



Kaunas University of Technology
Faculty of Mechanical Engineering and Design

Development of Wearable Upper Limb Exoskeleton

Master's Final Degree Project

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Kaunas, 2024



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Mechatronics (6211EX017)

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Development of Wearable Upper Limb Exoskeleton

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Task of the Master's Final Degree Project

Given to the student – Eligija Jonušaitė

1. Title of the Project

Development of Wearable Upper Limb Exoskeleton

(In English)

Dėvimo rankos egzoskeleto kūrimas

(In Lithuanian)

2. Aim and Tasks of the Project

Aim: to develop a wearable upper limb exoskeleton.

Tasks:

1. to design a frame of wearable upper limb exoskeleton;
2. to evaluate different materials for the upper limb exoskeleton frame;
3. to propose a control strategy for the exoskeleton;
4. to select components for the exoskeleton;
5. to define social, economic and environmental influence of the exoskeleton.

3. Main Requirements and Conditions

Use SolidWorks software for wearable upper limb exoskeleton's frame design. Exoskeleton must be lightweight, ergonomic, not cause injuries to the user, take into account natural upper limb movements and be easy to control. Exoskeleton has to suit people aged 50 to 80 years old.

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

Not applicable.

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Keywords: active exoskeleton; upper limb rehabilitation; assistive technology; 3D printing; harmonic drive.

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Summary

Upper limb immobility originated from strokes, injuries cause various problems in human life. People become unable to perform simple everyday tasks, and this as a consequence affects their mental health, as well it can also lead to financial problems – being unable to work and needing to hire a caregiver. To heal the patients as fast as possible effective physiotherapy is essential. For this purpose, robotic devices have emerged in the rehabilitation field. Such assistive rehabilitation devices not only help patients to achieve the best therapy results but also aid the medical staff since part of therapy can be performed by the device, also there is a possibility of remote control. In this study, 3 DOF upper limb exoskeleton is designed to assist the patient in elbow flexion/extension, shoulder flexion/extension and shoulder abduction/adduction movements. It is important to have a medical device that supports the most important upper limb movements and has a comparable range of motion as a healthy limb. Another important aspect is the mass of the exoskeleton system, to have a light frame that is durable and can withstand the required loads five materials are investigated of which three are plastics and two are composites. Manufacturing process of the exoskeleton is 3D printing, specifically FDM process, due to the economical and environmental benefits. After the analysis recycled composite material made from nylon and carbon fiber was selected, which demonstrated the best mechanical properties. For the actuation system brushless DC motor with harmonic drive is chosen. Such a combination provides high torque but a compact and lightweight design. Compact design allows to transport device easily and use not only in medical institutions. For the exoskeleton to operate safely encoders, hall sensors and emergency button is installed. Exoskeleton control is based on the user's input of desired speed, which is kept constant through the full range of motion.

Eligija Jonušaitė. Dėvimo rankos egzoskeleto kūrimas. Magistro baigiamasis projektas, vadovas prof. dr. Egidijus Dragašius; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.

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

Reikšminiai žodžiai: aktyvus egzoskeletas; viršutinių galūnių rehabilitacija; pagalbinės technologijos; 3D spausdinimas; harmoninė pavara.

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Santrauka

Rankų nejudrumas sąlygotas infarktų ar traumų, sukelia problemų įvairiuose gyvenimo aspektuose. Žmonės tampa nepajėgūs atlikti nesudėtingus kasdieninius darbus, dėl to nukenčia jų psichinė sveikata, taip pat gali kilti ir finansinių problemų – nedarbingumas, kuris veda prie sumažėjusių pajamų, poreikis įdarbinti slaugytoją. Norint kuo greičiau išgydyti ligonius, būtinos veiksmingos fizioterapijos sesijos. Tam tikslui reabilitacijos srityje pradėti naudoti robotiniai prietaisai. Tokie pagalbiniai reabilitacijos prietaisai ne tik padeda pacientams pasiekti geriausių terapijos rezultatų, bet ir padeda medicinos personalui, nes dalis terapijos gali būti atliekama aparatu, taip pat yra nuotolinio valdymo galimybė. Šiame tyrime 3-iejų laisvės laipsnių rankos egzoskeletas yra skirtas padėti pacientui atlikti alkūnės lenkimo / tiesimo, peties lenkimo / tiesimo ir peties abdukcija/adukcija. Svarbu, kad medicininis prietaisas palaikytų svarbiausius viršutinės galūnės judesius ir turėtų panašų judesių diapazoną kaip sveikos galūnės. Kitas svarbus aspektas – egzoskeleto sistemos masė, siekiant lengvo rėmo, kuris būtų patvarus ir atlaikytų reikiamas apkrovas, tiriamos penkios medžiagos, iš kurių trys yra plastikai ir dvi – kompozitai. Dėl ekonominių ir aplinkosauginių priežasčių egzoskeleto rėmo gamybai pasirinkta FDM 3D spausdinimo technologija. Atlikus analizę, buvo pasirinkta perdirbta kompozitinė medžiaga iš nailono ir anglies pluošto, kuri pasižymėjo geriausiomis mechaninėmis savybėmis. Judesiui atlikti pasirinktas bešepetelinis variklis kartu su harmonine pavara. Toks derinys užtikrina didelį sukimo momentą, kompaktišką dizainą, bei lengvą konstrukciją. Tokia kompaktiška konstrukcija leidžia prietaisą lengvai transportuoti ir naudoti ne tik gydymo įstaigose. Kad egzoskeletas veiktų saugiai, ikomponuojami skaitmeniniai kodavimo įrenginiai, Holo efekto jutikliai ir avarinis mygtukas. Egzoskeleto valdymas pagrįstas vartotojo įvestu norimu greičiu, kuris išlieka pastovus per visą judesių diapazoną.

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List of Abbreviations and Terms

Abbreviations:

DOF – Degrees of Freedom

ROM – Range of Motion

PLA – Polylactic Acid

ABS – Acrylonitrile Butadiene Styrene

PETG – Polyethylene Terephthalate Glycol

PET – Polyethylene Terephthalate

CF – Carbon Fibers

PA – Polyamide

FDM – Fused Deposition Modeling

BLDC – Brushless DC Electric Motor

FOS – Factor of Safety

Introduction

Based on the data from The World Bank the global median age is continuously rising [1]. As a result, there is a notable increase in patients facing immobility due to strokes and other health conditions. Additionally, factors like injuries and surgeries contribute to upper limb immobility, causing issues such as reduced muscle tone, coordination loss and partial movement abilities [2]. Consequently, people who have had a stroke or other injuries that lead to upper limb impairment lose their independence in daily activities because they are unable to perform even simple tasks with their affected limb. Physiotherapy is one of the primary treatments for such health issues. The goal of rehabilitation is to integrate patients back into active social life. Rehabilitation is based on repetitive movements, which demonstrated efficacy in enhancing muscle strength and movement coordination. However, ensuring optimal and consistent treatment during conventional physiotherapy can pose challenges for healthcare staff with a high volume of patients as well it requires frequent hospital visits. Therapy duration may vary based on the severity of the injury which results in significant costs if therapy is conducted individually with physiotherapists. In recent years, rehabilitation based on robotic devices has emerged due to the ability to offer enhanced intensity and repeatability for rehabilitative treatments [3]. Among these technologies, exoskeletons hold particular promise for enhancing upper-limb functionalities essential for daily activities. By blending principles from mechanical, electrical, and computer engineering, robotic devices can precisely control movements and provide measured assistance levels tailored to individual patient needs. Importantly, these devices enable patients to continue therapy at home over extended periods, which is critical for long-term healing and recovery [4]. Researches indicate that physical therapy with robotic devices can outperform conventional therapy in terms of flexibility and accessibility leading to faster and complete recovery outcomes. Even though this field evolves rapidly it requires deep research to address technical challenges such as kinematic compatibility and effective human-robot interaction. Furthermore, it is necessary to address cost, efficiency, bulkiness and safety challenges to guarantee wider availability of such devices in the market. Regarding these challenges manufacturing processes and materials must be analysed. The advancements in 3D printing technology and the growing range of materials that are accessible for this technology optimize medical devices. Utilizing 3D printing for medical products ensures superior quality, lightweight structures, and the ability to customize devices, all while reducing overall costs by minimizing material wastage thus letting 3D printing technology be competitive with other manufacturing processes. The proposed upper limb assistance device is designed for myopathy or hemiplegic patients who are capable of controlling the fingers but struggle to lift arms independently. Designed to mimic the kinematics and dynamics of the musculoskeletal system, this exoskeleton holds the potential to significantly improve the quality of life for individuals who have upper limb impairments empowering them to regain autonomy in their daily activities.

Aim: to develop a wearable upper limb exoskeleton.

Tasks:

1. to design a frame of wearable upper limb exoskeleton;
2. to evaluate different materials for the upper limb exoskeleton frame;
3. to propose control strategies for the exoskeleton;
4. to select components for the exoskeleton;
5. to define social, economic and environmental influence of the exoskeleton.

Hypothesis: The wearable upper limb exoskeleton can lift the human arm, offering assistance and delivering rehabilitation benefits.

1. Analysis of Upper Extremity Exoskeletons

Exoskeletons are used for a variety of purposes with their primary application found in medical or industrial fields, more extensively being investigated for applications in rehabilitation as well for assistance in daily life activities. Not only do they enhance the quality of life by giving disabled patients mobility but aid patients who are recovering from various injuries and managing muscle weaknesses [3]. Particularly, wearable exoskeletons are vital to regaining independence and accelerating the healing process by supporting physical therapy. Beyond the medical field, wearable exoskeletons are valuable assistive tools for labor-intensive tasks. Exoskeleton reduces loads borne by the user which in return decreases muscle fatigue and lowers the risk of musculoskeletal injuries which are a prevailing problem in the industry [5].

1.1. Exoskeletons for Upper Extremity Rehabilitation

Exoskeletons are extensively studied in the rehabilitation field and used for musculoskeletal disorders treatment. Musculoskeletal disorders affect joints, bones, muscles, tendons [6]. Such conditions can be congenital or arise as a response to traumas or disease. As an example, global population ageing reflects the increase in median age, leading to a rise in the number of patients that suffer from various degrees of immobility after stroke or neuron-related illnesses such as Parkinson's [1]. Based on the World Health Organization's estimation approximately 1.71 billion people worldwide have musculoskeletal problems [7]. Moreover, a lot of people experience different kinds of injuries that lead to diminished muscle tone, loss of coordination and limited range of motion after operation. After strokes or traumatic brain injuries, people experience muscle weakness or paralysis in the upper limb. It has an enormous impact on limb functionality impeding daily activities and quality of life. However, assistive exoskeletons not only provide exercises for limb rehabilitation but also offer support to individuals with physical impairments in their daily activities (ADL) such as eating, drinking, etc.

Shoulder is one of the most intricate human joints which has an extensive range of motion [8]. Shoulder joint is crucial for a person to correctly position and orient the arm, thus impacting everyday life activities and life quality [9]. Spinal cord injuries, strokes or other injuries can cause harm to the shoulder and decrease shoulder's range of motion [9]. Stroke is a prevailing threat to humans and according to the data more younger people experience it resulting in the loss of some motor functions [10]. As a consequence of hemiplegia shoulder subluxation and malfunction occur causing harm not only to the physical body but also to psychology [8]. Therefore, motor impairments must be treated through physical therapy which helps to restore muscular strength, prevent atrophy and improve mobility to varied degrees. Exoskeletons indicate great success rates in improving manual dexterity. Physical therapy using robotic devices is proven by researchers to be equally effective as conventional physical therapy and in some cases, it can surpass traditional therapy [11]. Conventional therapy has several drawbacks such as being inflexible and posing accessibility issues. This in return can result in slow and incomplete recovery. For instance, rehabilitation procedures usually require frequent attendance, it is recommended to do exercise sessions lasting between 20 and 30 minutes per day and complete three therapy sessions per week [12]. Such frequent visits can be an issue for some people, also, taking into account that treatment should be long-term. Depending on the degree of injury severity, therapy can be extended to several months resulting in considerable expenses if sessions are conducted individually with the professionals [9]. Similarly, people who have undergone elbow injuries or surgeries, such as tendon repairs or joint reconstructions, often require targeted

rehabilitation to regain strength and mobility in the elbow joint and biceps. Additionally, both users and trainers may find traditional rehabilitative training methods monotonous. To address this problem, the integration of virtual reality (VR) and augmented reality (AR) has witnessed a significant increase in demonstrating enhanced effectiveness [3]. Exoskeletons, specifically wearable, offer a solution by allowing patients to continue therapy at home by exercising. With this method there are more chances for patients to stick with a program for a long period of time, also, it is a convenient solution, since the rehabilitation process is accessible anytime. Long-term treatment is crucial for rehabilitation success, as well it helps alleviate the burden on healthcare staff who are facing shortages in the face of an increasing number of patients requiring rehabilitation. As a consequence, a greater number of patients can be supervised during the rehabilitation process since the staff is not required to instruct users all the time. One of the biggest challenges arose during the Covid-19 pandemic when patients could not get appropriate treatment. During this period assistive robotic devices played a crucial role in patient's health progress.

Over the last decade, a notable quantity of research on exoskeletons focused on therapeutic, assistive or occupational purposes started to surge [3]. Certainly, over these years a diverse quantity of advanced designs and control methods were introduced, which helped to make rehabilitation more efficient. A. Frisoli et.al in research [13] examined the effectiveness of a therapy program utilizing an exoskeleton in comparison to a conventional therapy, where no robotic assistive devices were used. Two groups were formed in order to properly evaluate results. In the first group, a multi-joint upper extremity assistive exoskeleton was employed. It is worth mentioning, that both session groups underwent sessions with the same duration and intensity. The results revealed a significant functional improvement in both groups. Nevertheless, the first group demonstrated notably greater recovery and took less time to complete required tasks. These research findings suggest the potential of robotic therapy. Results are shown in Fig.1. In the figure yellow markers shaped like diamonds depict the average results of different criteria/tasks with a 95% confidence interval. Data points positioned to the left from the 0 value favours conventional therapy and points positioned to the right signify more significant enhancements regarding robotic therapy. Consequently, the first group, which used exoskeletons showed better progress.

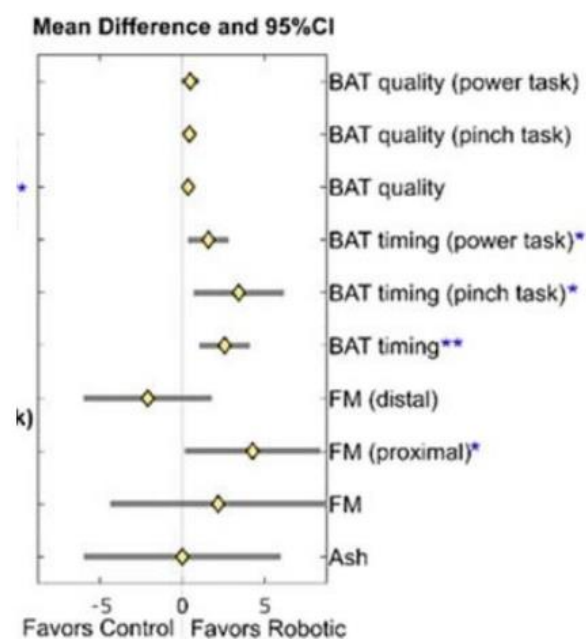


Fig. 1. Forest plot of clinical results [13]

1.2. Exoskeletons for Labor Intensive Tasks

Exoskeletons have been the subject of research mainly in the rehabilitation field for an extended period, however, only recently has it gained more attention in adaptation for occupational tasks [14]. Businesses that employ people in labour-intensive tasks are increasingly more interested in investing in exoskeletons due to their effectiveness in enhancing human physical capabilities and their positive impact on employees by reducing physical demands for the body [15]. A rising concern involves musculoskeletal disorders which are correlated with labour work. An alarming statistic indicates that approximately 60% of health problems related to work in the European Union are associated with musculoskeletal ailments [16]. Over time these diseases make it difficult for people to engage in physical activities and have an impact on daily tasks by limiting full mobility. Moreover, these conditions result in long-term issues such as decreased overall well-being, psychological problems and early retirement. Exoskeletons in the workplace provide the needed support to the human body and as a consequence prevent muscle overuse. Such condition can result in permanent damage to muscles and disrupt movements by making it hard for a person to control joint positions. Workers who have to lift heavy loads suffer from elbow epicondylitis and bicep tendinitis and many more conditions [17]. A bundle of research is conducted to show the benefits of exoskeletons in the workplace since they demonstrated great benefits by reducing the stress and strain on specific body regions [16]. Among the common musculoskeletal disorders in the manual work field elbow injuries are prevalent. This happens because the elbow joint takes a crucial role in numerous work-related activities such as load lifting and placing. This makes the elbow joint prone to injuries and can lead to elbow tendinopathy. This disorder prevails and stems from tasks that require prolonged bending and heavy lifting. Additionally, during tasks involving grasping and lifting loads eccentric contractions of the biceps occur and can result in tendon rupture [18]. To address such issues exoskeletons are produced, they distribute loads correctly and stabilize joints. In the D. Park et. al [18] research the effectiveness of the elbow joint exoskeleton “Elbow-sideWINDER“ was demonstrated while performing flexion and extension movements. In Fig.2 the exoskeleton is shown on the person’s body while doing the physical task of lifting and placing the box.



Fig. 2. Elbow-sideWINDER exoskeleton [18]

The influence of the exoskeleton was determined by measuring biceps brachii and triceps brachii activation ranges while lifting 2 kg and 7 kg weights and results were compared to the activation levels of muscles lifting weights without assistive robotic device. Findings demonstrated a positive impact of elbow-side WINDER reducing the activity of the biceps brachii responsible for elbow flexion, the activation decreased by approximately 39% lifting 2 kg and by 26% lifting 7 kg. Furthermore, the average activation reduction in triceps brachii was 37% at 2 kg and 35% at 7 kg. Results highlight the exoskeleton's effectiveness in safeguarding the muscles of workers. However, wearable exoskeletons not only help to protect health but also offer other benefits, such as enhanced speed of work execution. In addition, exoskeletons can broaden accessibility to work for a diverse range of people. As a consequence, people with physical limitations would be more integrated into the society.

1.3. Classification of Robotic Devices

Robotic devices can be divided into three categories which are depicted in Fig.3 [19]. Grounded exoskeletons are affixed to a stationary object, such as a wall, platform or for example, it can be firmly attached to the wheelchair. Positioned at the end of a robotic arm, grounded end-effectors serve as fixtures that patients can grasp and interact with during exercises. Comparing a grounded end-effector with a grounded exoskeleton the former provides patients with a greater range of movement which as a consequence fosters neural plasticity linked to motor learning and restoration of movements as well as dexterity [20]. Another group of robotic devices is wearable exoskeletons. Wearable exoskeletons are on the rise both in the industrial field and medical area [19].

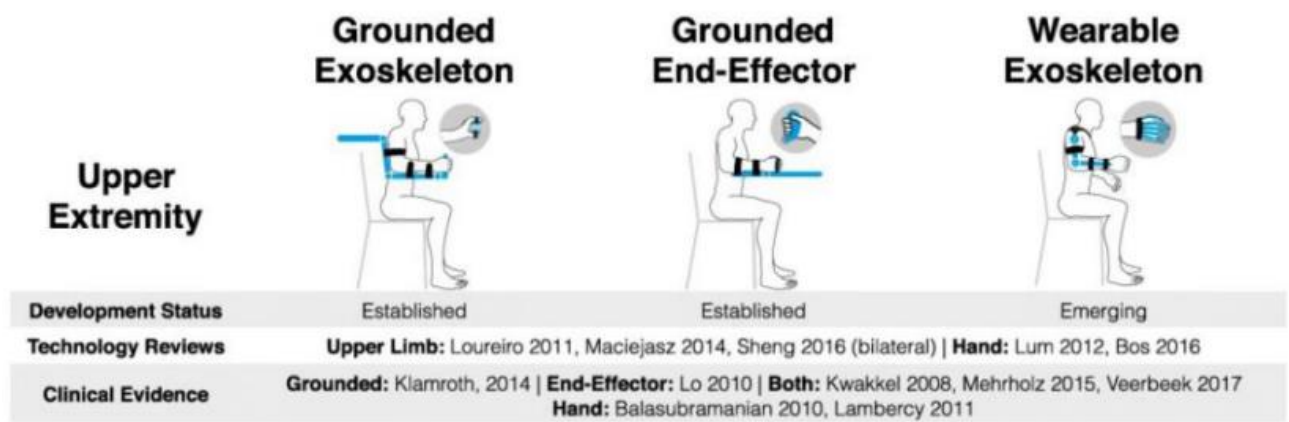


Fig. 3. Categories of Robotic Devices for Upper Limbs [19]

While the benefits of the exoskeletons are evident, devices are not widely adopted due to certain challenges such as design constraints, usually wearable exoskeletons are bulky and heavy. The creation of a functional exoskeleton depends heavily on ergonomics in terms of mechanical design. Limitations of energy efficiency and price are noteworthy factors. The cost issue is a prevailing factor in terms of accessibility for patients who require rehabilitation. According to the data, only 5% to 15% of stroke patients who need robotic devices can access it [11]. Regarding this issue, efforts to propose more cost-effective designs have been made. Researchers and engineers are investigating affordable materials and manufacturing processes. M.Muhatisim et.al in the study [21] presented an affordable powered arm exoskeleton tailored specifically for people with paralysis. Motors and linear actuators are employed to actuate the joints of the arm. Regarding control electromyographic (EMG) signals from the biceps muscle are collected. Such control method is a convenient approach for the

user. This exoskeleton stands out for its affordability in comparison to other assistive devices in the market with a production cost of less than 70 \$. The exoskeleton frame was made from aluminium, however, potential enhancements can be implemented involving alternative materials in order to reduce weight and improve weight distributions. Such researchers are addressing the crucial issue of limited accessibility of exoskeletons due to high prices.

