output pin number 2 in order to sense when the object is passing through the sensor's fork. A connection called "L" is connected to the source of 5 V. This connection only turns on the LED of the sensor to let us know if the object is passing through the sensor, this pin is not necessary.

3.3.4. Power Source

The power source must be selected according to the energy consumption of the sensors in the microcontroller and micro controller itself. From the electronic component research, we have data that the micro switch uses a maximum 30 mA, the photo micro sensor uses a maximum 12 mA, and the microcontroller itself uses a maximum 500 mA. Adding these values result in 542 mA and it is understandable that the power source must give a minimum of 542 mAh. Also, it should provide a minimum of 5 voltage. The best option is to use an external, rechargeable battery, it is visible in the Fig. 58.

Fig. 58. Li-polymer battery pack power source for microcontroller [48]

"Day Wolf" Li-ion 4400 mAh rechargeable battery pack stores the energy that employs the reversible decrease of lithium ions. The anode of a traditional lithium-ion battery is commonly graphite, which is comprised of carbon. The cathode is usually made of metal oxide. Typically, the electrolyte is a lithium salt in a solvent. When discharging, lithium ions transport current from the negative to positive electrodes of the battery cell via the non-aqueous electrolytes and separator diaphragm [48]. An external electrical power source delivers an overvoltage during charging, causing a charging current to flow through each cell from of the positive to the negative electrode. In a process known as intercalation, the lithium ions move from the positive to the negative electrode by becoming entrenched in the porous electrode material. "Day wolf" battery has a 7.4 voltage and 4400 mAh. This battery will provide a power source to a microcontroller for minimum of 8.1 hours if the microcontroller with sensors will work in a 100 % regime. For the battery to discharge in 8.1 hours, a person would have to do squats non-stop. Since this is not possible, it can be said that the battery will not discharge for 10 hours a day. However, this battery will need to be charged every day after the end of work to be fully functional again the next day. The price of the Li-ion battery pack is 54.47 euros without VAT.

3.3.5. Positions of Electrical Parts in the Knee Exoskeleton and Control Algorithm

The sensors used can be fixed with screws or simply with double-sided adhesive tape if the working environment is closed. It is visible in the Fig. 59.

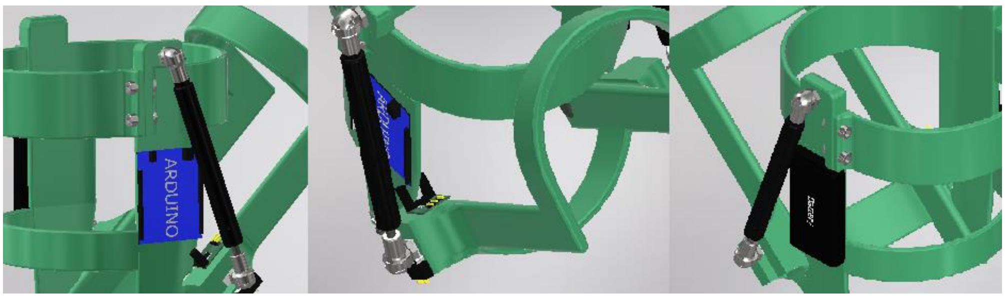

Fig. 59. Positions of sensors, power source and microcontroller on knee exoskeleton

The micro switch will be attached to the slider area of the knee exoskeleton. When the slider goes all the way down, the handle will be fully depressed and will send a signal to the microcontroller. The optical sensor will be fixed on the lower part of the exoskeleton in such a way that the plastic of the upper part appears between the U-shaped diode sensor, thus blocking the light transmission, the signal will be transmitted to the microcontroller. The microcontroller will be mounted on the top left side of the exoskeleton, as it will not interfere and will be protected from possible damage from the environment. The power source will be attached on the right side of the exoskeleton by double side tape.

A block diagram of the working principle of knee exoskeleton sensors is visible in the Fig. 60.