Furthermore, exoskeletons are categorized by the setup into active and passive. The latter one redirects potential energy created by the person's actions to support user's movements. The primary aim of passive upper limb exoskeletons is to alleviate arm weight and any additional weight when the arm is elevated. In this case device reduces muscular strain [22]. Specifically, actuation in passive exoskeletons is accomplished using mechanisms such as springs, elastic bands and dampers. Such exoskeletons are commonly used for labour work. In contrast, active exoskeletons incorporate elements like motors, sensors and have advanced control systems. This helps to significantly increase the capacity of the limb to support weight. Comparing these types of exoskeletons, it is seen that active exoskeletons are typically more expensive due to their complex design, also they must rely on a constant power supply which makes them heavier. To address these challenges researches, incorporate a blend of active and passive power transmissions. The incorporation of passive mechanisms helps to reduce size and weight [22].

1.4. Control Strategies of Exoskeletons

Robotic-assisted devices employ three main control strategies which include assistance, resistance and correction. Assistance mode provides limb support, the device bears its weight and supplies the force to accomplish required tasks. Degree of the assistance can vary and tasks can be completed even with minimal effort from the patient [23]. In the realm of assistive control three distinct operational modes can be identified which are passive, triggered passive and partially assistive [10]. For the best motor function recovery these modes are usually combined during the rehabilitation process. Also, these modes can be changed depending on the patient's illness phase – movement capabilities. For example, after a stroke patients commonly experience a full loss of foundational motor skills. As a consequence, the device needs to have passive assistance mode. Exoskeleton must support limb weight and provide assistance to accomplish tasks without the need for the patient to generate force [10]. Triggered passive mode is beneficial for people who suffer from tetraplegia and have limited prospects for recovery. In this mode, an additional device is recommended such as a Brain-Computer Interface (BCI). BCI is capable of translating the user's cognitive signals into actions executed by the exoskeleton, thereby enabling a fluid and intuitive interaction between the individual and the assistive technology. This provides a positive influence on neuroplasticity [10]. Partially assistive mode is employed when a patient has regained some degree of motor functions. Both the exoskeleton and the patient contribute to facilitating limb movement. On the contrary, correction mode does not provide assistance, the device intervenes only when a patient makes an incorrect move. In such instances, the device forces the patient to be on the correct movement track, it constantly modifies limb trajectory until limb movement matches the expected path. Rehabilitation commonly uses a blend of these strategies and mostly integrates both assistive and corrective control. Resistive mode device opposes the patient in carrying out the motor task. Individuals during this mode gradually restore the capacity for voluntary movement and adapt motions to external disturbances which teaches them to accomplish precise motions and brings patients closer to a functional level comparable to a healthy individual. Usually, this mode encompasses two methods – damper and spring type. The spring

variant impedes movement by restoring the limb to its initial position using a spring, while the damper generates an opposing force to resist motion [10]. Also, resistive control is used in particular scenarios, for example for tremor suppression [23]. Fig.4 depicts each mode and explains its features and usage purpose.

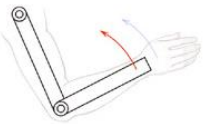
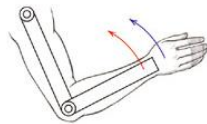
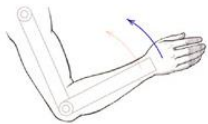
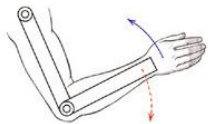
High-level modalities	Passive	Active-assistive	Active	Resistive
Features	The robot performs the task without accounting for subject's effort. The robot corrects trajectory errors	The robot and the subject perform the task cooperatively. The robot can provide weight counterbalance or trajectory-based corrective assistance	The subject actively performs the task. The robot does not provide assistance nor resistance to the subject. No time-dependent trajectory is present	The subject actively performs the task. The robot resists to the movement by providing opposing forces
Human-robot interaction				
Rationale	Prevents soft tissue stiffening. Passive mobilization generates somatosensory stimulation	Preserves subject motivation and self-esteem. Subject's involvement promotes motor learning	The robot is a measurement device. Permits ROM exploration and do not limit subject's voluntary free movements	Promotes subject's involvement and potentiate muscular strength

Fig. 4. Upper limb control modalities [24]

Controlling the movements of the exoskeleton presents noteworthy challenges. The device must exhibit swift and accurate responses to user movements/intentions while maintaining a stable support system. Exoskeletons are integrated with sensors and control algorithms that form a closed-loop control system. Such system can adapt to the user's motions. Nowadays, to improve control mechanisms with precision and agility machine learning algorithms are used in order to predict movements and proactively adjust the device's behaviour in anticipation of these motions. When it comes to control of exoskeleton movements joysticks, buttons, switches can be employed. More advanced and modern approaches to moving limbs with an exoskeleton include smartphone apps [25]. However, these methods may not always be practical, particularly when the exoskeleton is required to assist in routine activities like lifting. For more intuitive control motions can be triggered by voice commands. Yunfei Guo et.al [26][17] proposed a rehabilitation exoskeleton glove that is activated by voice. This exoskeleton uses the user's voice as a biometric authentication and utilizes it as an input. The device then identifies the command and conducts it in real time [26] [17]. This system comprises a smartphone, a microcontroller and a microphone which is placed on the wearer's shirt. The information from the microphone flows to the smartphone via the wire. Bluetooth facilitates communication between the smartphone and the microcontroller. After processing the signals microcontroller sends a signal to the exoskeleton. Although, this method is a hands-free method the effectiveness of this strategy depends on noise-free environments, thereby limiting its applicability. In addition, Thøgersen M.B et.al [27] study presented advanced and not conventional way to control the exoskeleton. The device uses an intraoral tongue control interface to move the exoskeleton, it works by analysing the movements of the tongue. As well, the brain-computer interface (BCI) can also be used for more natural and intuitive device control [28]. BCI system detects the activity of the central nervous system and converts it into artificial output which works as a direct pathway between the patient's brain to the exoskeleton. An interface can be based on electroencephalogram (EEG) which enables to command the robot by engaging in motor imagery. This method enhances the patient's neuroplasticity. However, additional tools are required such as EEG caps with conductive gels which are inconvenient and also can be costly [29]. Another way to obtain signals from the body

is to use electromyography. This technique signals from the muscles' generated electrical potentials. This allows to move exoskeleton with the limb movement intention even though the impaired limb does not move. In order to obtain myoelectric signals electrodes are strategically placed on the skin over the targeted muscle. However, EMG signals are erratic due to this nature preprocessing steps must be utilized, for example, preamplifiers and filters should be integrated. Since control of these signals is challenging hybrid brain-computer interface systems are explored to address the issue. A hybrid system of EMG and EEG combination signals was employed in the Li et.al [30] research. Data from both the brain and muscles had been obtained for the purpose of climbing the stairs. Such system facilitates instantaneous adaptation to the user's physiological condition.

1.5. Exoskeletons for Shoulder and Elbow Joints

Robotic systems can be designed as an exoskeleton where the device engages in joint-based exercises or it can be an end-effector type. During the rehabilitation process, usage of both approaches may be needed for a patient. Md Rasedul Islam et al. [31] introduced the seven degrees of freedom "u-Rob" exoskeleton for upper limb rehabilitation. This device functions as an exoskeleton and as an end-effector. Worth mentioning, that the exoskeleton includes an innovative upper arm cuff integrated with sensors that monitor the patient's contract forces. The device forms from three modules: shoulder, elbow and wrist. The shoulder module has three degrees of freedom, whereas the elbow and the wrist each encompass two degrees of freedom. The human shoulder has three primary motions known as glenohumeral articulations. Additionally, two motions are present in frontal and sagittal planes which are elevation/depression and protraction/retraction. These motions also contribute to other shoulder movements. In order to let the wearer perform additional movements in the frontal and sagittal planes device employs a hybrid design approach that integrates both parallel and serial mechanisms as illustrated in Fig.5. Upon integration, these mechanisms effectively facilitate the dynamic mobility of the shoulder joint instantaneous center of rotation, allowing for versatile motion in both the frontal and sagittal planes, respectively. This innovative design enhances the overall functionality of u-Rob, contributing to its adaptability and effectiveness in accommodating a wide range of shoulder movements.

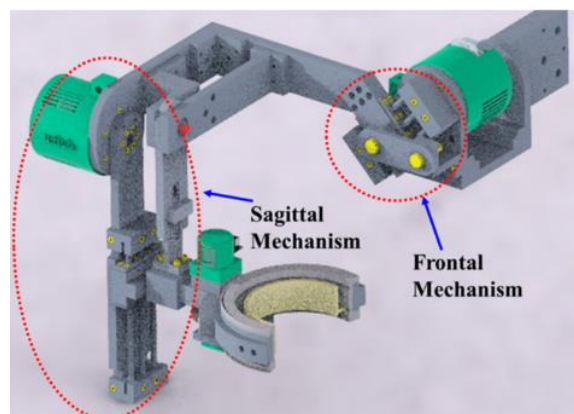


Fig. 5. Shoulder motion support [31]

In this study, a simple PID controller was utilized to validate the desired functionality of the constructed robot. The exercise trajectory was controlled by adjusting the joint torque which was calculated by the controller. Since the device has a dual setup two control systems were introduced

to accommodate each of them. Joint-based control was employed for the exoskeleton configuration, while Cartesian-based control was implemented for the end-effector setup.

The design of upper body exoskeletons faces a notable challenge in facilitating the complete range of motion for the shoulder complex without causing discomfort to the user. It is crucial to have sufficient degrees of freedom ensuring that the wearer does not experience constraints [32]. In the Chang Liu et.al [33] paper wearable upper limb exoskeleton for power assistance is presented and researchers concentrated on creating a lightweight device with a full degree of freedom. The presented exoskeleton's design incorporates passive and active assistance where active components provide power assistance for joints when performing arm extension and flexion movements. Active joints are propelled by the motors, actively enhancing the user's movements in a specific direction, such movements are intended to support weight lifting. Each joint – shoulder and elbow – have separate motors. In order to design an exoskeleton ergonomically, the device must move seamlessly with the body meaning that degrees of freedom are identical to joints' degrees of freedom. Therefore, passive joints synchronize with the wearer's motion ensuring comfort. The mechanical framework of the exoskeleton is shown in Fig.6. It is primarily composed of two arms that are identical and back support shafts. Each arm is composed of 2 active joints – shoulder and elbow and 4 passive joints.

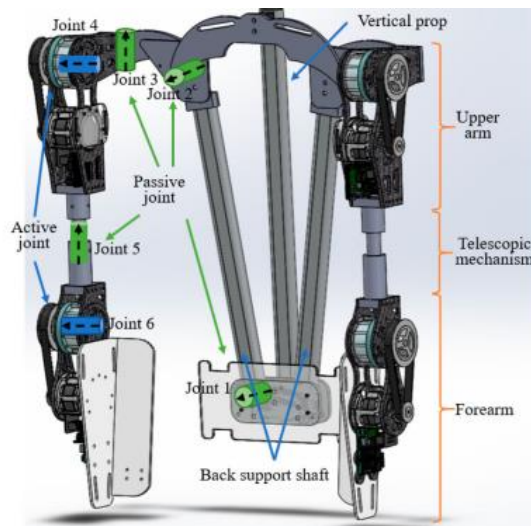


Fig. 6. Mechanical structure of the exoskeleton [33]

The hinge-type elbow joint, which has a single degree of freedom for flexion and extension, serves as the connection between the upper arm and the forearm. For elbow joint brushless DC motor is implemented. Regarding the compact design, the motor is chosen to be flat, as well harmonic gear to increase torque is connected to the motor. Furthermore, to get the required torque and rotational speed pulley-timing belt mechanism is employed. This drive mechanism attains a reduction rate of 300:1. Driving torque from the motor is first transmitted to the pulley-timing belt, then to the harmonic gear, and finally to the output section. To achieve optimal design, the selection of material importance must be emphasized. Materials are selected by their load conditions. To produce this exoskeleton aluminium alloy, polycarbonate and carbon fiber are chosen.

Since passive joints are important for comfortable movements Joint 5 has a telescope mechanism that enables rotation of the elbow. However, this joint is not unrestrained, regarding the different needs of the wearer, joint can be restrained with the screw of the rotation shaft. The objective is to guarantee stability and precision when the wearer is executing tasks that do not need internal/external rotation

of the elbow joint. Additionally, with the elbow's one degree of freedom, the shoulder joint possesses two extra degrees of freedom enabling rotational movements in both directions (internal and external). The exoskeleton's shoulder complex is crafted to provide the wearer with freedom in various directions. For example, Joint 4 which is active and responsible for flexion and extension mimics the structure of the active elbow joint. On the other hand, Joint 2 and Joint 3 serve as passive joints and are accountable for abduction and adduction. In order to adapt to the user's shoulder movements, specifically elevation and depression back support shafts are included. Regarding design adaptability, this factor is important for versatile and comfortable usage. Exoskeleton shoulder width can be customized letting accommodate various shoulder widths among different users [33].

M. Ahsan Gull et.al [34] present four degrees of freedom upper limb exoskeleton, which can be mounted on a wheelchair. This exoskeleton is created to help disabled people while doing daily activities. As well this exoskeleton can be used for patients that have completely paralyzed upper body. Elbow and shoulder joints have motors whose torque can be changed regarding needed assistance. The ability to maintain the full weight of a human's arm in the required position without energy consumption is executed by using a worm gear for the elbow joint due to its non-backdrivable mechanism. Since upper body biomechanics is complex exoskeleton's kinematics are simplified. According to researchers instead of 7DOF exoskeletons 4DOF could be an optimal system used to support people in daily life activities. In Fig.7, the exoskeleton for the right arm is shown.

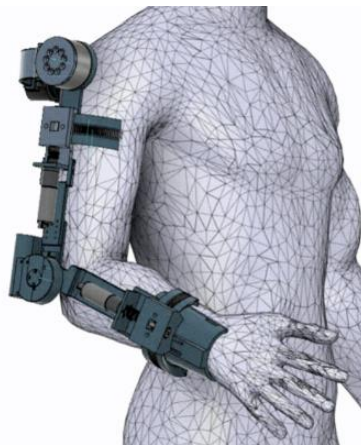


Fig. 7. A 4-DOF arm exoskeleton [34]

The exoskeleton supports two degrees of freedom excluding shoulder abduction and adduction, these movements can be passively adjusted. In order to provide the ability for a shoulder to have internal and external rotation C-ring mechanism is used. For shoulder extension and flexion, a brushless DC motor and harmonic drive for torque amplification are employed. Exoskeleton also includes the wrist part, which similarly to the shoulder complex uses a C-ring mechanism that supports rotation movements. Regarding the control system, it includes path planning of the exoskeleton route and computations are integrated into the robotic operating system (ROS). Whole exoskeleton's control system comprises four motors encoders and controllers. Exoskeleton has several control modes and some parameters can be changed.

Mikkel Berg Thøgersen et.al [27] presented an “Exotic” assistive exoskeleton that is designed for people who have tetraplegia. Individuals who have this illness cannot move their limbs properly. In such case exoskeleton is crucial which gives for person independence. The goal was to produce an exoskeleton that would be functional and be able to assist individuals who suffer from complete

tetraplegia. Usually, these types of devices are distinguished as bulky. In order to minimize bulkiness as well as weight researchers decided to reduce the device's degrees of freedom. The mechanical design of the exoskeleton is shown in Fig.8 where three motors can be seen which are used for the activation of elbow extension/flexion; upper arm rotational movement and wrist supination/pronation. For torque increasement planetary gears are incorporated. In order to move the shoulder joint more powerful motor must be used, also, a strain wave gear is employed. Direct actuation is used for shoulder and elbow joints, whereas rotational movements are exerted using two dovetail, half-circular ring designs. The actuator engages a gear that rotates a semi-circular set of teeth. For elbow and wrist movements non-backdrivable motors had been used, although shoulder flexion and extension are backdrivable under significant loads. This exoskeleton is designed to be mounted onto the wheelchair and has 5 DOFs. To ensure precise motor control and to monitor position encoders are used, for this exoskeleton incremental encoders are employed. Similarly, tiny magnetic absolute encoders integrated into the axes of the elbow and shoulder joints provided angular control at the joint level. Regarding wrist and shoulder rotation encoders could not be implemented due to the internal location of the joint axes within the wearer's arm. This exoskeleton is controlled via tongue movements with assistance from computer vision.

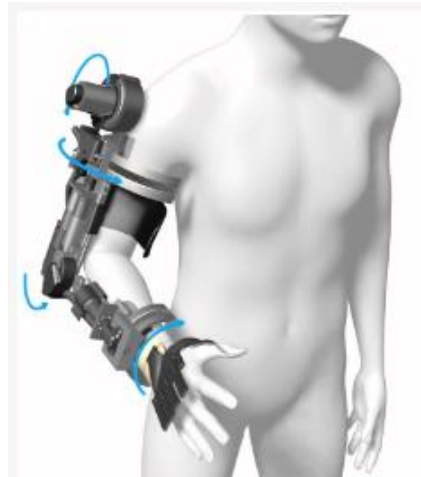


Fig. 8. “Exotic” exoskeleton [27]

Exoskeleton aimed to address multiple hurdles related to the wearable exoskeleton such as compactness, comprehensive upper limb support, ergonomically secure attachments, the ability for patients to use the device for a variety of ADLs and also efficient and intuitive control interface.

Numerous upper-body exoskeletons are available in the market and focus on supporting the glenohumeral (GH) joint, although they typically exclude the shoulder girdle from their design. Consequently, it allows to simplify device construction. However, without a connection to the upper arm, these exoskeletons have reduced sensitivity to kinematic disparities around the shoulder which limits their capacity to completely support the upper limb's mobility and coordination. Bongsu Kim and Ashsih D. in the research [35] introduced a cutting-edge rehabilitation exoskeleton for the upper extremities, showcasing an extensive range of motions while preserving natural coordination and controllability over force and resistance. “Harmony” exoskeleton has five degrees of freedom for the shoulder complex, alongside the elbow and wrist mechanisms, each featuring one degree of freedom. The exoskeleton is shown in Fig.9. To mimic shoulder joint movements, the device incorporates a series of elastic actuators utilizing a cable and pulley system. This lets to mimic natural human movements thereby mitigating the risk of injury. A pivotal part of the exoskeleton is sensor

implementation, in this case, force sensors are incorporated to monitor both the exoskeleton's and the user's forces. This integration includes six-axis force sensors placed throughout the exoskeleton, altering the level of support provided by the device. Through continuous analysis of sensor data exoskeleton can dynamically adjust its assistance level in real time, ensuring that the user receives optimal support. Due to the synergy of sensors and control algorithms device is notably sophisticated, offering multiple operation modes tailored to diverse patient needs. An adaptive control algorithm is employed to fine-tune the torque applied to the exoskeleton based on the user's movements. The exoskeleton can be configured to deliver either active or passive assistance. As well, researchers integrated a hierarchical control system to guarantee meticulous control over the exoskeleton's movement. Emphasizing safety in the system's design is crucial, incorporating numerous layers of control that can promptly end the motion of the exoskeleton when needed. It is worth highlighting that the design approach relies on the modular methodology. It facilitates straightforward customization and flexibility to address different requirements for individual patients. As a consequence, the exoskeleton can be applicable to a diverse range of patients with varying rehabilitation requirements. For example, some modules can be replaced or removed according to the patient's needs. Also, the design is made for different anthropomorphic parameters like the length of the arm. However, a potential drawback of the system is its complexity which can prolong the time of configuration and setup, also, expenses can increase in order to maintain the system. Moreover, the system's weight and dimensions are not appropriate for application outside clinical environments. Future research initiatives could delve into strategies to simplify the system's intricacy and diminish its weight as well as dimensions, all while maintaining its technical capabilities.

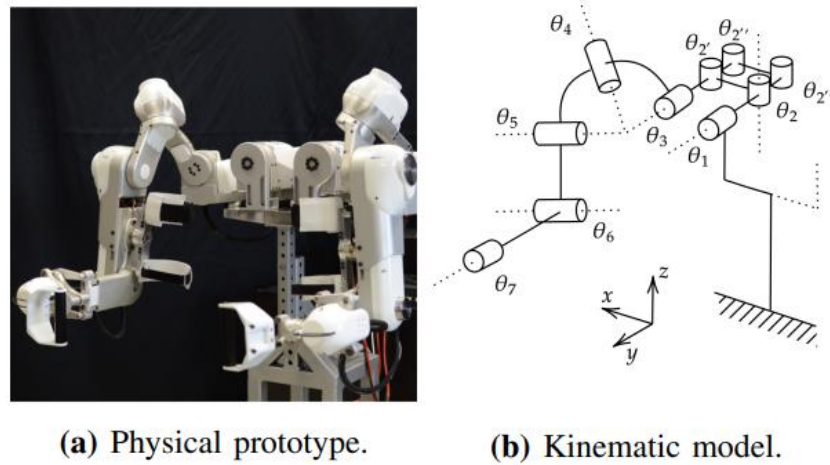


Fig. 9. “Harmony” exoskeleton’s mechanical structure and kinematic model [35]

1.6. Chapter Summary

Wearable exoskeletons are usually employed in rehabilitation promoting mobility and accelerating recovery for disabled or injured individuals. It also supports user's independence by aiding in daily activities. According to the researches, active exoskeletons are preferable to use in medicine and industry applications due to precise control and ability to hold and lift required loads. Upper limb exoskeletons usually employ electric motors to produce the motion and gearboxes to increase the torque. However, each active joint makes the exoskeleton bulkier and heavier, which binds the exoskeleton to clinical settings, thus passive joint incorporation can be used as a solution. Shoulder and elbow joints are crucial for mobility and daily task execution. Consequently, researchers tend to prioritize designs incorporating both joint structures. However, the shoulder joint is a complex

structure and this poses a challenge for researchers to create a device that can mimic shoulder movements without causing discomfort to the user. Moreover, the control method is an important factor for recovery. Control strategies for exoskeletons include assistance, resistance, and correction modes, which are tailored to the patient's needs and phase of recovery. Also, torque control is an important feature in the exoskeleton which directly influences the assistance provided to the user. Overall, exoskeleton technology continues to evolve, offering promising solutions for assistance in different fields.

2. Development Methodology of Upper Limb Exoskeleton

Development of the advanced exoskeleton requires a comprehensive analysis of mechanical structure, electrical components and control system. This examination includes nuanced considerations of sophisticated control methods, actuation mechanisms and components that directly contribute to the device's mass and efficiency. Also, the integration of sensors for data acquisition is a crucial part of obtaining essential data for control. Ensuring the development of a secure, efficient, ergonomic and user-friendly device all these aspects must be analysed carefully. Implementation of a well-designed exoskeleton in rehabilitation for patients with impaired joints can contribute to the partial restoration of muscle function and aid in the recovery of essential motor functions [8].

2.1. Anatomy and Biomechanics of Upper Limb

Upper extremities play a pivotal role in executing various daily activities including lifting items, eating, cleaning and many more [8]. For the rehabilitation process to be efficient and prevent damage to the joints, the device must closely collaborate with the human body to establish coordination. Consequently, an analysis of anatomy must be performed as well as movement characteristics of the upper limb. Upper limb's anatomy is illustrated in Fig.10.

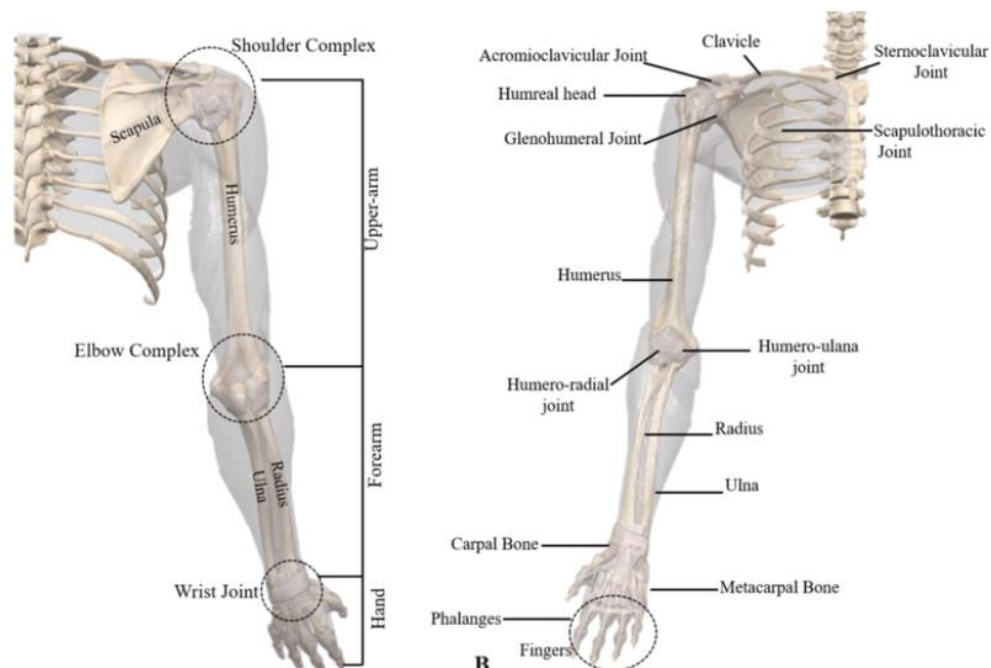


Fig. 10. Human's arm anatomy [23]

The human arm encompasses seven primary Degrees of Freedom (DOFs), which should be incorporated into the exoskeleton's design if the aim is to replicate a similar workspace to the healthy human arm. The shoulder joint is one of the complex structures within the musculoskeletal system [8]. The shoulder complex entails four articulations, specifically the glenohumeral joint (GH), acromioclavicular joint (AC), sternoclavicular joint (SC) and scapulothoracic joint (ST), shaped by three bones which are clavicle, humerus and scapula [23]. The glenohumeral joint exemplifies a classic ball-and-socket joint capable of rotation around three mutually perpendicular axes [8]. The glenohumeral joint is regarded to be the most mobile joint and this joint allows movements such as abduction and adduction, flexion and extension as well as internal/external rotation. Conversely, the sternoclavicular joint and acromioclavicular joint are intricately interconnected with the

scapulothoracic joint. This connection encompasses movements such as elevation/depression, protraction/retraction, along with upward and downward rotation [33]. As a result, the instantaneous center of rotation (ICR) within the glenohumeral joint changes with the motions of the shoulder complex [33].

The elbow complex is made of three bones ulna, humerus, radius and elbow joint. The elbow joint is an important link that connects the forearm to the upper arm and is a synovial compound joint made of two joints – humeroradial and humeroulnar [23]. The humeroradial joint is characterized as a concave spherical joint, while the humeroulnar joint functions as a hinge joint. These joints aid in extension and flexion movements. The proximal radioulnar articulation is responsible for supination and pronation movement [36]. In literature, most exoskeletons for elbow joints are designed for 1DOF – flexion and extension [23]. Many muscles are attached to the shoulder and elbow joint which during rehabilitation can be healed.

The wrist serves as the link between the forearm and the hand and possesses significant workspace with flexion and extension, radial and ulnar deviation as well as pronation and supination [37].

Shoulder and elbow joints are responsible for extensive upper limb motions as well as determining the limb's position. Conversely, the wrist joint is mainly responsible for hand posture, including the wrist active joint in an exoskeleton design may introduce unnecessary complexity without significant functional benefits [8]. Regarding upper limb rehabilitation, in this paper shoulder and elbow joints will be the main subject since an increase in DOF means a more intricate exoskeleton structure and additional weight which can potentially decrease the system's efficiency [38]. The natural and physiologically feasible range of motion (ROM) is a crucial consideration in designing exoskeletons due to inherent biological constraints limiting the orientation and motion of the human arm. According to the literature healthy human shoulder abduction/adduction movements, range from -20° to 180° , flexion/extension from -60° to 180° . Elbow flexion and extension movements range from 0° to 140° [32]. Degrees of range of motion for the shoulder and elbow joints are illustrated in Fig.11.

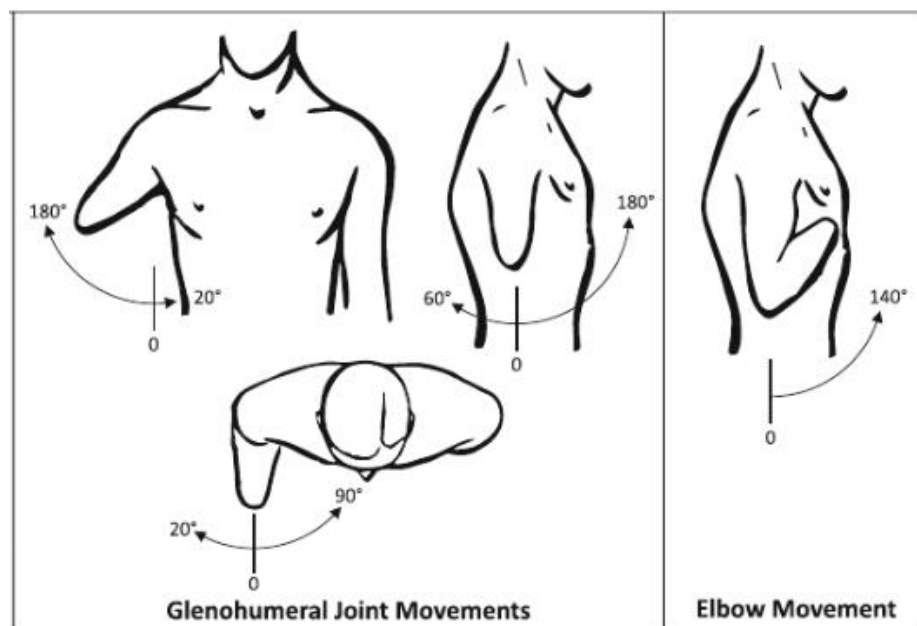


Fig. 11. Range of motion of human's upper limb [32]

However, for rehabilitation devices, it is a challenge to provide a full amplitude of motion due to construction constraints. ALE_x arm exoskeleton [4] can access approximately 90% of the natural range of motion of the human arm without colliding with the human body. Shoulder abduction/adduction range is from 0 to 100 degrees. Shoulder flexion/extension from 10 to 155 degrees.

The range of motion of the upper limb is primarily determined by the elbow and shoulder structures. However, many simplified exoskeletons are created only including elbow joint. Exoskeletons for elbow joint are designed to support only one degree of freedom, however, such devices can even increase the burden on the shoulder because of the weight they carry. Consequently, prevailing research on upper-limb exoskeletons tends to prioritize designs incorporating both shoulder and elbow joint structures [33]. Designing exoskeletons intended for rehabilitation, assisting in everyday life or for occupational tasks needs to have an established power assistance rate. This needs to be selected carefully since it poses a trade-off dilemma – the higher power assistance the heavier the exoskeleton and vice versa. This is due to actuators/motors which have size and weight correlation to the output torque. Since the exoskeleton's purpose is to rehabilitate people with various degrees of immobility the output torque must hold the whole arm's weight. As well lightness can be achieved by removing some degrees of freedom from the exoskeleton construction, thereby minimizing the count of actuators [33]. Regarding this approach horizontal arm adduction/abduction is not supported by the exoskeleton. In this case shoulder has two degrees of freedom instead of three and for elbow joint exoskeleton will support one degree of freedom. Fig.12 depicts the kinematic schemes of the human arm and the exoskeleton. The exoskeleton will provide 3 degrees of freedom – elbow flexion/extensions, shoulder flexion/extension and shoulder abduction/adduction.

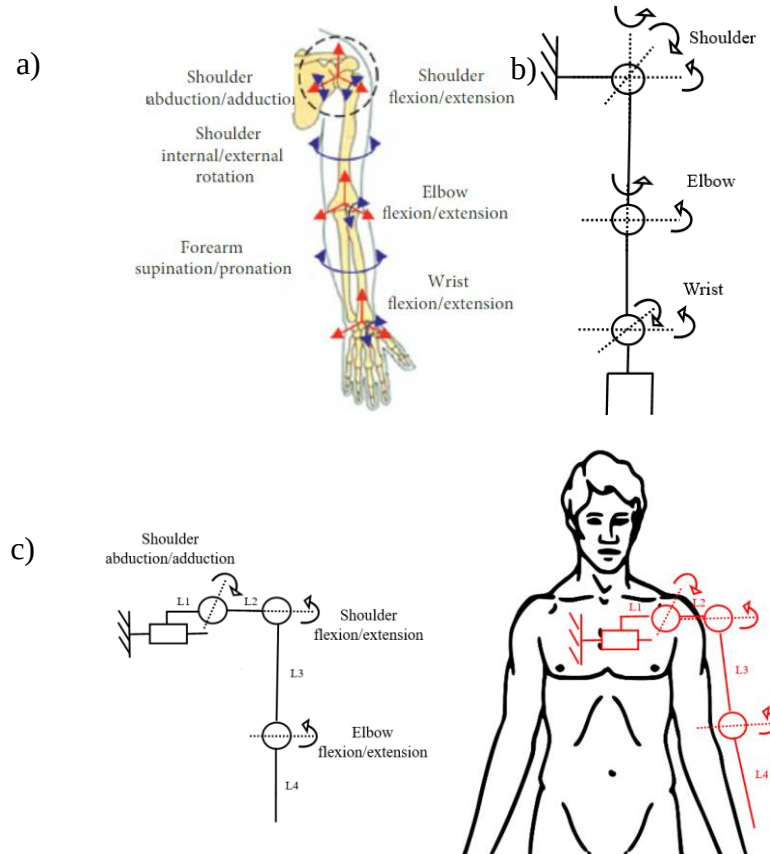


Fig. 12. a) Human arm degrees of freedom; b) Kinematic scheme of human arm; c) Exoskeleton's kinematic scheme

2.2. Targeted Audience and Anthropomorphic Parameters for Exoskeleton's Design

Adaptability stands as a pivotal factor when designing an exoskeleton. It should be accommodated to a variety of people across a spectrum of anthropomorphic parameters such as weight, height as well as age and other variables. In most cases, an effort is made to design an adaptable system that accommodates users' individual dimensions of the upper limb [34]. Therefore, each upper limb's segment mass and length must be obtained. Table 1 provides information about the mass and length of each upper limb segment relative to the whole body mass and height, respectively.

Table 1. Upper limb's segment mass as a percentage of the body, mass and length as a percentage of the body height [39]

Segment	Segment mass, %	Segment length, %
Upper arm	3.00	17.20
Forearm	1.76	15.70
Hand	0.73	5.75

This exoskeleton is primarily intended to be used for people who have muscle weakness. After a stroke, people can experience hemiparesis, which causes one-sided muscle weakness and the rehabilitation process is crucial for recovery. Age is a significant factor defining the probability of enduring a stroke. The risk of experiencing stroke doubles every decade beyond the age of 55 [40]. Consequently, due to vulnerability to stroke people falling within the age bracket of 50 to 80 years are the targeted group. Within this demographic, variations in weight, height of males and females across all races, ethnicities are observed. Table 2 provides anthropometric data of people living in the United States [41].

Table 2. Mean mass and height of adult females and males. United States 2015-2018 [41]

Age group	Mean mass, kg		Mean height, cm	
	Female	Male	Female	Male
50-59	78.7	91.9	161.3	175.4
60-69	78.2	91.2	160.7	174.4
70-79	74.7	87.7	158.2	173.0

The length of the links of the exoskeleton must correspond to human upper limb lengths. Therefore, the minimum and maximum length values of each limb segment need to be calculated. Similarly, according to the upper limb mass actuator's lifting capability is chosen, thus the maximum value of mass for each segment – upper arm, forearm, hand - must be calculated. The mean mass for females and males is in the range of 74.7 kg to **91.9 kg**, as well as height from **158.2 cm** to **175.4 cm**. These values are used for Eq.1 and Eq.2. Table 3 depicts each segment's calculated mass and length.

Calculation of maximum mass of each segment:

$$m_{seg} = \frac{m_{max}}{100} * m_{\%}, \quad (1)$$

where: m_{seg} is the mass of a specific body segment (kg); m_i is the maximum mean mass of an adult human (kg) [41]; $m_{\%}$ is the percentage of upper limb segment mass (%) [39]

Calculation of minimum and maximum length of each segment:

$$l_{seg} = \frac{h_i}{100} * h_{\%}, \quad (2)$$

where: l_{seg} is the length of a specific body segment (cm); h_i is the mean maximum or minimum height of adult human (cm) [41]; $h_{\%}$ is the percentage of segment length (%) [39]

Table 3. Calculated length of each upper limb segment

Mean height of adult human, cm		Upper limb segment	Length, cm	
Min	Max		Min	Max
158.2	175.4	Upper arm	27.2	30.2
		Forearm	24.8	27.5
		Hand	-	10.1

Table 4. Calculated mass of each upper limb segment

Mean maximum mass of adult human, kg	Upper limb segment	Maximum mass of upper limb segment, kg
91.9	Upper arm	2.8
	Forearm	1.6
	Hand	0.7

2.3. Methodology for Analysing Torques and Inertia Moments

To generate upper limb movement, an actuation system must be used. In order to select the appropriate motor and gear, it is essential to calculate the torque required for moving the hand, forearm, upper arm and exoskeleton's links. In this case pivotal point is established at the elbow or shoulder joint. Torque calculations must take into account the worst-case scenario, where the torque around the pivot point is maximum depending on the distance at which the force is applied as it is shown in Fig.13 [38]. According to Eq.3 maximum torque is calculated when the exoskeleton link is aligned perpendicular to the vector of gravity force.

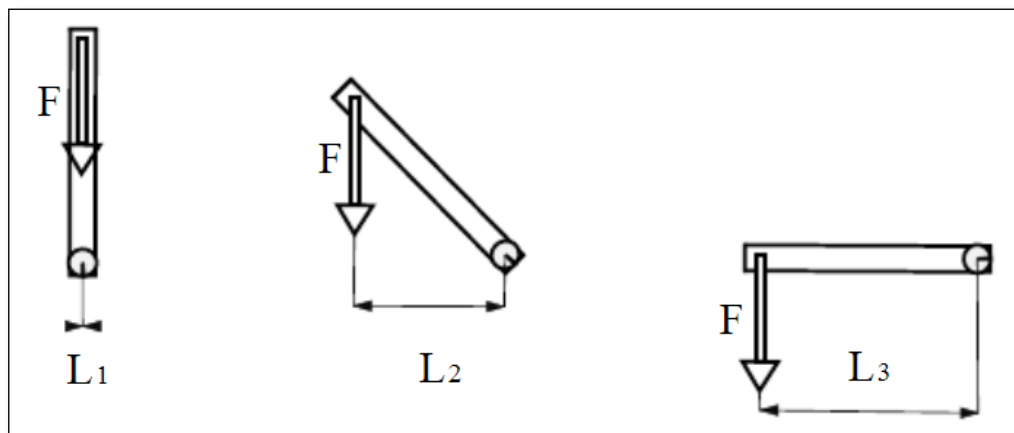


Fig. 13. The variation of distance from the pivot point to the force point relative to the position of the link [38]

Maximum torque is calculated by using the Eq.3.

$$\sum \tau = FL = mgL - \tau = 0, \quad (3)$$

where: τ is the torque (Nm); F is the applied force (N); m is the mass of the link (kg); g is the gravitational acceleration constant ($\frac{m}{s^2}$); L is the distance from the force to the pivot point (m)

However, using Eq.3 only static forces were considered when the arm is positioned horizontally, however, it is not the worst-case scenario since the arm needs to be accelerated in order to move from the resting point. Regarding dynamic forces, additional torque must be taken into account. Eq.4 provides additional torque calculation utilizing rotational kinematics.

$$\sum \tau = I\alpha, \quad (4)$$

where: τ is the torque (Nm); I is the moment of inertia ($kg \cdot m^2$); α is the angular velocity (rad/s^2)

When calculating the moment of inertia of the arm, the arm rotates around the pivot located at the end of its tail. The moment of inertia is calculated as shown in Eq.5.

$$I = \frac{mr^2}{2}, \quad (5)$$

where I is the moment of inertia ($kg \cdot m^2$); r is the distance from the mass center to the pivot (m); m is the mass of the link and the upper limb segment (kg)

Each joint's moment of inertia is calculated by the sum of all masses – exoskeleton and human upper limb segments and multiplied by the square of the distance from the pivot. For simplifying purposes mass of an exoskeleton and upper limb segments are considered to be at the same distance from the pivot point, thus the distance of this sum mass is stated to be in the middle of the exoskeleton's link. In addition, when calculating the moment of inertia for elbow or shoulder joints, that joint actuator's mass cannot be accounted for, as it does not contribute to the torque relative to its axis.

$$I_N = \sum_{i=0}^{N-1} \frac{m_i r^2}{2}, \quad (6)$$

where I_N is the moment of inertia ($kg \cdot m^2$); r is the distance from the mass center to the pivot (m); m_i is the mass of the link and upper limb segment (kg)

Angular acceleration can be derived and computed from the Eq.7:

$$\theta = \frac{1}{2} \alpha t^2, \quad (7)$$

where θ is the angle travelled by the joint (deg); t is the time interval (s); α is the angular acceleration (rad/s^2)

2.4. Selection Principles of Actuation System

Exoskeletons can support users using artificial muscles, as well as by distributing the external load using the bypass principle or supporting joints with an assistive torque. Active exoskeletons utilize powered actuators while passive exoskeletons employ springs or other types of actuation that produces torque. In both scenarios, the exoskeleton supplies the required torque for the joint to lift

the arm, which allows the human muscles to relax to a specific extent. An advantage of this approach is the alleviation of joint compression and the potential to prevent conditions like osteoarthritis. This is because joint support reduces muscle forces by generating the torque around the exoskeleton joint and conveying it through the rigid frame as a force perpendicular to the body. This mechanical distinction may result in a general decrease of the joint's compression force [42]. Various actuators can fulfil the demand to produce torque for arm lifting, however, it is important to consider weight and size criteria for efficient, portable and light system [43].