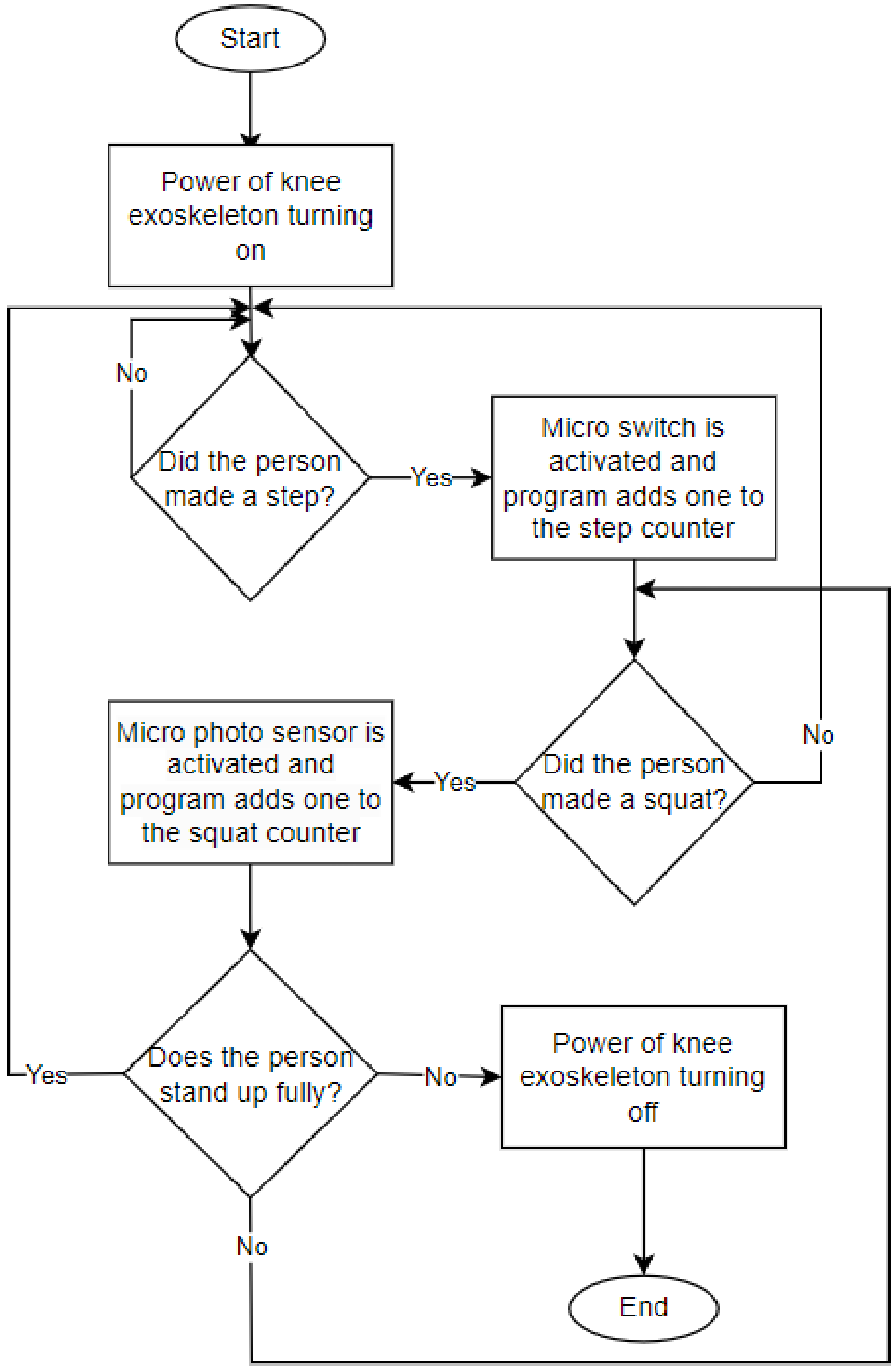

Fig. 60. Knee exoskeleton block diagram of working principle.

When the knee exoskeleton is put on the leg, it is activated. When a person bends his leg to 48 degrees while walking the micro switch is activated and the information is sent to the program, which adds one value to the steps counter. If the angle of the leg is returned to the zero angle (to the initial position), the micro switch is deactivated and continues to wait for the person's leg to bend up to 48 degrees. When the micro switch is activated and the human leg bends up to 145 degrees, the micro photo sensor is activated, which sends a signal to the program, the value of which is added to the squat counter. If a person starts to stand up until the leg is bent for 48 degrees, photo micro sensors is deactivated, although the micro switch is activated. If a person stands up into the ordinary position of 0 degrees, both sensors are deactivated. If a human removes the knee exoskeleton, it is turned off.

3.4. Summary

Using the stress analysis option of Autodesk Inventor 2023 the stresses and displacements of different plastic materials were analysed and obtained the safety factor from this. It is hard to see any displacements in thigh band and thigh support, it is because the upper side of exoskeleton frame is much durable than calf's support frame. Rotational angle of knee is neglected, due to the fact that it would lower the resistance of exoskeleton frame. Weight is determined with different materials included and all components such as fasteners and gas springs. It was also concluded that all these plastics can be used in 3D printers. After conducting a search in online stores, the price of 1 kg of plastic was obtained without VAT for each material. Having the two most important parameters at the moment the safety factor and the price of material, it is possible to compare them and decide which material will be the most suitable for the production of the knee exoskeleton. The ratio between price and Von Misses Stress is visible in the Fig. 61.

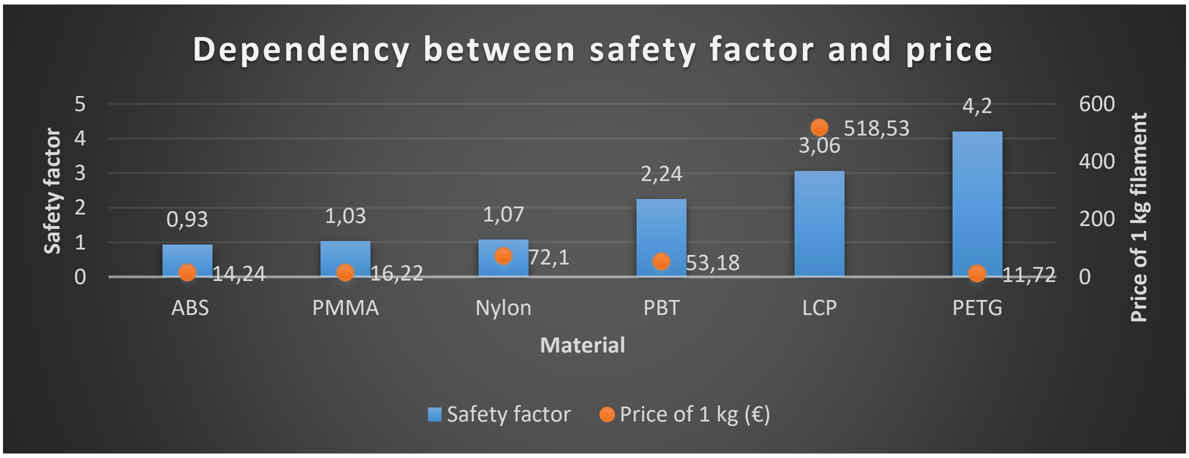

Fig. 61. Ratio between price and Von Misses stress.