Electric actuators are often used in rehabilitation devices due to their ability to generate relatively high-power output [44]. Specifically, DC motors are frequently used in robotics instead of AC due to the straightforward control capability, precision, as well, they are more efficient. Comparing motor with brush and brushless motor, the latter is more extensively used and preferable due to the high power-to-weight ratio, also it is more reliable and does not require frequent maintenance [45]. For an electric motor on its own, it is challenging to produce significant forces that are necessary to assist the user, in this case, gears with an appropriate reduction ratio must be incorporated. For an exoskeleton to achieve a compact design harmonic gears are one of the most popular selections. Harmonic drive gear has an exceptional reduction ratio while having a compact-flat design as well it provides minimal backlash which leads to high accuracy, robust torque capacity and smooth motion. These qualities are essential for the exoskeleton to imitate natural human motions. The gearbox can be integrated directly into the joint eliminating the belts and that ensures the system's rigidity and minimizes slippage [46]. Also, compared to the reduction ratio of other types of gearboxes, it has a relatively light structure. Since the criteria of actuation system components include a high power-to-weight ratio, minimized system dimensions and lightweight DC brushless motor and harmonic gear combination is selected for each movement. This combination is common for wearable rehabilitation devices and is applied for both upper and lower limb exoskeletons [47].

2.5. Control Principle of the Exoskeleton

For rehabilitation, it is crucial to have an adaptive assistance level regarding a person's ability to move the limb. It allows to tailor the rehabilitation process to the individual's condition, which leads to faster strength regain. Also, the progress can be tracked. To achieve an assistance level, the appropriate voltage values must be selected as well as current limitations. DC motors have the flexibility to operate across a range of voltages. From Fig.14 it can be seen that voltage change shifts the torque-speed curve parallelly which changes no-load motor speed n_0 as well as starting torque M_H . At higher voltages, the line goes up increasing starting torque and no-load speed, which results in a higher supplied current at the same speed value and vice versa. Furthermore, current and torque are directly proportional to each other and this ratio is constant for every motor. Hence, solely measuring the motor current provides sufficient information about the motor's torque. Due to this correlation, current limitations can be introduced, consequently, in this way maximum assistance level can be altered. To have a safe functioning device constant motor speed should be maintained. The torque of the motor fluctuates due to the external load applied as well because of environmental condition changes, thus having a constant torque value or constant voltage will result in speed fluctuations. This as a consequence leads to the instability of the system causing discomfort to the user as well disrupts the precision and smoothness of movements. With this control principle, constant speed is maintained even though at different movement path points the force exerted by the user

varies due to the lifting capacity of the muscles. Consequently, the current is adjusted accordingly to provide the necessary assistance torque.

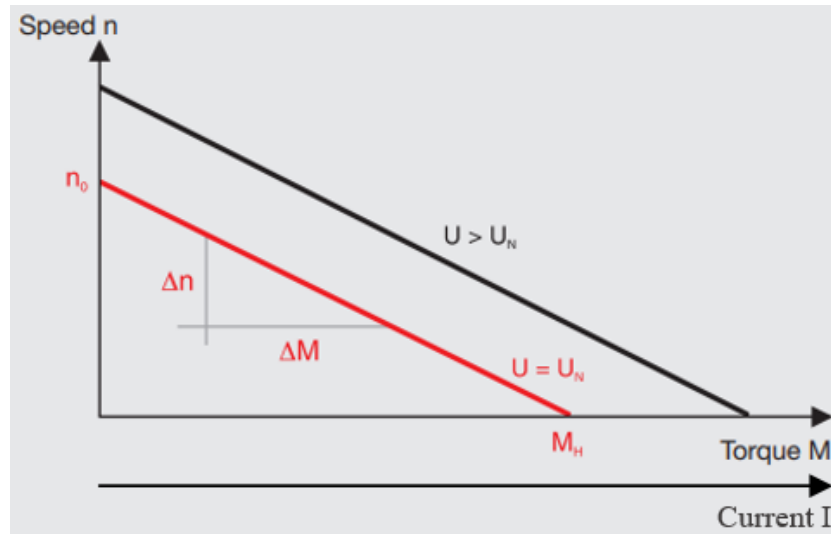


Fig. 14. Motor's torque-speed dependency at different voltage values [48]

In order to select appropriate voltages for the operation Eq.8 is used. In the equation exact values of k_n and $\frac{\Delta n}{\Delta M}$ are provided in the motor's datasheet [48].

$$n = k_n * U_{mot} - \frac{\Delta n}{\Delta M} * M, \quad (8)$$

where n is motor speed (rpm); k_n is speed constant (rpm/V); U_{mot} is motor voltage (V); $\frac{\Delta n}{\Delta M}$ is curve gradient (rpm/mNm); M is motor torque (mNm)

According to Chang Liu et.al [33] exoskeleton sensors play an important role in abnormality detection in movements. sEMG sensors and encoders are collecting the data and if irregular values are detected exoskeleton is immediately shut down. Control software helps to have an indicated range of allowable angles when the arm is extended or bent. A similar approach is used for modelled exoskeleton in this paper. Controlling the speed can be done both ways with open loop or closed loop. Worth mentioning that current control also can be controlled in the same way. Open loop does not have feedback and output value is not measured and compared to the set value. On the other hand, the closed-loop has feedback, the output value is measured and adjusted. Closed-loop control offers better accuracy and robustness by continuously comparing actual performance to desired setpoints and making adjustments accordingly. Since the exoskeleton is used for human beings and has medical purpose more precise and accurate measurements are essential. As a consequence, encoder sensors are implemented to measure the speed and position. Encoders not only deliver information about the speed but also the direction and position. For the position control measured position of the motor shaft is compared to the target position. When abnormal feedback values are obtained, the system does not let to move the arm out of the allowable range and corrects the position. In addition, Hall sensors provide information on the arm's position, so double check of values are implemented. Digital incremental encoders provide square signals – pulses that are counted to evaluate the speed. This measured speed is compared to the desired speed and the resulting difference is minimized by adjusting the power output. In the meantime, current is also measured and controlled not to exceed the limitations. Closed-loop speed control system is shown in Fig.15.

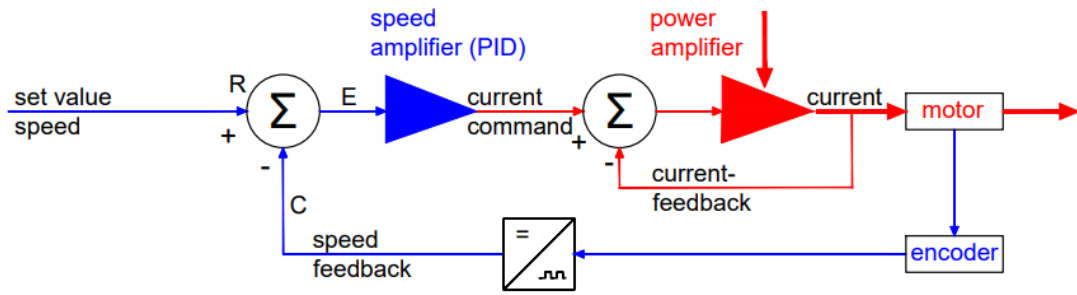


Fig. 15. Speed control system of the motors (closed-loop)

2.6. Exoskeleton's Structural Analysis Method

A 3D model of the upper limb exoskeleton is produced by SolidWorks 3D CAD design software and simulated with the required conditions in order to approve the design's suitability. The exoskeleton consists of several links. Static analysis of the exoskeleton's frame is a critical step, which identifies the potential malfunctions that might affect the components' performance and the device's safety [49]. Following the analysis construction can be improved by reinforcing vulnerable areas or reducing unnecessary material, which leads to a lighter structure. Additionally, stress analysis aids in material selection, aiming to create a lightweight frame for enhanced user comfort. The workflow starts with forearm frame design, after the design is finished static analyses are performed with different materials. After the material selection electronic components such as motor, gear and sensors are selected. Then the sequence repeats with the upper arm frame and shoulder frame – static analysis, torque calculations are performed following motor and gear selection. Such workflow lets have more accurate weight of the frame, which is used to calculate necessary torques for each joint in order to be able to lift the arm.

2.6.1. Possible Materials for Exoskeleton Frame

Selecting the appropriate material is a pivotal aspect of the design phase, as it has a significant impact on functionality and comfort. One of the issues with wearable exoskeletons is their bulkiness and heavy structure. One of the aims of this proposed exoskeleton frame is to be lightweight, regarding this, the amount of material is reduced to maintain appropriate weight. Manufacturing process dictates the selection of material as well as geometric shapes since every process has specific requirements and capabilities. For example, 3D printing allows to produce parts with intricate geometries it is more cost-efficient due to lower material waste, equipment setup costs and is suitable for low-volume production compared to CNC machining which requires materials with good machinability like aluminium or steel [50]. In recent years 3D printing as a manufacturing process for parts has emerged. The advancements in 3D printing technology and the growing range of materials that are accessible for this technology and can interact with human tissues foster the development of novel concepts, optimizing medical devices [51]. One of the most popular 3D printing processes is fused deposition modeling (FDM) which is cost-effective and produces durable parts in a shorter time compared to other deposition processes such as SLA. Moreover, there is a large selection of various materials with superior properties that are compatible with fused deposition modeling. FDM uses thermoplastic filaments, which are heated to the liquid and extruded on the build platform layer by layer. After deposition material quickly solidifies. Nearly half of the 3D printing materials market is comprised of thermosetting photopolymers such as Acrylonitrile Butadiene Styrene (ABS), polylactic acid (PLA), nylon which are inexpensive and can be utilized by FDM technology [51]. 3D printed medical

products can ensure superior quality and the ability to personalize devices while reducing overall costs due to a decrease in material wastage. Such approach lets 3D printing technology be competitive regarding other manufacturing processes. Al Bakri et.al [52] produced an arm exoskeleton employing 3D printing materials like PETG, nylon and validated that plastics can effectively withstand varying mechanical loads on the structure. Furthermore, composite materials for 3D printing are also a great option since they provide strength, stiffness but at the same time have lightness. Webb et.al [53] engineered the upper limb exoskeleton from ABS plastic and carbon fiber. Structurally vulnerable places were reinforced with carbon fibers without major mass increase. In this paper 3D printing manufacturing process is selected for the research. Since the device must maintain a delicate balance between being lightweight yet capable of bearing the necessary loads, while also considering cost-effectiveness, plastic and composite materials will be investigated. In this research five 3D printing materials will be analyzed: PLA, ABS, PETG, rPACF and PET CF. The first three plastic materials – PLA, ABS, PETG are often employed in FDM technology and are known as affordable solutions to produce parts with advantageous strength characteristics. NYLON PA6 + CF (rPACF) is a composite based on nylon material and infused with micro carbon fibers, resulting in high strength and toughness. Used in diverse industries where durable but lightweight components are necessary. As well, composite PET with carbon fiber will be investigated, this combination provides exceptional mechanical properties and is suitable for load-bearing structures. PLA, ABS, PETG and PET CF material mechanical properties are taken from the datasheets provided by the “Ultimaker” manufacturer, rPACF material’s mechanical properties are provided by the “Reflow” manufacturer. All technical documentation of materials is provided in the Appendix 1 – Appendix 5. However, datasheets are missing Poisson’s ratio which is necessary for static simulation. For this reason, values of each material Poisson’s ratio are found or preliminarily determined from the research studies [54] [55] [56]. Material properties are shown in Table 5.

Table 5. Mechanical properties of materials

Properties	Materials				
	PLA	ABS	PETG	rPACF	PET CF
Young’s modulus (MPa)	3250	1962	1939	8838	4342
Poisson’s ratio	0.33	0.394	0.35	0.4	0.4
Tensile strength (MPa)	45.5	33.9	38.5	127	49.3
Yield strength (MPa)	52.5	38.1	46.2	127	50.6
Density (kg/m ³)	1240	1100	1270	1140	1330
Price (Eur/kg)	72	72	72	97	173

Regarding finite element analysis, it is preferable to have a factor of safety of more than 1 indicating the system's capacity to surpass maximum loads. According to the articles [57] [58] [59] the safety factor for exoskeletons ranges from 1.5 to 2.7. However, many exoskeletons exhibit a safety factor value exceeding 2. The factor of safety (FOS) for each exoskeleton frame is selected to be no less than 2.5. In addition, displacement is a crucial factor that needs to be taken into account since it can directly affect the human body. Large displacement can cause misalignments between the device and arm joint, also forces can be transferred. Thus, to achieve the exoskeleton’s comfort, displacements must be minimal.

2.7. Arrangement of Exoskeleton Components

The exoskeleton system combines various devices and it requires careful consideration of their arrangement to achieve both compactness and comfort in the design. It is important to consider the location of the actuation system. In order to minimize bulkiness as well as weight several strategies can be employed such as moving the actuation mechanisms directly off the exoskeleton arm frame and moving it toward the base frame using Bowden-tube cable drives. However, this approach has disadvantages like non-linear actuation which results in not reliable positional feedback. Similarly, the Stuttgart Exo-Jacket was developed for both shoulder and elbow joints to actively aid in flexion and extension. During the designing process, a crucial concern emerged regarding the micro-misalignment of the non-coincident center of rotation between the joints of the human arm and those of the exoskeleton. However, this emerging issue was solved by mounting motors directly at the joint locations [23]. Regarding this analysis in this project, actuators are placed directly on the arm joints [27]. Jinwoo Lee et.al [60] designed an exoskeleton with a mass of 4.7 kg. The system mass includes the battery, printed circuit boards, PAM frames and cables. These components are packed in the backpack, this way the load is distributed evenly across the shoulders and back. This approach ensures greater stability compared to the other methods. Also, this load can be easily carried by a person who has reduced strength in their limbs. Various studies suggest that a load of up to 10 % of body mass should not cause major discomfort [60].

2.8. Chapter Summary

The development of an advanced exoskeleton involves intricate considerations of mechanical, electrical, computer, and control systems. Key aspects include sophisticated control methods, actuation mechanisms, and sensor integration to ensure device efficiency. The actuation system is an essential part of the wearable exoskeleton, it is responsible for generating the necessary torque to assist the user and in achieving suitable parameters and weight considerations electric motors and harmonic gears are selected for the design. The actuation system will be placed directly on the joints in order to obtain reliable position feedback of the motors and avoid misalignments. Moreover, encoder integration in every joint and closed-loop control ensures precise movements and user safety. Exoskeleton aims to be lightweight yet capable of bearing necessary loads, thus materials such as plastics and composites will be analysed and manufactured via 3D printing technology. To achieve ergonomics for the exoskeleton and ensure safe movements forearm and upper arm frames should be adaptable length. Furthermore, to distribute the exoskeleton's load, additional system components are usually placed on the human's back. Overall, the design process prioritizes achieving ergonomics and functionality by integrating sufficient degrees of freedom as well as making the device compact and lightweight.

3. Upper Arm Exoskeleton Development

3.1. System of the Exoskeleton

The exoskeleton has several requirements that must be taken into account. First of all, the device must be wearable and should firmly attach to the human's body. Actuation components are mounted on the exoskeleton's frame, as a consequence, the mass of each component must be taken into account. Moreover, since the exoskeleton supports three degrees of freedom of the arm, the actuation system must support high torque requirements, which include a motor with a gear. Furthermore, safety precautions must be employed such as sensors with limited movement range as well as an emergency button. For the rehabilitation process to be configurable for each person control of motor speed should be available. The system has three controllers for each motor. The host computer enables the configuration of the desired position, current and speed limitations. Fig.16 depicts a block diagram of the exoskeleton's system with mentioned components.

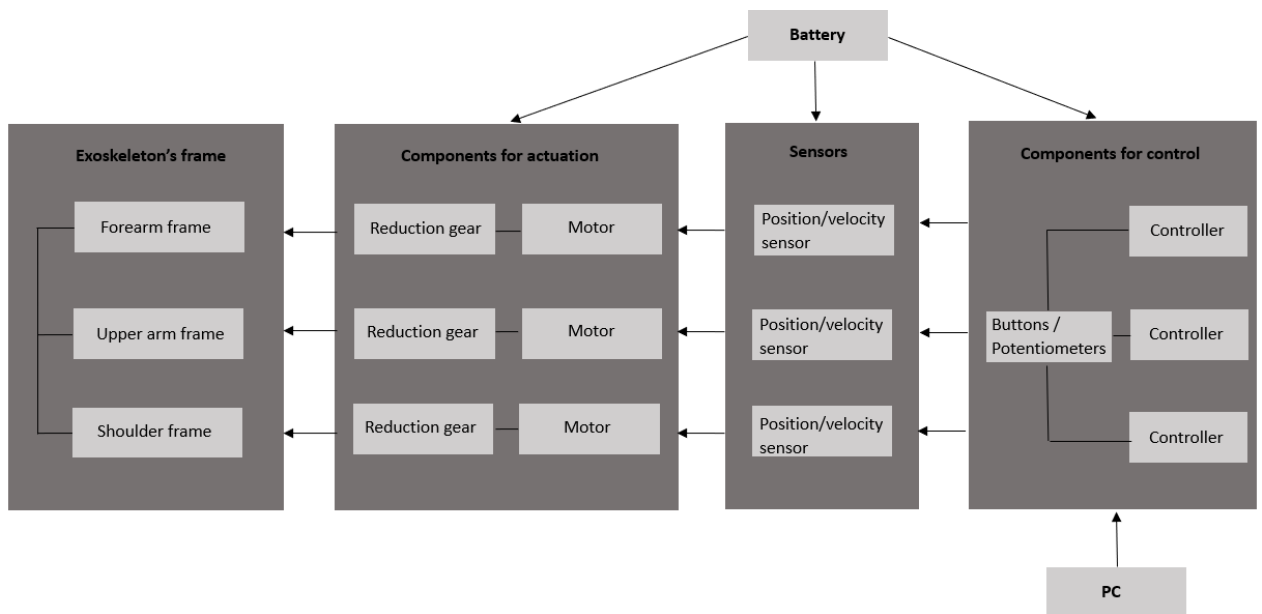


Fig. 16. Block diagram of the exoskeleton's system

3.2. Static Analysis of Upper Limb Exoskeleton

Static analysis of the exoskeleton is essential to ensure the structural integrity and safety of the device during operation. Each exoskeleton frame must withstand the weight of each body segment and counterbalance its weight while performing rehabilitative training. Static analysis is performed by selecting each frame segment from the forearm link, upper arm link and shoulder link. Fig.17 shows the exoskeleton's links that are analysed and Fig.18 shows the calculation scheme for simulation. The mass of each body segment is taken from Table 4 and link lengths are taken from Table 3. Maximum values are used since simulations must reflect the worst-case scenario.

For each exoskeleton frame, fixation points are selected where the actuator is mounted. Gravitational force is applied and a remote load with a distributed connection is placed. Distributed connection denotes that nodes of a chosen geometry have the ability to move in relation to each other. Remote loads correspond to the center of weight of each human's body segment. For each frame, the finest mesh density is selected to get the most accurate results. Bonded interaction is applied to all components. Finite element meshes of parts are given in Appendix 6 – Appendix 8.