Materials such as ABS, PMMA and Nylon have suitable prices for knee exoskeleton production, although safety factors are too low, which will appear failure of using knee exoskeleton out of these materials. PBT material has higher result of safety factor according to ABS, PMMA and Nylon also, the price also would be suitable for knee exoskeleton, although it is necessary to have some reserves of resistance of material. LCP material have even higher SF result of 3.06 than PBT material, although the price is too high, it would even cost 518.53 € of 1 kg which is 44 times higher than the material which has the lowest price. The last material is PETG, it is the most suitable material for the production of knee exoskeleton. It has the best result of safety factor (4.2) and price (11.72 euro). All obtained results are visible in the Table 4.

Table 4. Results of material resistance, weight, and price

Material	Displacement (mm)	Von Misses Stress (MPa)	Safety factor	Mass with all components (kg)	Price of 1 kg (€) without VAT
Acrylonitrile butadiene styrene (ABS)	0.954	270	0.93	1.118	14.24
Polymethyl methacrylate (PMMA)	0.781	242.1	1.03	0.743	16.22
Nylon	0.730	233	1.07	0.697	72.10
Polybutylene terephthalate (PBT)	0.243	108.1	2.24	1.250	53.18
Liquid crystal polymer (LCP)	0.155	78.2	3.06	1.418	518.53
Polyethylene terephthalate glycol (PETG)	0.082	46.39	4.2	1.373	11.72

From the data presented in the table, it is possible to see that material PETG has the lowest displacements of 0.082 mm, lowest results in Von Misses Stress of 46.29 MPa, highest safety factor of 4.2, mass of 1.373 kg with all components and the lowest price of 1 kg, which is 11.72 € without VAT.
Selected sensors such as the “Omron” EE-SX674 photo micro sensor and the “RND Components” 210-00744 end stop switch will be able to successfully count steps and squats performed by a person. The sensors will be connected to the Arduino Uno Wi-Fi Rev2 microcontroller, since this microcontroller will be able to send signals to the computer, and there collect data about the work performed by the person. When a certain number of contractions of the gas spring is reached, it will be possible to predict the end of the work of this actuator. “Day Wolf” rechargeable Li-ion battery pack will provide power to the microcontroller of 7 V and 4400 mAh. Electrical equipment will be able to work for at least 10 hours, although it will be necessary to charge this battery every day in order to keep it running. Electronical parts will cost 111.96 euros without VAT.

3.5. Discussion

Six different plastic materials were compared for the production of the knee exoskeleton frame, as polymethyl methacrylate, acrylonitrile butadiene styrene, liquid crystal polymer, polyethylene terephthalate glycol, polybutylene terephthalate and nylon. Using Autodesk Inventor 2023 the constraints were applied where the human body’s thigh and calf will rely on the knee exoskeleton’s frame and pin constrain where thigh and calf supports are connected. Forces of 100 N were applied to the place where the gas spring will be attached. By changing the type of plastic, but keeping the same constraints and forces, it was found that the material which had the highest safety factor was polyethylene terephthalate glycol. Although acrylonitrile butadiene styrene is usually used for 3D printing, but it is too weak for the knee exoskeleton frame. Just like in the scientific article called “A numerical simulation of the mechanical structure of an ankle exoskeleton oriented to elderly people” ABS plastic gave the worst parameters [49]. The goal of this article was to develop an ankle exoskeleton for elderly people (see Fig. 62), because the ankle happens to be one of the most injury-prone joints because of its irregular sphere shape, and the elderly are more vulnerable to this injury (around 80% of individuals with a history of ankle sprain go through surgery for post-traumatic ankles osteoarthritis).

Fig. 62. Mechanical design of ankle exoskeleton [49]

Two different materials (carbon fibre reinforced polymer and ABS) were compared. Von Misses Stress result of ABS plastic was 20.26 MPa and the safety factor was 0.99. Carbon fibre reinforced polymer gave a result of 20.18 MPa Von Misses Stress just like in the Fig. 63 and a safety factor of 14.87.