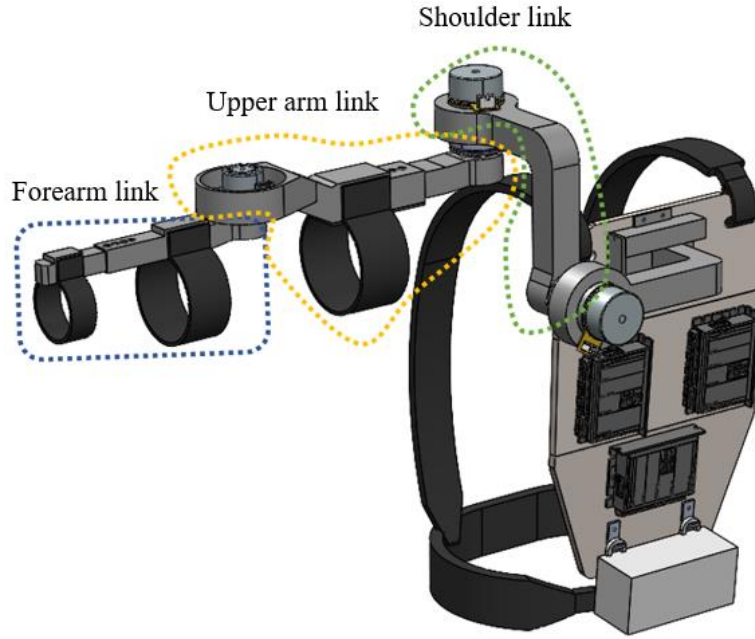


Fig. 17. Links of the exoskeleton

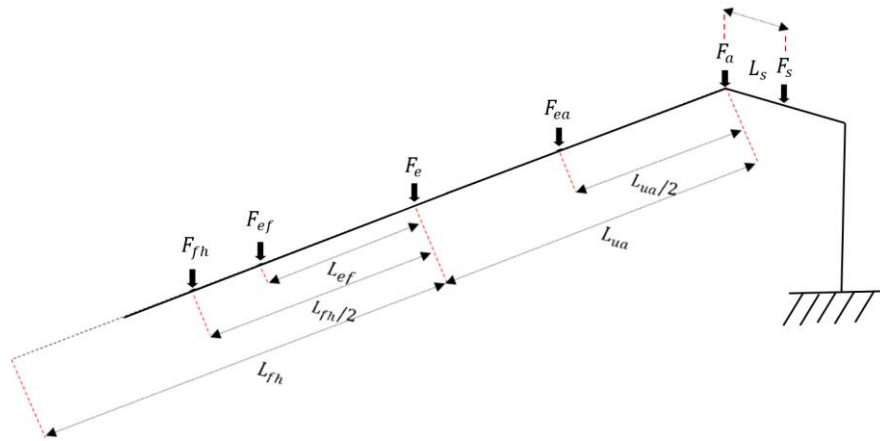


Fig. 18. Calculation scheme for exoskeleton's frames

On the forearm link frame, two forces are acting – gravitational and the weight of the human forearm, hand. The remote load affects the supports' internal surfaces which are in contact with the forearm's bottom part. In Fig.19 an image from the SolidWorks static simulation environment is shown which corresponds to the forces depicted in the calculation scheme for the forearm frame. The magnitude of acting forces is calculated by formulas:

$$F_{fh} = m_{fh} * g , \quad (9)$$

where F_{fh} is the weight of the forearm and hand (N); m_{fh} is the mass of the forearm and hand (kg); g is the gravitational acceleration constant ($\frac{m}{s^2}$).

$$F_{ef} = m_{ef} * g , \quad (10)$$

where F_{ef} is the weight of the exoskeleton (N); m_{ef} is the mass of the exoskeleton forearm frame (kg); g is the gravitational acceleration constant ($\frac{m}{s^2}$).

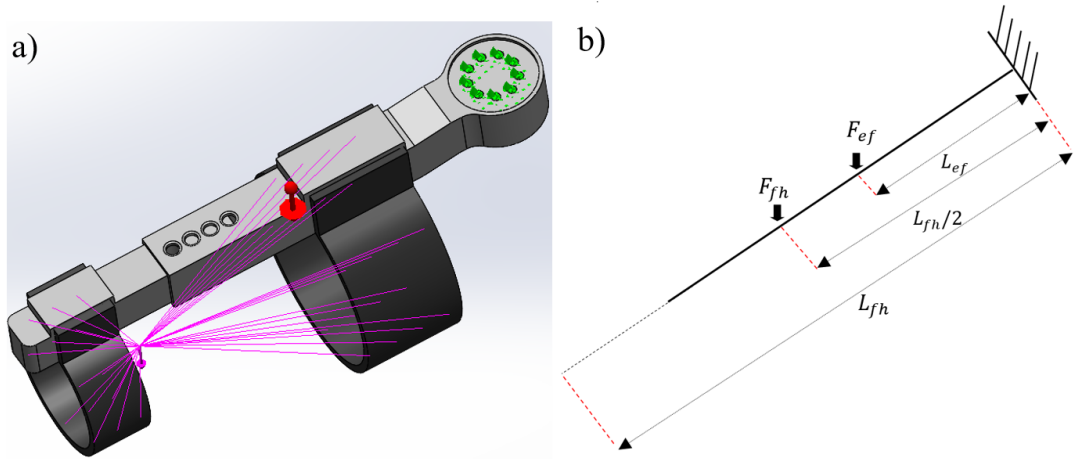


Fig. 19. a) forearm frame in static simulation environment; b) forearm's frame calculation scheme of acting forces

For upper arm link frame static analysis fixation points are selected where the actuator responsible for shoulder flexion/extension is mounted. Since the forearm's remote load transmits to the upper arm frame, this load is concentrated on the surface where the actuator is mounted. In addition, the actuator and gearbox weight is added. As well gravitational force is added with remote load of upper arm weight mass center. The upper arm's remote load has an effect on the upper arm support's internal surfaces which are in contact with the upper arm's bottom part. In Fig.20 an image from the SolidWorks static simulation environment is shown which corresponds to the forces depicted in the calculation scheme for the upper arm frame. The magnitude of acting forces is calculated by formulas:

$$F_e = m_e * g , \quad (11)$$

where F_e is the weight of the actuation system (N); m_e is the mass of the actuation system (kg); g is the gravitational acceleration constant ($\frac{m}{s^2}$).

$$F_{ea} = (m_{ef} + m_{af}) * g , \quad (12)$$

where F_{ea} is the weight of the exoskeleton and forearm (N); m_{ef} is the mass of the exoskeleton's upper arm frame (kg); m_{af} is the mass of the upper arm (kg); g is the gravitational acceleration constant ($\frac{m}{s^2}$).

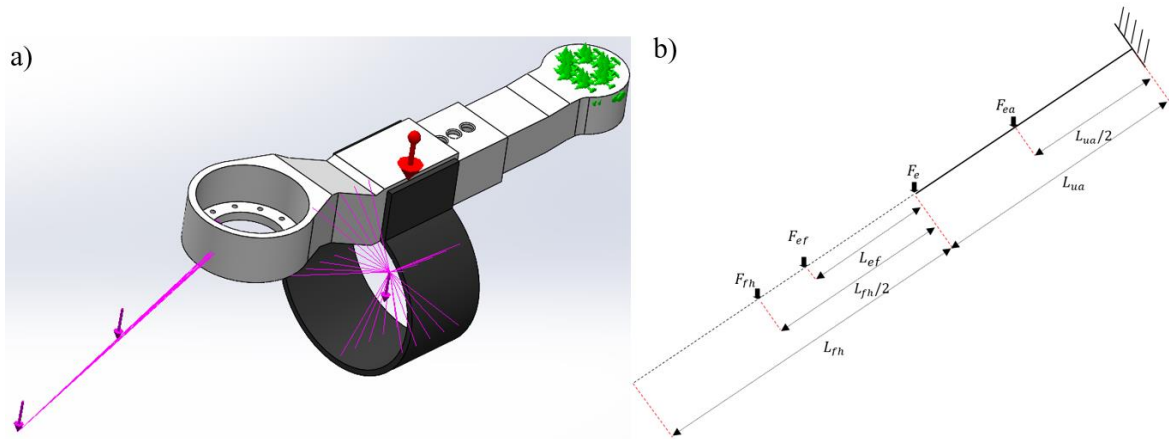


Fig. 20. a) upper arm frame in static simulation environment; b) forearm's frame calculation scheme of acting forces

For shoulder abduction and adduction, the shoulder frame must be analysed. Similarly to the previous frame analysis, fixation points are selected where the actuator responsible for shoulder abduction/adduction is mounted. Arm weight together with actuator, gearbox weight and exoskeleton weight are transmitted to the shoulder link frame. As well gravitational force is added. Schematics are shown in Fig.21. Magnitude of acting forces are calculated by formulas:

$$F_a = m_a * g, \quad (13)$$

where F_a is the weight of the actuation system (N); m_a is the mass of the actuation system (kg); g is the gravitational acceleration constant ($\frac{m}{s^2}$).

$$F_s = m_s * g, \quad (14)$$

where F_s is the weight of the shoulder frame (N); m_s is the mass of the exoskeleton's shoulder frame (kg); g is the gravitational acceleration constant ($\frac{m}{s^2}$).

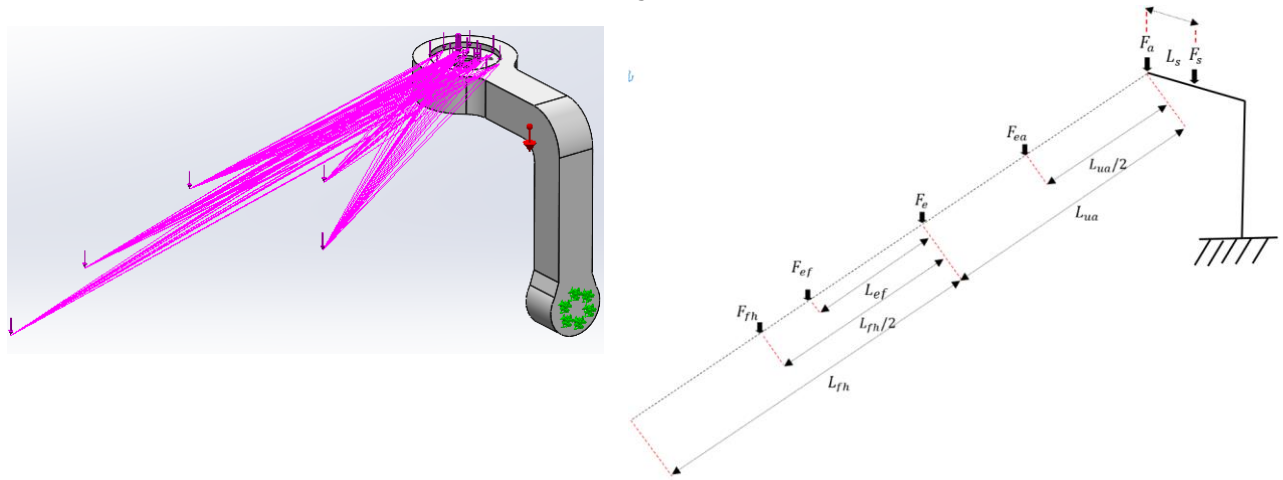


Fig. 21. a) upper arm frame in static simulation environment; b) forearm's frame calculation scheme of acting forces

Results of each exoskeleton's frame with described acting forces and different materials are shown in Table 6.

Table 6. Results of static analysis with different materials

Segment	Property	PLA	ABS	PETG	rPACF	PET CF
Forearm frame	Max Stress (MPa)	3.882	3.826	3.889	3.853	3.874
	Max Displacement (mm)	0.922	1.504	1.543	0.339	0.701
	Min FOS	13.5	9.96	11.9	33	13.1
	Mass (kg)	0.168	0.149	0.172	0.154	0.180
	Price (Eur)	12.1	10.73	12.38	14.94	31.14
Upper arm frame	Max Stress (MPa)	13.645	12.937	13.468	13.821	14.858
	Max Displacement (mm)	2.539	4.151	4.260	0.928	1.912
	Min FOS	3.85	2.95	3.43	9.19	3.41
	Mass (kg)	0.550	0.488	0.563	0.506	0.590
	Price (Eur)	39.6	35.14	40.54	49.082	102.07

Shoulder frame	Max Stress (MPa)	12.138	11.956	12.171	12.019	12.139
	Max Displacement (mm)	1.697	2.794	2.857	0.617	1.260
	Min FOS	4.33	3.19	3.8	10.6	4.17
	Mass (kg)	0.573	0.509	0.587	0.527	0.615
	Price (Eur)	41.26	36.65	42.26	51.12	106.4
Sum of mass (kg)		1.291	1.146	1.322	1.187	1.385
Sum of price (Eur)		92.95	82.51	95.18	115.139	239.61

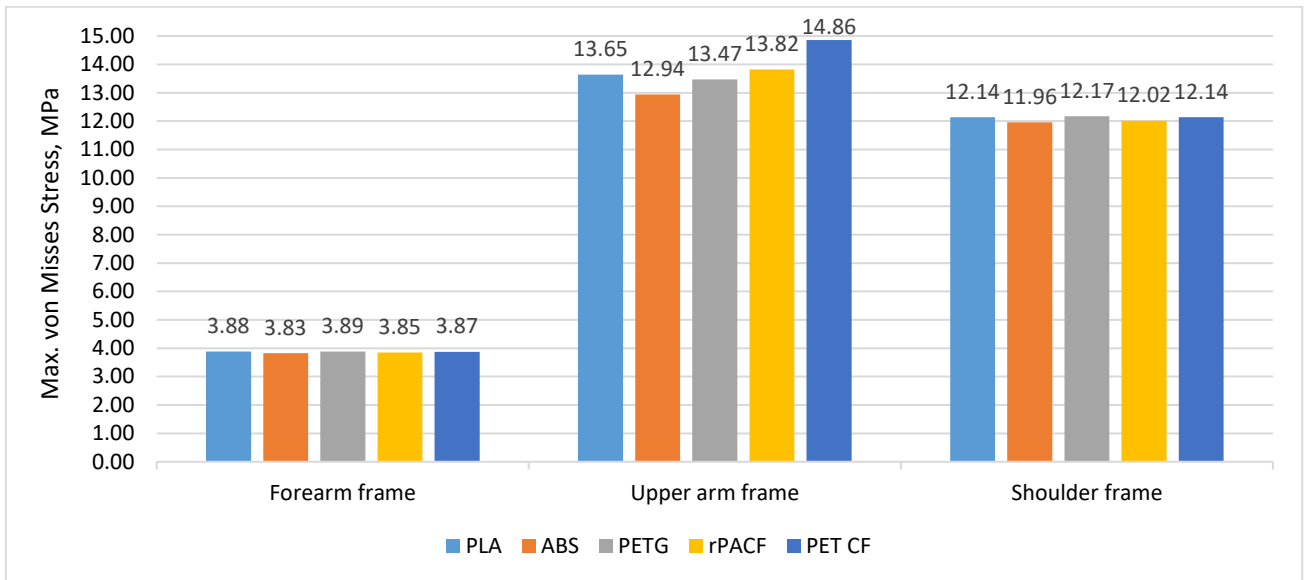


Fig. 22. Maximum von Mises stress of each exoskeleton's frame with different materials

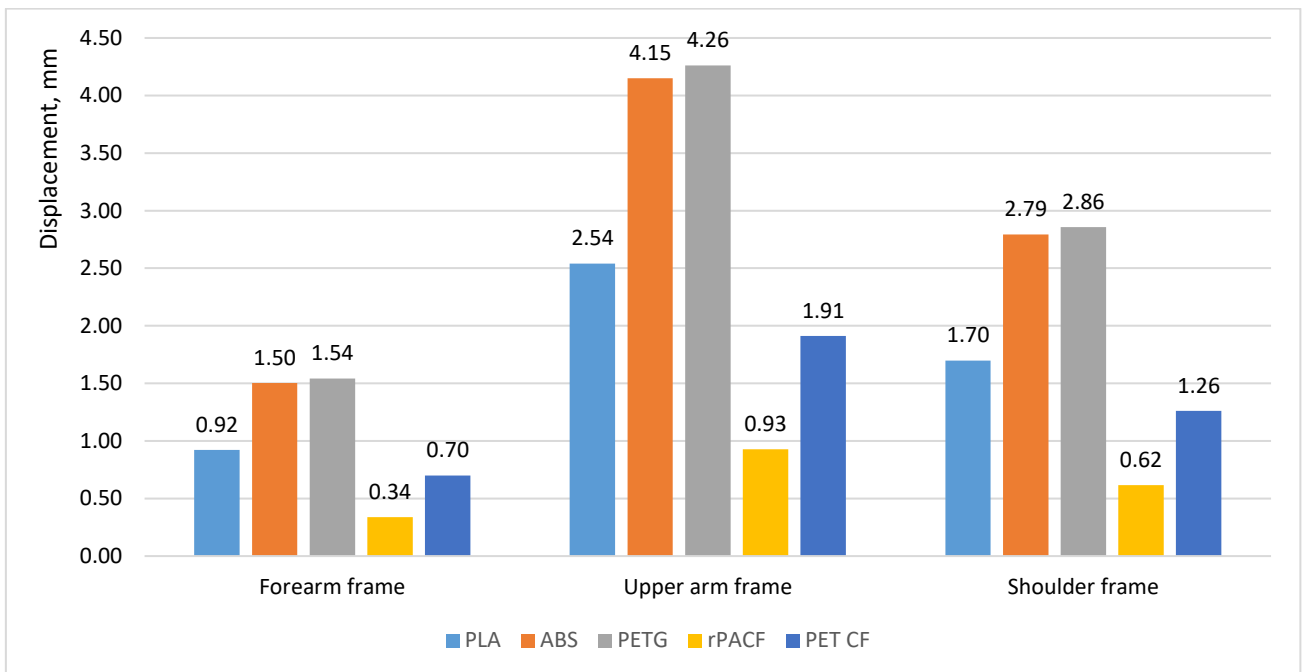


Fig. 23. Maximum displacement of each exoskeleton's frame with different materials

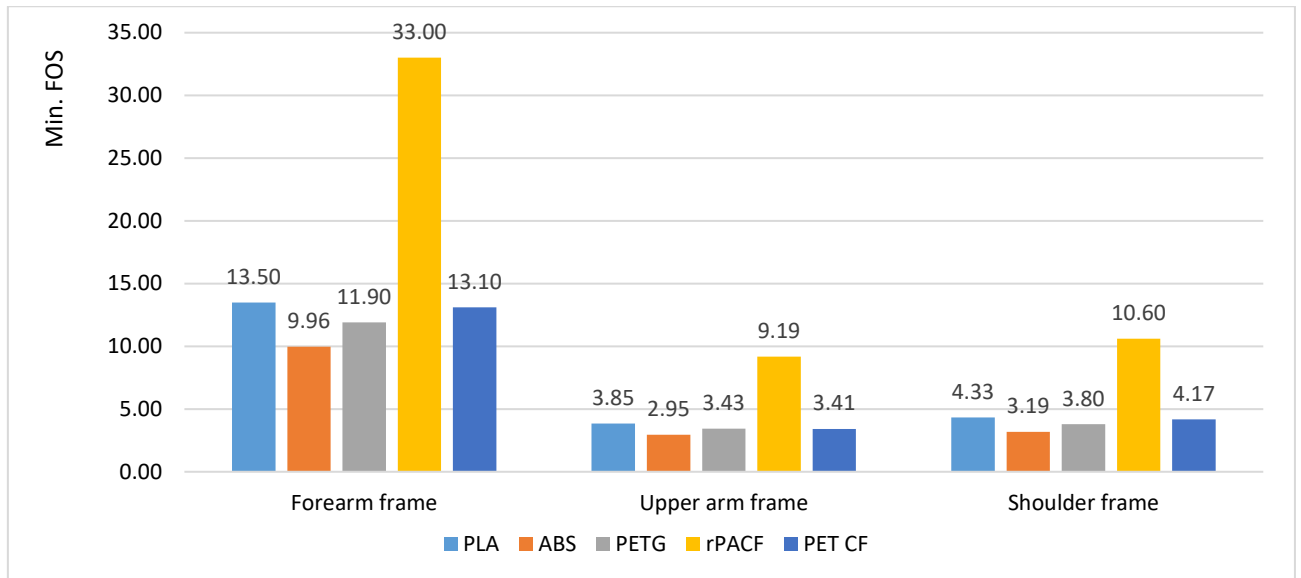


Fig. 24. Minimum factor of safety of each exoskeleton's frame with different materials



Fig. 25. Dependency between the mass of the exoskeleton's frame and the price of each material

As it can be seen from the simulation results in Fig.22 maximum stresses are low and below yield strength. Fig.24 shows that parts obtained a high minimum factor of safety which ranges from 2.95 to 33, these parameters ensure that part is durable, safe and can withstand forces without failing. Maximum displacement is the most critical parameter which influences what material should be used, similarly, the mass of the frames must be analysed which influences the price and the whole system's mass.

From the analysis of maximum displacements in Fig.23 composite materials show best behaviour. Plastic materials produce larger displacements than composites. Regarding the price aspect analysis shown in Fig.25 parts from PET CF material are the most expensive and have the highest mass. However, the best results are simulated with rPACF material. This material exhibits exceptional

properties which leads to the highest factor of safety and least displacement. Additionally, it is one of the lightest materials and the price is not high compared to other conventional materials such as PLA, ABS, PETG. Thus, for the production rPACF filament is selected.

3.3. Analysis of Actuation System

3.3.1. Torque Calculations for Arm Joints

Torque calculations for each joint must consider the most extreme circumstance. In this case, the worst scenario is when the arm performs adduction movement and is in a horizontal position. The scheme in Fig.26 depicts the loads that the motors must lift. Static torque required for each joint is calculated using Eq.3. Each variable's meaning is explained in Eq.9-Eq.14.