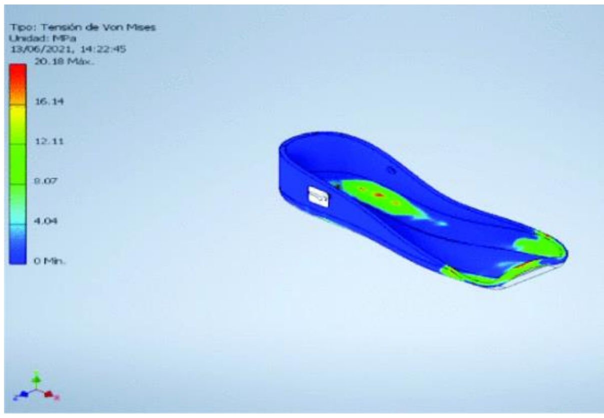

Fig. 63. Carbon fibre reinforced polymer Von Mises stress result [49]

Similarities with this research is that the different materials were compared and the result of ABS plastic is that it is one of the weakest plastics that can be used in exoskeletons frames by the 3D printing manufacturing method. Differences are that it is not known the price of the whole ankle exoskeleton, there are no sensors or any electronic components attached to the exoskeletons frame, so there is also no wiring diagram. There is no additional force or actuator to let the ankle move easier. For the ankle exoskeleton to be more useful, it would be advisable to install elastic bands at the ankle support, which would prevent the ankle from bending more than necessary, and provide an additional auxiliary force when moving the ankle. At the bend of the ankle support, a micro-switch could be installed to measure the steps taken by the person. In this case, it would be possible to determine which elastic bandages are needed, depending on the steps taken per day or week. The construction of the sole is uncomfortable, it lacks the anchoring of the human foot, as the heel will always touch the construction of the sole, but the part of the leg leading from the sole will lift off the construction of the sole. The suggestion would be to fix them evenly, with the same elastic bandages.

4. Cost, Social and Environmental Aspects of Knee Exoskeleton

Knee exoskeleton prices can vary greatly based on aspects like as design, materials, and methods of production. While these devices may be prohibitively expensive for some people, others may be willing to pay the price in order to regain mobility and independence. Furthermore, the societal effects of knee exoskeletons should be considered, as their use could have implications for social inclusion and healthcare access. The environmental effect of plastic knee exoskeletons cannot be overstated. Plastic manufacturing and disposal have well-documented environmental consequences, and the manufacture of knee exoskeletons is no different. As a result, it is critical to make knee exoskeletons in such a way that they do not harm the environment.

4.1. Knee Exoskeleton Cost

After performing the construction of the exoskeleton of the electronic components, their cost prices were determined. We also know how much a PETG plastic coil for a 3d printer costs. To find out a more accurate cost of the knee exoskeleton, it needs to know how much PETG plastic will be used in total to print three different parts of the knee exoskeleton. For this task, the Idea Maker program was used to prepare the parts for 3D printing. The Raise3D N2 3d printer was selected for the program due to its print space area of 305x305x305 mm. All three components can be successfully placed in this area. The nozzle extruder will be “Raise3D” PETG 1.75 mm and the infill density will be of 100 % in order to make the knee exoskeleton as sturdy as possible. Also, to avoid any defective printed parts, it will be necessary to use supports and printing mode of quality this means that it will print only at 70 mm/s of speed. The results of the sliced parts are visible in the Fig. 64.

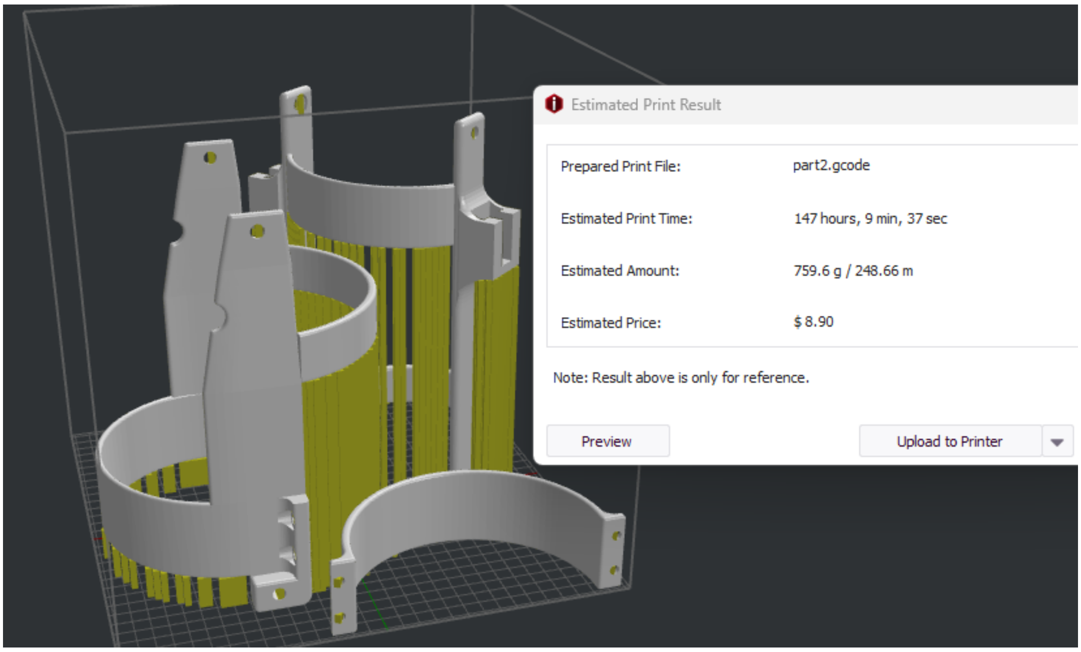

Fig. 64. Estimated print result of knee exoskeleton

Three knee exoskeleton parts printing will take 147 hours, this is due to slow and high-quality printing. Using faster printers and wider extruder nozzle or changing the print speed could lower the printing time. Using PETG material, with all supports and 4 parts, only 760 g of plastic will be used. This amount will cost 8.07 euros. Usually, the average cost for the 3D printing manpower is 9,09 € an hour and power consumption per hour should be about 320 W, which will cost around 0.05 € [50].