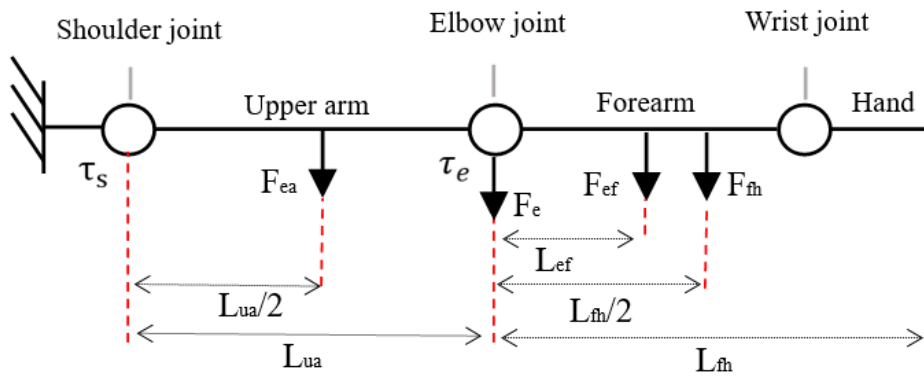


Fig. 26. Torque calculation scheme for arm joints

$$\tau_e(static) = F_{ef} * L_{ef} + F_{fh} * \frac{L_{fh}}{2} = m_{ef} * g * L_{ef} + m_{fh} * g * \frac{L_{fh}}{2} = 0.154 * 9.81 * 0.128 + 2.3 * 9.81 * \frac{0.376}{2} = \mathbf{4.44 Nm}$$

$$\tau_s(static) = F_{ef} * (L_{ua} + L_{ef}) + F_{fh} * (L_{ua} + \frac{L_{fh}}{2}) + F_e * L_{ua} + F_{ea} * \frac{L_{ua}}{2} = m_{ef} * g * (L_{ua} + L_{ef}) + m_{fh} * g * (L_{ua} + \frac{L_{fh}}{2}) + m_e * g * L_{ua} + m_{ua} * \frac{L_{ua}}{2} = 0.154 * 9.81 * (0.302 + 0.128) + 2.3 * 9.81 * (0.302 + \frac{0.376}{2}) + (0.075 + 0.13) * 9.81 * 0.302 + (2.8 + 0.506) * 9.81 * \frac{0.302}{2} = \mathbf{17.21 Nm}$$

$\tau_e(static)$ and $\tau_s(static)$ correspond to static elbow joint and static shoulder joint torque, which are necessary to lift the described weight.

According to the [38] paper maximum angular velocity for each joint doing everyday tasks is 90 deg/s. This value is taken to calculate angular acceleration for each joint.

Angular acceleration is computed using the Eq.7:

$$\alpha = \frac{2\theta}{t^2} = \frac{2 * 90}{1} = 180 \frac{deg}{s} = 3.14 \frac{rad}{s^2}$$

where θ is the angle traveled by the joint (deg); t is the time interval (s); α is the angular acceleration (rad/s²)

Dynamic torques for elbow and shoulder joints are calculated using Eq.4 and Eq.6. Each variable's meaning is explained in Eq.4, Eq.6 and Eq.9-Eq.14.

$$\tau_e(dynamic) = \frac{mr^2}{2} * \alpha = \frac{(m_{ef} + m_{fh})L_{fh}^2}{2} * \alpha = \frac{(0.154 + 2.3)0.376^2}{2} * 3.14 = \mathbf{0.55 Nm}$$

$$\begin{aligned}\tau_s(dynamic) &= \frac{mr^2}{2} * \alpha = \frac{(m_{ef} + m_{fh} + m_e + m_{ua} + m_{eu})(L_{fh} + L_{ua})^2}{2} * \alpha \\ &= \frac{(0.154 + 2.3 + 0.205 + 0.24 + 3.306)(0.376 + 0.302)^2}{2} * 3.14 = \mathbf{4.48 Nm}\end{aligned}$$

$\tau_e(dynamic)$ and $\tau_s(dynamic)$ correspond to dynamic elbow joint and dynamic shoulder joint torque.

Minimum torques that are needed to be produced by the actuators in order to lift the arm without human assistance:

$$\begin{aligned}\sum \tau &= \tau_{static} + \tau_{dynamic} , \\ \tau_e &= 4.44 + 0.55 = \mathbf{5 Nm} \\ \tau_s &= 17.21 + 4.48 = \mathbf{21.7 Nm}\end{aligned} \tag{15}$$

τ_e and τ_s correspond to the sum of the static and dynamic elbow joint and shoulder joint torque.

3.3.2. Selected Actuation Components

Electric motors are employed in the exoskeleton, specifically a flat type. Flat type motors are chosen due to the compact design, which is favourable since it occupies less space. Manufacturer “Maxon” produces high quality electric motors, compared to other motors they provide light assembly and sufficient torque. Similarly, “Harmonic Drive LLC” provides a compact and light design of harmonic drives with a high torque ratio. Motor and gear combinations are shown in Table 7. For elbow flexion and extension EC45 flat motor is used, which delivers a nominal torque of **56.9 mNm**. To increase the torque harmonic drive gear is attached to the motor’s output (CSD-20-100-2A-GR, Harmonic Drive AG, Limburg-Lahn, Germany). The gear’s reduction rate is 100:1. This combination can generate a continuous net torque of **5.7 Nm**. Similarly, for shoulder motions EC60 flat motor is used, which delivers a maximum continuous torque of **272 N**. To increase the torque harmonic drive gear is attached to the motor’s output (CSG-17-120-2UH-LW, Harmonic Drive AG, Limburg-Lahn, Germany). The gear’s reduction rate is 120:1. This combination can generate a continuous net torque of **32.64 Nm**. The datasheet of the motors can be found in Appendix 24 and Appendix 25. Gearbox datasheets can be found in Appendix 26 and Appendix 27.

Table 7. Motors and gears used for different arm motions

Movement	Motor	Gear	Continuous Net Torque, Nm
Elbow flexion/extension	EC45, 30 W brushless DC motor with Hall sensors (Maxon Motor AG), 24V 339281	CSD-20-100-2A-GR (Harmonic Drive LLC)	5.7 Nm
		Reduction 100:1	
Shoulder flexion/extension	EC60, 100W brushless DC motor with Hall sensors (Maxon Motor AG), 24V 625855	CSG-17-120-2UH-LW (Harmonic Drive LLC)	32.64 Nm
		Reduction 120:1	
Shoulder abduction/adduction	EC60, 100W brushless DC motor with Hall sensors (Maxon Motor AG), 24V 625855	CSG-17-120-2UH-LW (Harmonic Drive LLC)	32.64 Nm
		Reduction 120:1	

The factor of safety of the actuation system can be calculated by taking the calculated maximum torque to produce the movement and actual rated torque of the motor and gearbox combination:

$$FOS = \frac{\tau_i}{\tau_k}, \quad (16)$$

where FOS is a factor of safety; τ_i is the maximum continuous net torque that can be produced by the motor; τ_k is the maximum required torque for the motor

$$FOS_e = \frac{5.7}{5} = 1.14$$

$$FOS_s = \frac{32.64}{21.7} = 1.50$$

where FOS_e is a factor of safety of the elbow actuation system; FOS_s is a factor of safety of the shoulder actuation system

3.4. Selected Sensors and Control Components

In order to control speed and track position of exoskeleton links Maxon ESCON50/5 controller is used, controller is shown in Fig.27. Maxon ESCON50/5 is a compact yet robust PWM servo controller designed to precisely and efficiently control DC motors. The controller has three operating modes – speed control, which can be a closed loop or open loop and current control, which alters torque. It can be controlled through analog and digital I/O signals, configuration is facilitated through USB with the “ESCON Studio” graphical interface, where required values are set. During current control mode controller compares the motor’s real-time current with the desired setpoint. This is achieved by measuring the motor’s winding current. Any deviation prompts adjustments to the motor's current. Similarly with closed-loop speed control mode actual speed of the motor is compared to the set point and any deviation triggers adjustment to maintain the desired speed. On the contrary, with open loop speed control load variations are adjusted by using the IxR method. In the controller encoder and hall sensor can be connected. The current and speed control can be achieved by integrating the potentiometers.



Fig. 27. Maxon ESCON50/5 controller

DC brushless motors have integrated Hall sensors for position and speed monitoring, however, they are not accurate for position sensing since they detect the presence or absence of a magnetic field. For this purpose, an encoder must be used, an incremental MILE encoder from the “Maxon”

manufacturer is chosen. The MILE encoder provides two channels (A, B) with differential electrical signals by using an inductive angle measurement technique to produce incremental quadrature output signals, these signals are analysed in order to determine the rotation direction of the motor and monitor speed. These encoders are engineered to be durable for industrial environments, they are suitable to work together with EC flat motors having the resilience to magnetic interference, which allows a seamless integration and minimal dimensions adjustment for a motor.

3.5. Control of the Exoskeleton

3.5.1. Electrical Schemes and Control Panel

Speed of rehabilitation exoskeleton joints can be changed by using the control panel shown in Fig.28. User can change the speed values of the motor, as well as control motion direction. Arrows according to the shown direction (up or down) decrease the bending angle or increase. Speed values are changed by using a potentiometer. For safety reasons, an emergency button is installed. Since there are three motors to transfer the required motion, three buttons corresponding to each motor are installed (M1, M2, M3). User can choose which one of the motors to control by pressing the assigned button. After that, a particular LED with specified colour lights up and indicates which motor is activated. At the same time, only one motor can be activated. While performing rehabilitation with one hand, the other hand is used to select necessary parameters in the control panel.

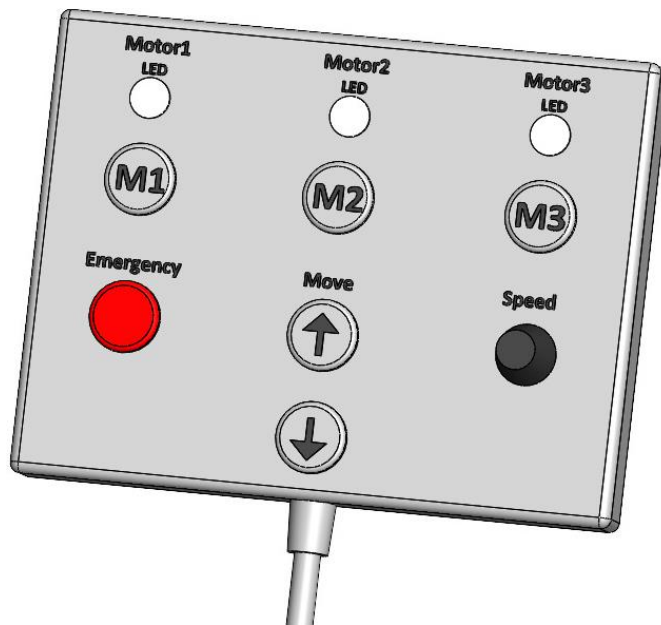


Fig. 28. Control panel

The exoskeleton has three motors and each of the motors must have a controller. Each controller communicates with the PC and accordingly transfers information to the motor. Controller 1 is assigned for elbow flexion/extension, controller 2 for shoulder flexion/extension and controller 3 for shoulder adduction/abduction. Each controller is connected to the specified motor and their sensors – the Hall sensor and encoder. Controller 1 is the main one, which controls the motion as well as the speed of all three motors. The “M1” button activates the motor responsible for elbow flexion/extension and the green LED is lit. Motion buttons “↑”, “↓” and the M1 motor selection button are connected to the digital inputs. LED is connected to the digital output. The speed potentiometer

is connected to the analog input. Controller 2 has connected the emergency button to the digital input as well as the “M2” selection button and the yellow LED is connected to the digital output. Controller 3 has the “M3” selection button connected to the digital input and the blue LED to the digital output. This electrical scheme lets to have a smaller number of buttons/potentiometers and still have control over the three motors. USBs from all three controllers are gathered to USB Hub and put into the PC, schematic is shown in Fig.29.