By having material consumption and hour of printing time, it is possible to calculate the cost of printing if the order would be fulfilled in any company, see Eq. 5.

Calculation of printing knee exoskeleton frame:

$$C = P \cdot t + M \cdot t + F, \quad (5)$$

where: C is the cost of printing the knee exoskeleton (€); t is the printing time (h); P is the power consumption per hour (€); M is the man power cost (€); F is the estimated filament price (€).

The cost of 3D printing the knee exoskeleton in a certain company will cost around 1351.65 €. This price is high, because of the many printing hours. A better solution would be to purchase a 3D printer and print it yourself, rather than ordering from other companies. Without manpower payment, printing cost would be around 15.42 euros.
The whole knee exoskeletons components prices are in the Table 5.

Table 5. Price of the knee exoskeleton

Component	Model	Quantity	Price without VAT
PETG filament	“Marwiol” PETG 1.75 mm	760 g	8.07 €
Gas spring	“Suspa” 16-1-131-104	2	117.88 €
Micro switch	“RND Components” 210-00744	1	0.96 €
Micro photo sensor	“Omron” EE-SX674	1	2.73 €
Micro controller	“Arduino” Wi-Fi Rev.2	1	53.80 €
Battery	“Day Wolf” Li-ion 4400 mAh	1	54.47 €

From the data presented in the table, it can be said that the highest cost of the exoskeleton will be electronic components. The print job is not calculated, as it can be printed with your own printer or on order. The whole knee exoskeleton with electrical components will cost 237.91 euros.

4.2. Eco-Friendly Manufacturing of Knee Exoskeleton

As the globe continues to sink in plastics, those involved in 3D printing must stand up and employ environmentally friendly ways. Plastic trash is still a problem for the environment since it ends up in landfill and affects our oceans. To make things worse, certain plastics might take thousands of years to disintegrate. However, the future does not have to be so grim because 3D printing aficionados may employ green printing technologies to recycle material from failed prints and leftover filament. 3D printing garbage may simply be transformed into a 3D treasure by recycling them. Plastic materials are collected and sent to a recycling facility where they are sanitized organized, shredded, and melted into useable plastic pellets. Because plastics exist in a variety of forms, they must not be combined or mixed with other substances or they will begin to lose their durability and strength. All thermoplastics, in principle, can be recycled to variable degrees of efficiency. For instance, the most common plastic like PET is used to produce plastic bottles. As a result, most recycling plants are designed to treat these materials. Although PETG is identical to PET/PETE, it has a lower melting point and can affect the stability of PETG if recycled combined [51]. Some of the recycling facilities have programs for collecting leftovers and may even pay for it. Filament recycling facilities are the greatest solution to reuse material from unsuccessful prints while spending less money on filament. They are intended to grind the material, melt it, and create a fresh spool of filament.

Recycling is not the only way to reduce 3D printer waste. Dealing with plastic build-up becomes simpler if it is done to avoid it in the very first place. Even if it is impossible to avoid having unsuccessful prints, it is possible to limit the quantity of waste generated by following these guidelines:

- Use fewer supports: While using supports is beneficial and sometimes required, they are not required for every project. Improve the layout and workflow to get rid of as many supports as feasible.
- Slow down and make it easy: some of the most prevalent causes of project failure involves printing too many components at once. When a component fails, it has a detrimental influence on the others who rely on it and renders them worthless, resulting in a large amount of plastic waste. It is advisable to break your project into parts and go through numerous prints rather than completing everything at once.
- Purchase recyclable filaments: Filament manufactured from plastic that has been recycled is available, and purchasing it will help to promote sustainability.

4.3. Social Aspect Using Knee Exoskeleton

A knee exoskeleton is created to help with physical labour can be of great societal benefit, particularly in sectors requiring hard labour. This form of the exoskeleton can help employees lift large loads, minimize accident risk, and increase overall productivity. Workers may do physical tasks with more comfort and for a longer amount of time by giving more support to the knee joint. As a result, job performance and job satisfaction may improve. Furthermore, the employing of exoskeletons in physically demanding work circumstances can help promote a safety culture in which employees feel more at ease and secure in their ability to perform their duties. In everyday life, wearing a knee exoskeleton can enhance mobility and minimize tiredness, making it simpler to accomplish daily chores while maintaining an active lifestyle. Furthermore, knee exoskeletons can be particularly helpful for people who have knee injuries or illnesses allowing them to engage in physical activities they were previously unable to do. Exoskeletons have the potential to boost physical health and welfare, enhance the quality of life, and increase overall productivity, rendering them a valuable tool for people of all ages and abilities. A knee exoskeleton meant to aid physical labour can also be of substantial social use to older people in their everyday lives. As people get older, their mobility and muscular strength may deteriorate, making simple tasks like walking or climbing stairs harder. A knee exoskeleton can offer support to the knee joint, lowering the risk of accidents and allowing older people to preserve their autonomy and mobility. This can lead to increased self-esteem and confidence, as well as an improved quality of life. Using a knee exoskeleton can also enhance physical health and lower the risk of chronic illnesses including obesity, diabetes, and heart disease. A knee exoskeleton has tremendous social usefulness for elderly people since it promotes active aging and allows them to participate in everyday activities with more ease and comfort.

4.4. Summary

After finding out how much the knee exoskeleton components will cost, it is possible to say that according to possibilities it will give, the price of about 240 euros is acceptable. However, the price of the manufacturing time of 3D printer is very high of around 135 €, although the 3D printer can be purchased or contacted the manufacturers, who will specifically tell the price based on the printing time. The printing time is 147 hours and 9 minutes, it is because the extruder nozzle is 1.75 mm and used infill is 100 %. To protect the environment when using PETG plastic, it is necessary to minimize the use of supports during printing, to slow down the printing speed, and to send the waste that is unavoidable to recycling centres. The knee exoskeleton project will be social because it can be used not only in physically demanding jobs, but also in everyday life. People who have injured their knees or people of respectable age who have already lost adequate strength to move will be able to successfully and safely by a knee exoskeleton.

Conclusions

1. After reviewing similar exoskeleton designs such as the C-Brace, Hybrid assistive limb exoskeleton, Archelis and Honda leg-walk assist exoskeleton, it is possible to say that one of the purposes of making all exoskeletons is for rehabilitation from lower-body treatments. The differences between these exoskeletons are actuators like a servo motor, a linear hydraulic cylinder or a mechanical brake. The construction itself differs a lot between them, although all exoskeletons have paddings, that provides comfortability of wearing.
2. The design of the knee exoskeleton frame was developed because it will be made of plastic in order it to be lightweight. Because of the plastic frame it was possible to make slopes and bends. Four different parts were designed, like thigh band, thigh support, calf support and slider. The thigh band and thigh support will be assembled by hex nuts screw, the thigh support will be attached to the calf support by pin and hole principle, the slider will be able to move in the guiding.
3. Selected actuators are “Suspa” 16-1-131-104 gas springs, its extension length is 100 mm that will be suitable for the knee exoskeleton and it will support the human lower body by 200 N force while squatting and standing up. Since this component will only be operated with human mass, it will not require any additional electronic components.
4. Knee exoskeleton frame will be manufactured by fused deposition modelling 3D printer. Using Autodesk Inventor 2023 stress analyser six different plastics, like ABS, nylon, PETG, PMMA, PBT and LCP were compared. From the achieved results of the safety factor and price of the 1 kg filament, was decided that PETG plastic is the most suitable for the production of the knee exoskeleton by 4.2 of safety factor and a price of 11.72 euro of 1 kg filament.
5. Selected sensors are the “Omron” EE-SX674 micro photo sensor for counting human body squats and “RND Components” 210-00744 micro switch for counting human steps. By supplying signal from “Arduino” Wi-Fi Rev.2 micro controller human steps and squats are counted. “Day Wolf” Li-ion 4400 mAh rechargeable battery pack will supply power for the micro controller and sensors.
6. The cost of the knee exoskeleton components are around 240 euros without VAT. If the exoskeleton is going to be printed by some company, the printing job can cost, even around 1350 euros. If the 3D printer is own, then the price of printing would be around 15 euros, without man power cost. In order to reduce the environmental pollution of PETG, plastic needs to be recycled and printed with 3D printers in such a way as to avoid waste as much as possible. The knee exoskeleton project will have big sociality influence, because it can be worn in everyday life to decrease the probability of injuries and improving the quality of physical work.

Recommendations

The research not only addressed many questions, but it also prompted new ones. The knee exoskeleton has the potential to increase efficiency in physical working places, because it will provide additional strength while squatting and standing up. More research, however, is required. Recommendations for further research are presented below.

1. After calculations of PETG plastic the result of the safety factor was got 4.2 it is way too much, it can be decreased if infill precents would be lowered in slice software. By this way, the printing time will be reduced and the quantity of PETG plastic would be also lowered.
2. Each of the knee exoskeleton will have a microcontroller and a battery, it would be possible to make one controller for both knee exoskeletons. Although some kind of backpack should be needed to install microcontroller and batteries.
3. It would be possible to assign a structure to the knee exoskeleton to protect and give additional strength to human body ankle. Attaching a sole to the exoskeleton frame, which would be on the hinge and held in place by elastic bandages. In this case, it would be possible to avoid ankle injuries.
4. To perform experimental research on knee exoskeleton movement in the human body in the KTU bio mechatronics laboratory. In this case, it would be possible to understand by how much the knee exoskeleton supports the human lower limb for physical work.
5. To attach a force sensor on the gas spring attachment place in order to have a dependence on gas spring wear and squats quantity performed. In this case, it would be possible to find out an even more accurate value of the units of contraction and relaxation of the gas spring until wear, and to study the service life of gas springs of different manufacturers.
6. Created exoskeleton is for only the average of height of a Lithuanian human, which is 180 cm. If this exoskeleton is used by a shorter or taller person, it may cause discomfort when wearing it. For this reason, such a knee exoskeleton frame should be designed, which would have the ability to lengthen or shorten the thigh and calf supports.
7. Knee exoskeleton does not allow the knee to rotate, it would be possible to make constraints of spherical bearings between thigh and calf support in order to make the wearer feel more comfort.