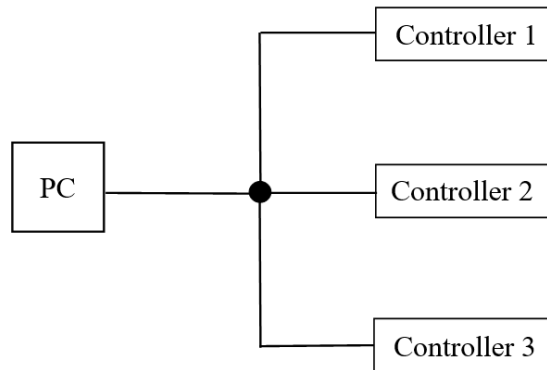


Fig. 29. Controllers' connection to PC

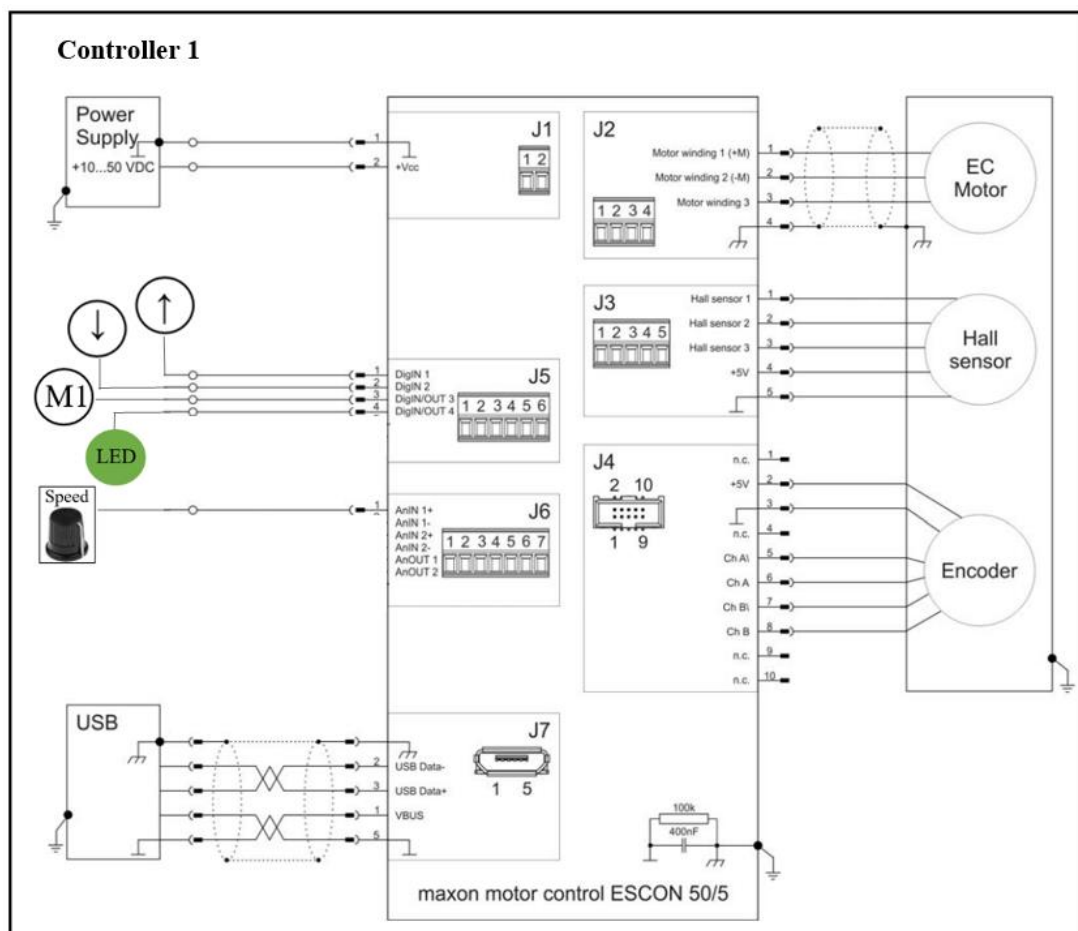


Fig. 30. General electrical scheme of the controller 1

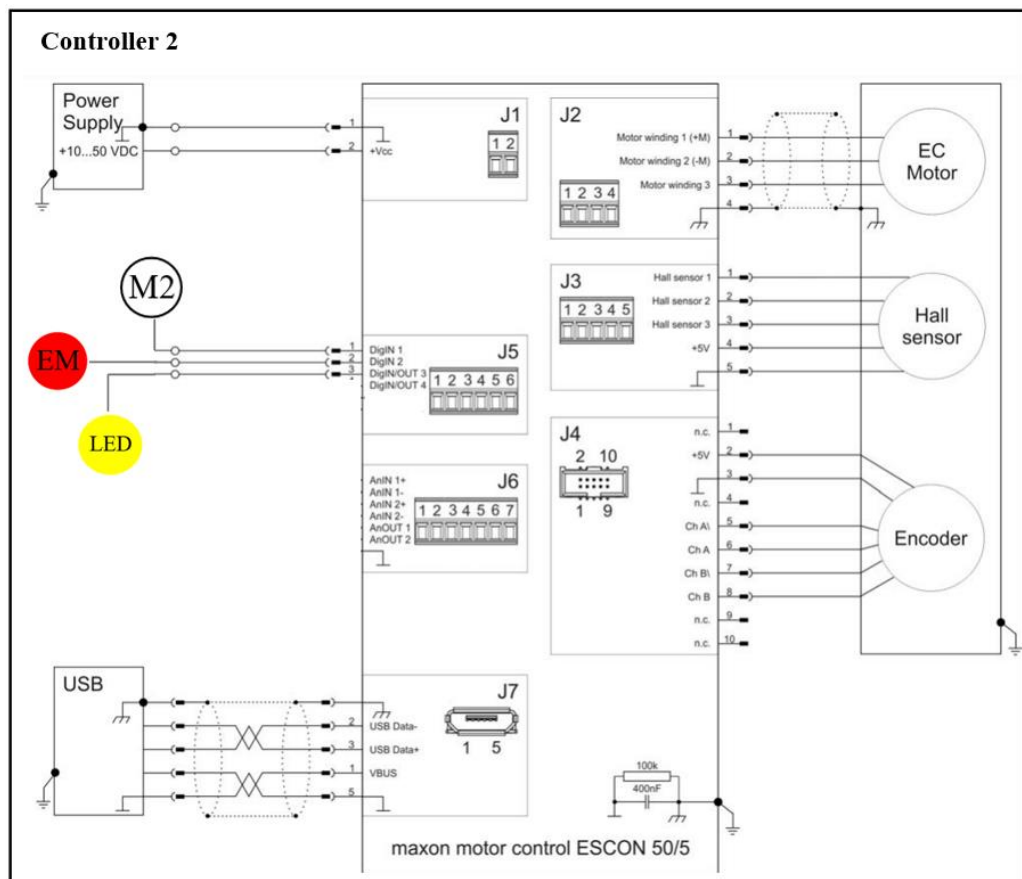


Fig. 31. General electrical scheme of the controller 2

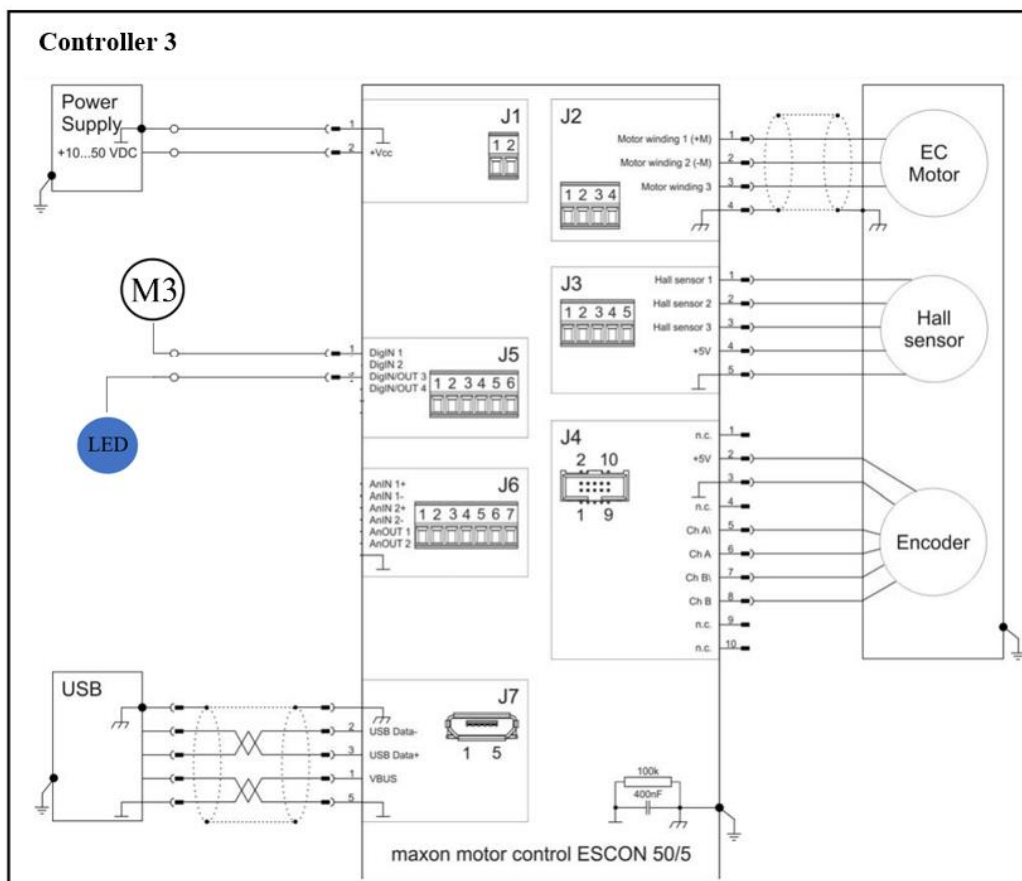


Fig. 32. General electrical scheme of the controller 3

3.5.2. Control Algorithm

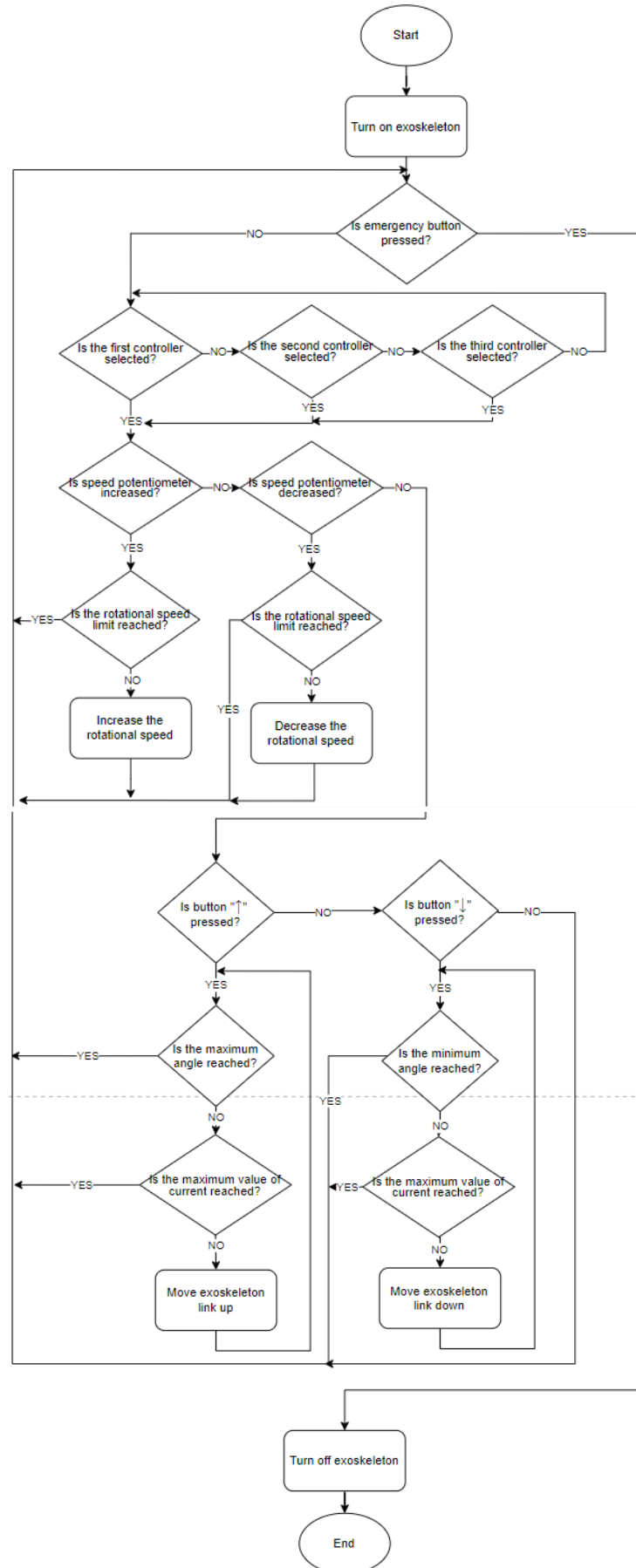


Fig. 33. Control algorithm of upper limb exoskeleton

The control algorithm of the exoskeleton is shown in Fig.33. First of all, the exoskeleton is turned on and after that, the algorithm checks if the emergency button is pressed. If the emergency button is pressed, the exoskeleton is immediately shut down. If it is not – it proceeds to check which motor is selected. After motor selection algorithm checks if the speed value is selected. If the user increases or decreases the values of the speed algorithm checks if the values do not exceed the minimum or maximum allowable values. If it is exceeded, the algorithm repeats till a suitable value is chosen, if not – values are increased or decreased according to the user's input. When the user presses the move button algorithm checks with the encoder and program if the maximum or minimum allowable angle is reached, if yes – the movement is not activated, and if no – it moves according user's input. Worth mentioning that if at any point an emergency button is activated system is immediately shut down.

3.5.3. Control of Motors' Electrical Parameters

For the exoskeleton to operate in a safe speed and torque range voltage and current supplied for the motor need to be assigned carefully. Maximum angular velocity for each joint doing everyday tasks is 90 deg/s or 15 rpm and it should not be exceeded. User with the control panel can assign speed which will be constant at every point of the arm movement. For this voltage and current are altered. In order to show the elbow's motor and shoulder's motors suitability speed-torque dependency of each must be analysed. Appropriate voltage values for elbow and shoulder joint motors are calculated using Eq.16. In order to have safe operation current limitations must be set, for the elbow 0.98 A is the maximum value and for the shoulder – 3.45 A, which corresponds to the maximum required torque, these values are calculated using Eq.17:

$$I = \frac{M_i}{k_m}, \quad (17)$$

where I is current (A); M_i is maximum allowable torque (mNm); k_m is torque constant (mNm/A)

$$I_e = \frac{50}{51} = 0.98 \text{ A}$$

$$I_s = \frac{181}{52.5} = 3.45 \text{ A}$$

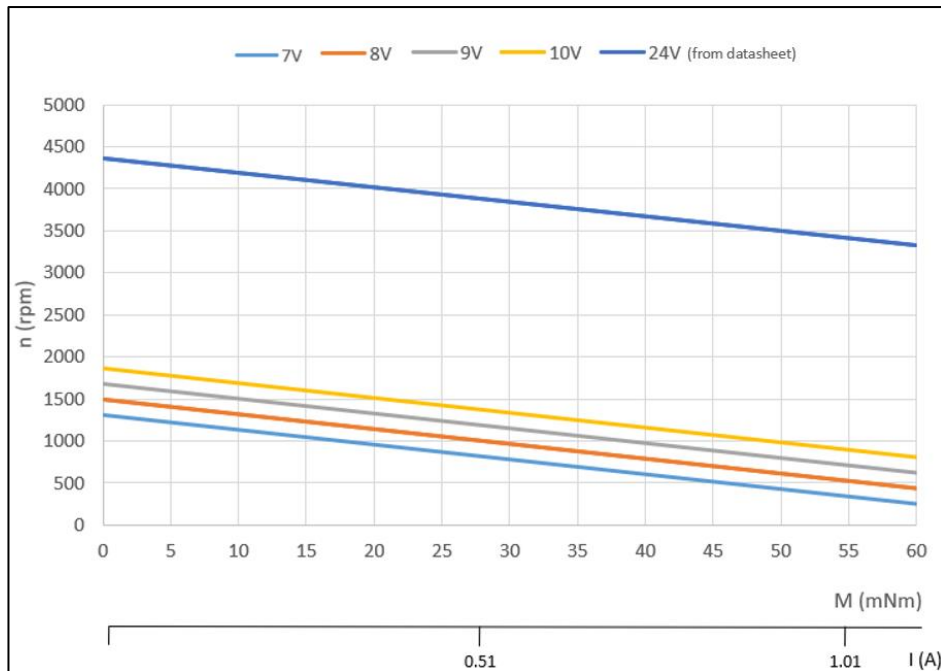


Fig. 34. Elbow's motor speed-torque dependency on the voltage

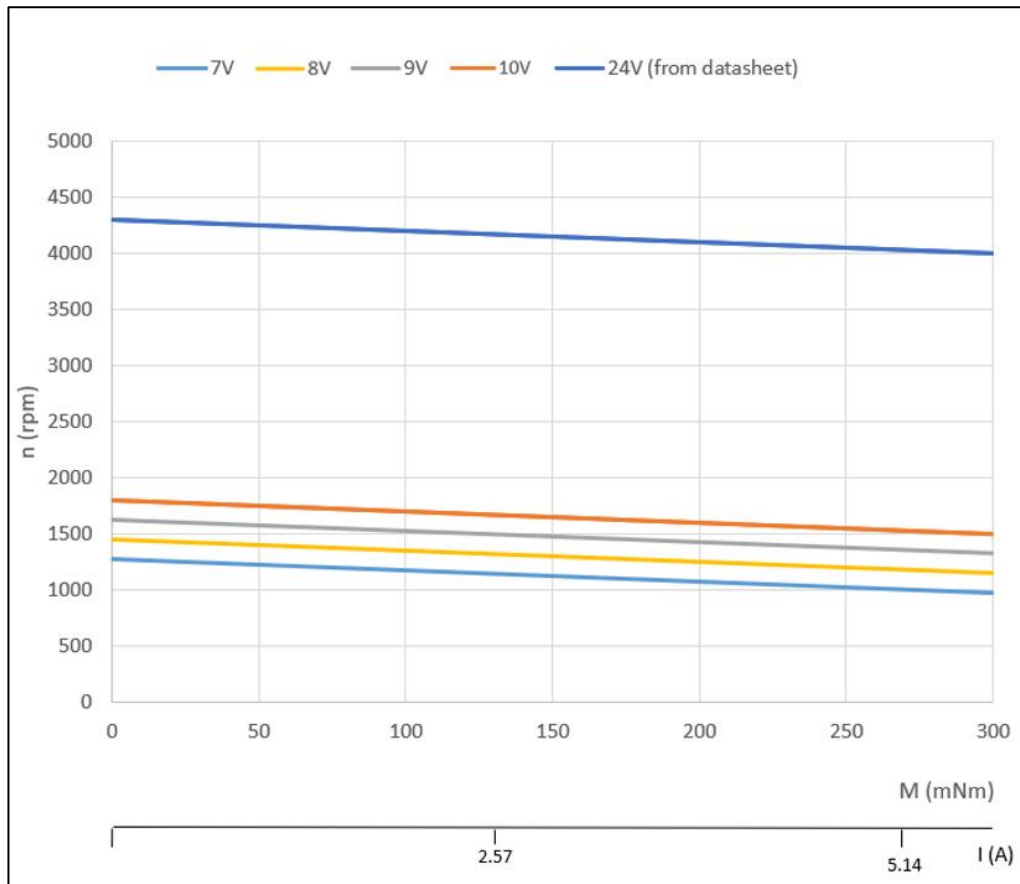


Fig. 35. Shoulder's motor speed-torque dependency on the voltage

Fig.34 and Fig.35 show elbow and shoulder motors' rotational speed dependency on current and voltage. According to the speed-torque dependency maximum torque assistance is obtained when the current is highest. The blue line indicates the nominal operating range, values are taken from motors' datasheets, however, these speed values are too high for limb movements and must be reduced for safe operation. Consequently, other lines represent reduced speed values, which are obtained by reducing the supplied voltage to the motors. The figures show that while having constant speed torque alters depending on the person's ability to lift the arm by himself/herself.

3.6. Exoskeleton's Working Time

For wearable exoskeleton a power supply is necessary, for comfortable usage, a battery will be used. Specifically, lithium-ion type batteries are commonly used in these types of devices due to their ability to deliver extended operating times and store substantial energy within compact packages. Moreover, these batteries are lightweight compared to the alternative types of batteries and offer versatility in various applications. Lithium-ion battery from DNK Power manufacturer will be used which is shown in Fig.36. It has a capacity of 10 Ah at 24 V.

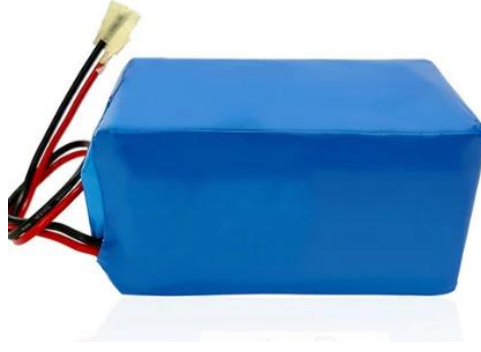


Fig. 36. Li-ion battery “DNK-LTB7S4PC18”

In order to calculate the working time of the battery maximum power of each motor must be calculated as well as controllers using Eq.19. Maximum voltage is obtained by using Eq.8 derivation Eq.18 at the maximum allowed speed which is 15 rpm and maximum torque. The current at the specified torque is taken from Eq.17.

$$U_{mot} = \frac{n_o * i + \frac{\Delta n}{\Delta M} * M}{k_n}, \quad (18)$$

where n_o is maximum allowed speed (rpm); i is gearbox reduction rate; k_n is speed constant (rpm/V); U_{mot} is motor voltage (V); $\frac{\Delta n}{\Delta M}$ is curve gradient (rpm/mNm); M_o is maximum allowable torque (mNm)

Maximum voltage for elbow motor:

$$U_e = \frac{15 * 100 + 17.7 * 50}{187} = 12.75 \text{ V}$$

Maximum voltage for shoulder motor:

$$U_s = \frac{15 * 120 + 1.01 * 181}{182} = 10.89 \text{ V}$$

$$P = U * I, \quad (19)$$

where P is power (W); U is voltage (V); I is current (A)

Maximum power for elbow motor:

$$P_e = U_e * I_e = 12.75 * 0.98 = 12.45 \text{ W}$$

Maximum power for shoulder motor:

$$P_s = U_s * I_s = 10.89 * 3.45 = 37.57 \text{ W}$$

Controllers also consume power, however, it is not significant, according to the Maxon Motors provided information controllers with connected peripherals draw current in the range of 100-200mA. Current consumption of one controller if the battery is 24 V:

$$P_{con} = U_{con} * I_{con} = 24 * 0.2 = 4.8 \text{ W}$$

Fully charged battery working time at maximum conditions is calculated using Eq.20:

$$t = \frac{E}{P} = \frac{Q * V}{P}, \quad (20)$$

where t is time (h); E is energy capacity of the battery (Wh); P is power required for the components (W); Q is charge capacity of the battery (Ah); V is voltage of the battery (V)

$$t = \frac{E}{P} = \frac{Q * V}{P_e + P_s * 2 + P_{con} * 3} = \frac{10 * 24}{12.5 + 37.57 * 2 + 4.8 * 3} = 2.35 \text{ h}$$

Battery working time is approximately 2.35 h, however calculations are based on maximum values. Using the exoskeleton at lower power levels can extend the battery's operating time.

3.7. Design Analysis

Through an examination of human upper limb anatomy and biomechanics, each link was designed to suit safe ranges of motion and anthropometric parameters. Fig.37 a), b), c) shows the elbow and shoulder joints drive mechanisms, the assemblies allow to perform elbow flexion/extension, shoulder flexion/extension, shoulder abduction/adduction. Each BLDC brushless motor is equipped with the “MILE” encoder and Hall sensor and is combined with a Harmonic Drive Unit. This combination achieves a compact design. All the components are fastened with DIN 7984 bolts with varying lengths. Given that patients vary in body size, the length of the forearm and upper arm frame can be adjusted with a spring mechanism for convenient usage. The forearm and upper arm frames consist of two parts that are inserted into each other as shown in Fig.37 d), the forearm frame can be adjusted in the range of 272 mm – 302 mm and has an adjustable length of 30 mm as shown in the image, similarly, the upper arm frame can be adjusted in the range of 245 mm – 275 mm and has an adjustable length of 30 mm. Fig.37 e) show back frame which is designed as a prismatic joint in order to change position when the motion of shoulder abduction/adduction is performed. This design not only ensures the exoskeleton's better alignment with the human body and comfortable motion execution but also makes it suitable for different patients with varying shoulder width. Fig.37 f) shows the shoulder frame which consists of two parts, this is due to the 3D printing process. In order to have the best properties of the part it should be positioned so that the majority of the part's surface area would be in contact with the printer's build platform.

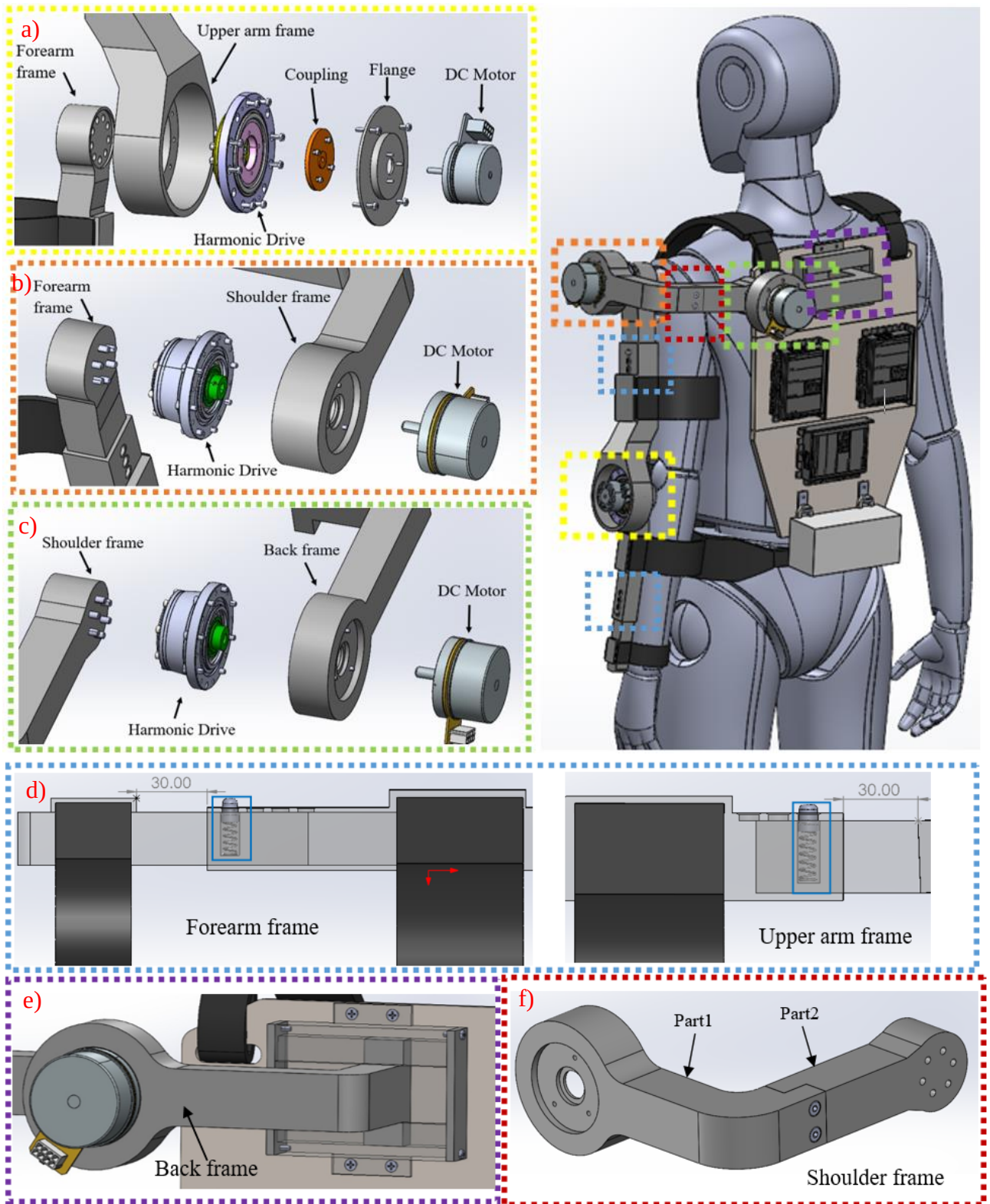


Fig. 37. Upper limb exoskeleton design

In order to have an ergonomic structure, straps are used to fix the exoskeleton to the patient. Two straps are used for the forearm arm and one wider for the upper arm. As well, foam is placed on the surfaces of the exoskeleton frames that are in contact with the human body to provide soft padding for the arm. Furthermore, foam padding helps to not transfer minimal forces that arise from the deformation of frame under the critical conditions. To have a comfortable wearable design,

controllers for each motor and battery are placed on the back, the placement of additional components is shown in Fig.38.