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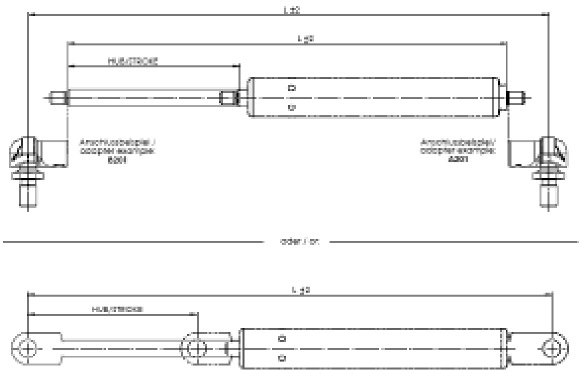
Appendices

Appendix 1. Suspa 16-1-131-104 gas springs parameters



Part number

16-1-131-104-A246-B246-100N

Description

Gas-Spring liftline16-1

Product Attribute	Value
Size	16-1
Stroke (mm)	100
Force (N)	100
Rod diameter (mm)	6
Tube diameter (mm)	15
Extended length L (mm)	235
Extended length L + end fittings (mm)	273
End fitting at rod	B246
End fitting at tube	A246

Address: SUSPA GmbH
Industriestrasse 12-14
D-90518 Altdorf
Germany

Phone: +49 (9187) 9 30-355
Fax: +49 (9187) 9 30-311
Web: www.suspa.com
Email: infoindustry@de.suspa.com

Appendix 2. RND 210-00744 micro switch parameters

Micro Switch

RND components

Features

- Snap-action switch
- Micro switch with solder/PCB terminals
- Simple construction and high reliability for long time
- Robust design

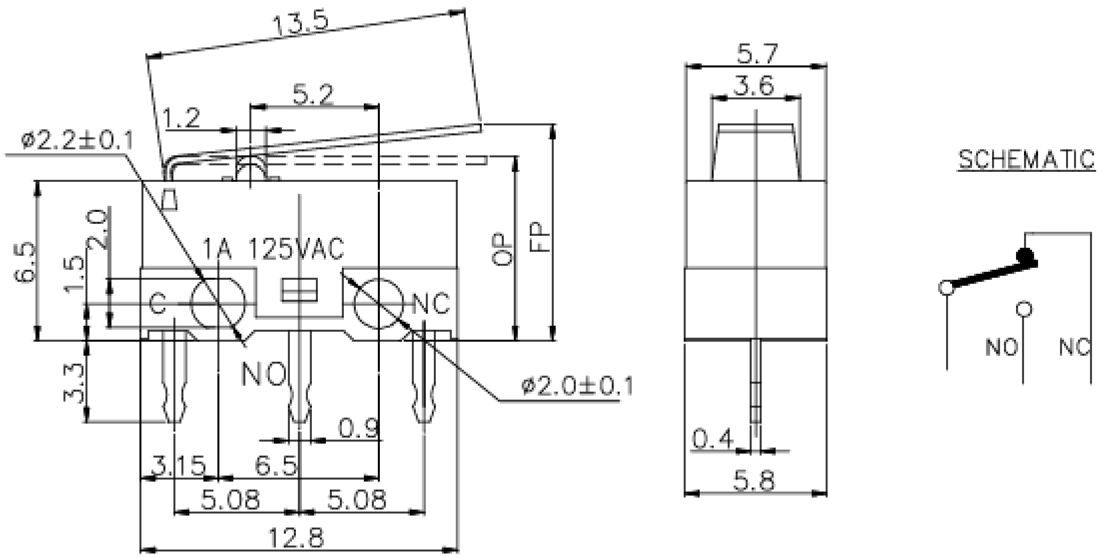
Functional Specification

Rated Voltage	125 VAC / 5 VDC
Rated Current	AC 1 A / DC 30 mA
Contact Resistance	100 mOhm
Operating Force	20 ... 50 gf
Free Position	10.4 ± 0.8 mm
Operating Position	8.8 ± 0.8 mm
Actuator Type	Hinge Lever
Termination Type	PCB Terminals

Reliability Rating

Mechanical Life	500000 Cycles
Electrical Life	10000 Cycles
Insulation Resistance	100 MOhm @ 500 VDC
Dielectric Withstanding Voltage	500 VAC 1 min
Soldering Type	Hand Soldering
Operating Temperature	-25 ... 65 °C
Ambient Humidity	< 85%RH

Drawing



Appendix 3. Omron EE-SX674 parameters

Ratings and Specifications

Item	Type	Standard	L-shaped	T-shaped, slot center 7 mm	Close-mounting		T-shaped, slot center 10 mm	F-shaped	R-shaped
NPN models	Connector models	EE-SX670 EE-SX670A EE-SX470	EE-SX671 EE-SX671A EE-SX471	EE-SX672 EE-SX672A EE-SX472	EE-SX673 EE-SX673A EE-SX473	EE-SX674 EE-SX674A EE-SX474	EE-SX675	EE-SX676	EE-SX677
	Pre-wired models	EE-SX670-WR	EE-SX671-WR	EE-SX672-WR	EE-SX673-WR	EE-SX674-WR	EE-SX675-WR	EE-SX676-WR	EE-SX677-WR
PNP models	Connector models	EE-SX670P EE-SX670R	EE-SX671P EE-SX671R	EE-SX672P EE-SX672R	EE-SX673P EE-SX673R	EE-SX674P EE-SX674R	EE-SX675P	EE-SX676P	EE-SX677P
	Pre-wired models	EE-SX670P-WR	EE-SX671P-WR	EE-SX672P-WR	EE-SX673P-WR	EE-SX674P-WR	EE-SX675P-WR	EE-SX676P-WR	EE-SX677P-WR
Sensing distance		5 mm (slot width)							
Sensing object		Opaque: 2 × 0.8 mm min.							
Differential distance		0.025 mm							
Light source		Infrared LED with a peak wavelength of 940 nm							
Indicator *1		Light indicator (red) (turns ON when light is interrupted for models with A or R suffix)							
Supply voltage		5 to 24 VDC ±10%, ripple (p-p): 10% max.							
Current consumption		12 mA max. (Connector models, L terminal open), 35 mA max. (NPN pre-wired models), 30 mA max. (PNP pre-wired models)							
Control output		NPN open collector: 5 to 24 VDC, 100 mA max. 100 mA load current with a residual voltage of 0.8 V max. 40 mA load current with a residual voltage of 0.4 V max. OFF current (leakage current): 0.5 mA max. PNP open collector: 5 to 24 VDC, 50 mA max. 50 mA load current with a residual voltage of 1.3 V max. OFF current (leakage current): 0.5 mA max.							
Protection circuits		Load short circuit protection (Connector models), No circuit protection (Pre-wired models)							
Response frequency *2		1 kHz min. (3 kHz average)							
Ambient illumination		1,000 lx max. with fluorescent light on the surface of the receiver.							
Ambient temperature range		Operating: –25 to +55°C, Storage: –30 to +80°C (with no icing or condensation)							
Ambient humidity range		Operating: 5% to 85%, Storage: 5% to 95% (with no icing or condensation)							
Vibration resistance		Destruction: 20 to 2,000 Hz (peak acceleration: 100 m/s^2) 1.5-mm double amplitude for 2 h (4-min periods) each in X, Y, and Z directions							
Shock resistance		Destruction: 500 m/s^2 for 3 times each in X, Y, and Z directions							
Degree of protection		IEC60529 IP50							
Connecting method		Connector Models (direct soldering possible), Pre-wired Models (Standard cable length: 1 m), Models with Connectors (Standard cable length: 0.1 m)							
Weight	Connector models	Approx. 3.1 g	Approx. 3 g	Approx. 2.4 g	Approx. 2.3 g	Approx. 3 g	Approx. 2.7 g	Approx. 2.2 g	Approx. 2.2 g
	Pre-wired models	Approx. 18.9 g	Approx. 17.3 g	Approx. 17.8 g	Approx. 16.8 g	Approx. 17.1 g	Approx. 18.3 g	Approx. 16.9 g	Approx. 16.9 g
Material	Case	Polybutylene phthalate (PBT)							
	Cover	Polycarbonate							
	Emitter/receiver								

Appendix 4. Arduino UNO WiFi REV2 parameters

Microcontroller	ATmega4809 (datasheet)
Operating Voltage	5V
Input Voltage (recommended)	6 - 20V
Digital I/O Pins	14 — 5 Provide PWM Output
PWM Digital I/O Pins	5
Analog Input Pins	6
DC Current per I/O Pin	20 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	48 KB (ATmega4809)
SRAM	6,144 Bytes (ATmega4809)
EEPROM	256 Bytes (ATmega4809)
Clock Speed	16 MHz
Radio module	u-blox NINA-W102 (datasheet)
Secure Element	ATECC608A (datasheet)
Inertial Measurement Unit	LSM6DS3TR (datasheet)
LED_BUILTIN	25
Length	68.6 mm
Width	53.4 mm
Weight	25 g

Appendix 5. Knee exoskeleton for physical work part documentation

Format	Sheet	Position	Document type	Designation	Name	Quantity
			Documentation			
A4	1/1		Assembly drawing	EXO-00.01.000	Knee exoskeleton for physical work	1
			Compounds			
		1			Thigh support	1
		2			Thigh band	1
		3			Calf support	1
		4			Slider	1
			Electronical devices			
		5			"RND Components" 210-00744 micro switch	1
		6			"Omron" EE-SX674 micro photo sensor	1
		7			Arduino Wi-Fi Rev.2 micro controller	1
		8			"Day Wolf" Li-ion 4400 mAh rechargeable battery pack	1
			Standart products			
		9			"Suspa" 16-1-131-104 gas spring	2
		10			ISO 2341 - B - 8 x 16 Clevis pins with head	2
		11			AS 1970 - 8 Conical spring washers (metric series)	2
		12			AS 1236 - 2 x 16 Split cotter pins (metric series)	2
		13			ISO 4762 - M6 x 16 Hexagon socket head cap screw	4
		14			ISO 4035 - M6 Hexagon thin nuts (chamfered) - Product grades A and B	4

	File name: Part List	Additional information	Material	Scale: 1:1
Resp. department: Dep. of Prod. and Manuf. Eng.	Technical reference: KTU	Document type: List of details		Document status: Educational
Legal owner: KTU	Created by: Martynas Zaleckis	Title, Supplementary title: Knee exoskeleton for physical work	EXO-00.00.000	
	Approved: Egidijus Dragašius		Rev.: A; Data: 2023-05-06; Lang.:	Sheet: 1/1

Appendix 6. Knee exoskeleton for physical work assembly drawing