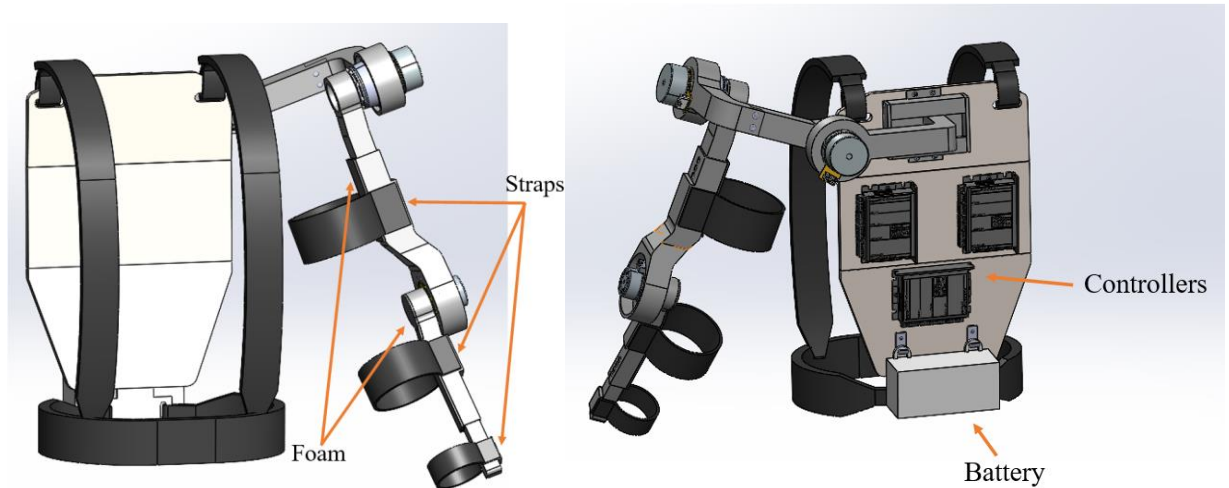


Fig. 38. Upper arm exoskeleton

Due to components exoskeleton cannot reach a normal human's range of motion. Table 8 shows the normal range of motion and the range of motion achieved with an exoskeleton. It is seen that shoulder abduction and adduction are constrained. However, this is common for wearable exoskeletons. Thus, elbow motion and shoulder flexion/extension motion can be carried out normally.

Table 8. Human's range of motion with and without upper limb exoskeleton

	Shoulder flexion/extension	Shoulder abduction/adduction	Elbow flexion/extension
Human ROM range	$[-60^{\circ}; 180^{\circ}]$	$[-20^{\circ}; 180^{\circ}]$	$[0; 140^{\circ}]$
Exoskeleton ROM range	$[-60^{\circ}; 180^{\circ}]$	$[-20^{\circ}; 95^{\circ}]$	$[0; 140^{\circ}]$

Table 9. Mass of the exoskeleton's components

Component	Mass (kg)
Exoskeleton's printed parts	1.352
Motors	0.785
Harmonic Drives	1.05
Controllers	0.612
Battery	~1
Backplate	~1
Other (bolts, foam, straps, spring)	~0.5
SUM:	6.3

The exoskeleton's total mass is approximately 6.3 kg. The weight is appropriate regarding the ability to provide high torque and support 3 degrees of freedom.

3.8. Chapter Summary

Static analysis was performed on the exoskeleton's forearm, upper arm and shoulder frames in order to determine the most suitable material from PLA, ABS, PETG, rPACF and PET CF. The most

important parameter was displacement, since the exoskeleton is connected to the human arm and forces of displacement can affect the human body, thus, rPACF material has been chosen. Parts simulated with rPACF material exhibit the least displacement and have the highest factor of safety, as well have light structure and competitive price. To fulfil high torque requirements harmonic drives and DC brushless motors were used with Hall sensors and encoders. Sensors were incorporated to follow the joints' angles and prevent any deviations. In order to control the exoskeleton's joint motors a control panel was designed. The control panel has a speed potentiometer which lets the user select the appropriate speed while performing training. Also, an emergency button is installed which shuts down the system. The exoskeleton's system weighs about 6.3 kg. According to the studies the load can make up to 10 % of body weight and it does not cause major discomfort to the user, even if the patient has lower muscle tonus. A lithium-ion battery is chosen to supply the exoskeleton's electronics and it can power the exoskeleton's electrical components for 2.4 hours at parameters that demand the highest energy resources.

4. Social and Economical Aspects of Wearable Upper Limb Exoskeleton

4.1. Exoskeleton's Impact on Social Lives

Individuals facing immobility due to strokes, injuries, or other health conditions encounter challenges such as reduced muscle tone and limited movement capabilities in their upper limbs. This can significantly impact their independence in daily activities, for example, a person can lose the ability to fulfil essential self-care activities. The consequences of immobility not only impose physical limitations but also affect psychology [2]. As an example, untreated health issues impact the ability to execute essential job functions, which leads to job loss, difficulty finding employment, contributing to financial strain and a sense of insecurity. Moreover, individuals experiencing immobility may also struggle with feelings of being a burden on their families or to their caregivers. In such cases, it is crucial to ensure optimal rehabilitation treatment for patients in order to return to normal active life. Conventional therapy is important, however, by combining therapy with robotic devices outcomes can be improved and healing achieved faster. Device portability and accessibility contribute to these positive impacts. For example, the portability of an exoskeleton enables to use it beyond medical institutions, providing flexibility and accessibility in various settings. This is beneficial if a patient needs to continue therapy at home since exoskeletons can be controlled via computer interfaces, enabling health specialists to customize therapy sessions remotely. This training method is convenient for both health staff and a patient, it saves time and energy since there is no need to travel to a hospital. Also, a person can train with the exoskeleton individually as well the caregiver can help with its control. This increases the likelihood of sticking to the program over a long time and performing exercises more frequently. This as a consequence helps to achieve better rehabilitation results. Wearable rehabilitation exoskeletons not only assist patients when performing exercises but also support therapists or caregivers since they perform exercises on patients manually. By ensuring the repeatability of exercises and ease of control, the physical burden can be relieved for health staff workers [61]. Moreover, the exoskeleton not only provides rehabilitation benefits but also can help in daily life activities that require lifting and transferring some light weight by supporting the arm's weight. Consequently, the exoskeleton gives some degree of independence.

4.2. Environmental Impact

3D printing technology holds promise in reducing environmental impact in manufacturing and extending sustainability potential across the entire product life cycle. 3D printing technology contrary to other conventional manufacturing processes provides the capability to produce various types of shapes and geometry of an exoskeleton while minimizing the waste of a material. 3D printing generates little waste during production, the waste is produced by the support structures which can be recycled or reused, on the contrary, conventional production methods involve subtractive processes to produce the part from raw material [50]. Moreover, it can reduce manufacturing energy and cut down CO₂ emissions by shortening the manufacturing processes, also it can decrease emissions linked with transportation since it enables on-site production [50].

Another issue is excessive plastic consumption. Plastic wastage remains one of the most significant environmental concerns. Annually, between 19 and 23 million tons of plastic waste infiltrate into the environment, contaminating rivers, oceans, lakes and landfills [62]. Furthermore, some plastics can take thousands of years to degrade [62]. Plastic is the most popular material employed in 3D printing technology. However, embracing sustainable 3D printing methods, such as recycling failed prints and

excess filament, as well as using recycled materials offers a promising solution for mitigating environmental harm. Regarding pollution issues, plastic wastage problems, recycled filament is chosen to produce the frame parts for the exoskeleton. Scientists are exploring different approaches to make 3D printing more sustainable and tackle the plastic waste problem. One of the ways is to use polymers such as nylon as a base material and reinforce it with fibers. This approach proved to be effective in enhancing mechanical characteristics while having a lightweight structure [63]. Consequently, the part's durability is higher leading to longer lasting product usage which directly contributes to the overall resource consumption. Additionally, the lightweight nature of carbon fiber reduces the weight of the final product, potentially leading to lower energy consumption during use. Furthermore, explorations into employing regenerated nylon-6 as an environmentally friendly material for FDM 3D printing filaments present a viable solution for managing waste [63]. It is also important to use materials that can be recycled and reused. However, recovering composite materials like carbon fiber reinforced plastics is a challenge due to their complex composition [64]. In the [64] paper this challenge has been addressed and a composite of polyamide 6 with carbon fiber was recycled using solvents. After the process, it was revealed that it is feasible to effectively remove the polymer from the fibers with minimal impact on the mechanical properties of the fibers. Recycling parts/products is an important step to decelerate the depletion of natural resources and support the circular economy model, particularly through multiple polymerization-depolymerization cycles [65].

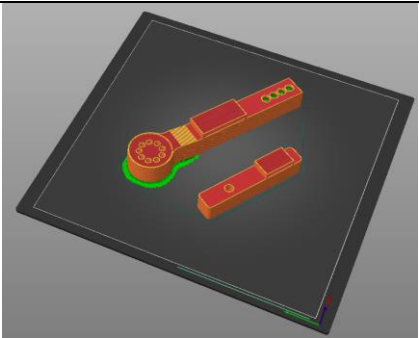
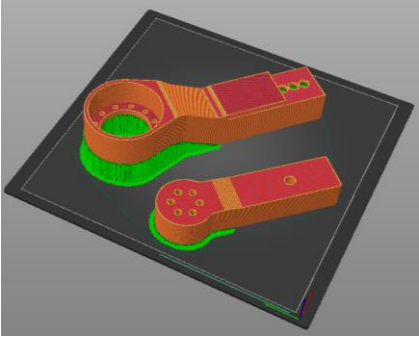
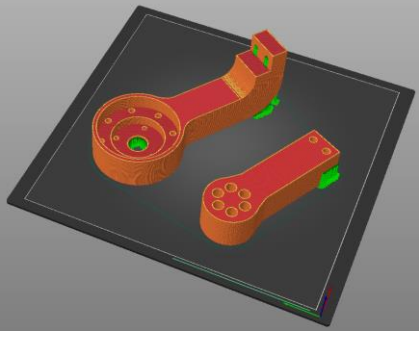
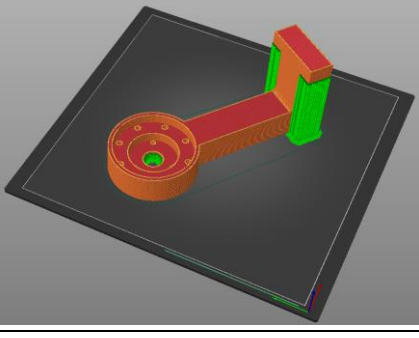
For the exoskeleton's frame manufacture a filament from Reflow company is used. Reflow managed to create composite filament with recycled polyamide 6 (rPA6) and carbon technical fibers from post-industrial recycling (PIR). 98% of the filament composition is recycled. Recycled nylon is sourced from post-industrial sources such as fishing nets and post-consumer sources being carpets or sofas. Worth mentioning that this material has been certified by third parties. Additionally, material properties are improved by introducing post-industrial recycled carbon fiber. Fibers are reclaimed from production leftovers or parts that were intended to be used in the aerospace industry. This rPACF material is created for engineering purposes, to create tough parts while keeping a lightweight structure. Manufacture claims that this recycled composite can replace virgin nylon without compromising performance while significantly reducing greenhouse gas emissions and tackling the plastic pollution problem.

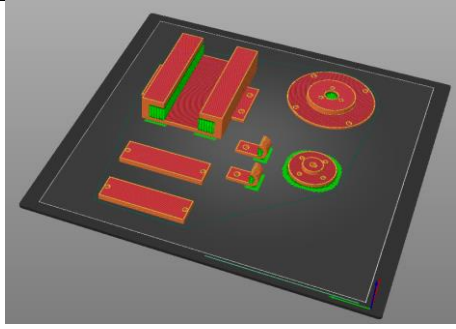
4.3. Economical Aspect of the Exoskeleton

Customization is an essential aspect of exoskeleton development. It must be tailored to specific requirements and adapt to the unique anatomical characteristics of individuals in order not to constrain or have adverse effects on physiology [66]. This approach is beneficial from the economical point of view since the same exoskeleton can be used for a range of people. Important to note that 3D printing technology's application is suitable for customized parts in small batches at a cost-effective rate. Compared to other types of manufacturing processes such as injection moulding, extrusion, 3D printing can produce parts without expensive tooling or moulds. Patients can even print the required parts at home or at the local town place where a 3D printer is available. Also, it allows to replace some parts due to anatomical changes in the body at the minimum cost. Another important aspect is the 3D printing material's ability to provide the required support while reducing the mass of the device. Within the clinical setting, rehabilitation devices are usually produced from heavy metals or similar materials, which increases the bulkiness and mass and is constrained by unwieldy dimensions. These aspects pose challenges in transportation as well as elevate the cost of the whole system [66].

To determine the prime price of the exoskeleton more accurately exact material consumption including supports needs to be obtained. For this purpose, the slicing program PrusaSlicer 2.7.0 is used. Infill for all parts is selected 100%, fill pattern is rectilinear, these parameters are chosen in order to have strong, sturdy parts and mimic simulation conditions. The forearm, upper arm, shoulder and back frame are printed using rPACF material and additional parts are printed from PLA material since they do not require superior mechanical properties, consequently, the price of the exoskeleton decreases. All information is shown in Table 10.

Table 10. Filament usage and estimated printing time for each exoskeleton part

Exoskeleton parts		Sliced info
Forearm frame		Sliced Info Used Filament (g) 160.78 Used Filament (m) 58.63 Used Filament (mm ³) 141032.33 Cost 15.60 Estimated printing time: - normal mode 14h37m
Upper arm frame		Sliced Info Used Filament (g) 552.08 Used Filament (m) 201.34 Used Filament (mm ³) 484280.35 Cost 53.55 Estimated printing time: - normal mode 2d0h55m
Shoulder frame		Sliced Info Used Filament (g) 534.17 Used Filament (m) 194.81 Used Filament (mm ³) 468572.31 Cost 51.81 Estimated printing time: - normal mode 1d19h12m
Back frame		Sliced Info Used Filament (g) 362.24 Used Filament (m) 132.11 Used Filament (mm ³) 317752.78 Cost 35.14 Estimated printing time: - normal mode 1d4h58m

Additional parts		Sliced Info Used Filament (g) 174.98 Used Filament (m) 58.67 Used Filament (mm ³) 141111.83 Cost 4.37 Estimated printing time: - normal mode 14h49m
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Analysis has shown that to produce exoskeleton's printable parts will need 1.79 kg of plastic and this would cost 160.76 Eur. Moreover, the energy also needs to be taken into account when producing part. Below is calculated the prime cost of the exoskeleton.

Parts production cost = Material consumption cost (Eur) + Printing time (h) * Power consumption (kW) * Price of 1 kWh

Power consumption value is taken after the analysis of popular printers which is approximately 350W. The price of 1 kWh is taken from the Lithuanian electricity supplier.

Parts production cost = 160.47 + 246.5*0.350*0.23 = 180.31 ≈ 180 Eur

The prices of all exoskeleton components are shown in Table 11.

Table 11. Price of exoskeleton components

Component	Price (Eur)
Exoskeleton's printed parts	180
Motors [67]	408
Harmonic Drives [69]	~1500
Controllers [67]	852
Battery [69]	~40
Backplate	~100
Other (bolts, foam, straps, spring)	50
Sum:	3130

Prices for the battery, harmonic drive and backplate are approximate because manufacturers do not provide information about the prices. Nevertheless, after performing an analysis of the market approximate prices are obtained. As can be seen from the table electronic products are the most expensive, particularly Harmonic drives. It is known that in order to have compact and high torque actuation system costs are elevated, which is associated with high expenses on harmonic drives [68]. However, harmonic drives can be purchased from different manufacturers/suppliers to receive the best offer. This proposed exoskeleton costs about 3130 Eur. For comparison, the typical cost of a fully equipped upper limb exoskeleton that has five or six active joints is approximately 121 000 Eur [68]. The price is way higher and restricts the accessibility of exoskeletons for therapeutic purposes.

4.4. Chapter Summary

Individuals who suffer from upper limb immobility encounter difficulties in everyday life that influence their independence while performing various activities as well as has a negative impact on their mental health. It is necessary to provide effective rehabilitation for the patients and help them to be an active participant in society. The upper limb exoskeleton can improve rehabilitation outcomes by providing accessibility to training outside the medical facilities. This flexibility enables therapy continuation at home, customized remotely via computer interfaces, saving time and energy for both patients and healthcare providers. Exoskeletons not only aid in exercises but also support daily activities, providing a degree of independence.

In terms of environmental impact, 3D printing technology minimizes waste compared to conventional methods, reducing manufacturing energy and CO₂ emissions. However, plastic waste remains a concern, regarding this problem, an eco-friendly filament from recycled carbon fiber and nylon-6 was chosen to produce the exoskeleton's frame. Cost-effective customization is made possible by 3D printing, which is essential for customized exoskeletons. After the analysis exoskeleton's printed parts cost 180 Eur. However, the whole exoskeleton's price is approximately 3130 Eur. The sum is elevated by the pricy harmonic drive components as well as controllers. However, this is a medical device that needs to be controlled with maximum safety and requires high torque reduction of the motor while aiming to have a light and compact design.

Conclusions

1. The exoskeleton's frame consists of a forearm frame, upper arm frame, shoulder frame and back frame. The forearm and upper arm frames consist of two parts in order to adjust the length, adjustment range is 30 mm according to analysed anthropometric parameters. To ensure ergonomics straps are employed to securely attach the exoskeleton to the patient's arm. Additionally, foam is placed on the surfaces of the exoskeleton frames that come into contact with the human body, this provides soft padding for the arms. Moreover, it helps to minimize the transmission of minimal forces resulting from frame deformations.
2. Production type of the exoskeleton's frame is selected to be 3D printing technology and specifically FDM process. Five filaments were analysed of which three are plastic materials and two are composites. After static analysis performed by SolidWorks software results were obtained which showed that parts simulated with composite materials had better mechanical properties than parts simulated with plastic materials. The best results were obtained by using a composite from recycled polyamide 6 (rPA6) and carbon technical fibers (rPACF). Parts simulated with this material had the highest displacement of 0.928 mm; minimum factor of safety – 9.19; highest Von Mises stress of 13.821 MPa, those values show that parts are strong, durable and safe. Moreover, it was the second lightest material and the price was not significantly higher than conventional plastics. Overall, this material has an optimal dependency on mechanical properties, lightness and price.
3. To ensure the device functions safely, a consistent motor speed must be maintained. Changes in external load and environmental conditions cause fluctuations in the motor's torque, thus the user can only adjust the speed input, maximum value is limited to 15 rpm. For the system not to exceed torque and not to hurt the user current limitations are established, for the elbow's motor - 0.98 A and for the shoulder's motors – 3.45 A. To have safe ranges of motion, sensors are implemented, which track position and do not let to exceed defined position values. The control panel is provided to the user to not only control speed but also movement direction. One motor can be used at a time for safe movement execution.
4. The actuation system consists of a BLDC motor equipped with an incremental encoder and a Hall sensor. To produce high torque and have suitable speed Harmonic Drive Units are employed. The rated torque of the elbow's actuation system is 5.7 Nm, while the shoulder's is 32.64 Nm. The lithium-ion battery is selected as a power supply. The battery provides about 2.4 h of working time at the maximum power.
5. The upper limb exoskeleton will have a positive impact on the patient's life by providing effective rehabilitation treatment for better and faster outcomes. FDM 3D printing technology selected for exoskeleton frame production is beneficial for small batches and customized parts at a cost-effective rate. Parts can be produced without expensive tools or moulds, also, parts can be easily reprinted and changed. The exoskeleton's price is approximately 3130 Eur. To print exoskeleton frames a recycled composite material made from nylon and carbon fiber was selected. 98% of the filament composition is recycled, this material is selected to help reduce greenhouse gas emissions and tackle the plastic pollution problem.

Recommendations

1. The exoskeleton's control system could be supplemented with an inertial measurement unit, since with the current design user can accidentally supply too much force and turn the motor's shaft resulting in the exact position of the arm being lost.
2. For more intuitive and less complicated control, electromyography signals can be used to analyse the user's intentions to lift a limb.
3. To minimize the dimensions and mass of the exoskeleton, different materials, such as aluminium alloys, could be analysed.

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Appendices

Appendix 1. Mechanical Properties of PLA Material From “Ultimaker”

All samples were 3D printed. See ‘Notes’ section for details.

	Test method	Typical value		
		XY (Flat)	YZ (Side)	Z (Up)
Tensile (Young's) modulus	ASTM D3039 (1 mm / min)	3250 ± 119 MPa	3292 ± 101 MPa	3071 ± 181 MPa
Tensile stress at yield	ASTM D3039 (5 mm / min)	52.5 ± 0.9 MPa	59.0 ± 0.7 MPa	No yield
Tensile stress at break	ASTM D3039 (5 mm / min)	45.5 ± 1.1 Mpa	56.0 ± 1.5 MPa	33.1 ± 2.8 MPa
Elongation at yield	ASTM D3039 (5 mm / min)	3.4 ± 0.0%	3.4 ± 0.1%	No yield
Elongation at break	ASTM D3039 (5 mm / min)	7.8 ± 1.2%	4.2 ± 0.7%	2.0 ± 0.2%
Flexural modulus	ISO 178 (1 mm / min)	3019 ± 87 MPa	2894 ± 53 MPa	2740 ± 47 MPa
Flexural strength	ISO 178 (5 mm / min)	96.8 MPa at 2.5% strain	101.3 MPa at 1.1% strain	52.0 MPa at 4.4% strain
Flexural strain at break	ISO 178 (5 mm / min)	4.8 ± 0.2%	No break (>10%)	1.9 ± 0.2%
Charpy impact strength (at 23 °C)	ISO 179-1 / 1eB (notched)	3.9 ± 0.4 kJ/m ²	–	–
Hardness	ISO 7619-1 (Durometer, Shore D)	84 Shore D	–	–

Appendix 2. Mechanical Properties of ABS Material “Ultimaker”

All samples were 3D printed. See ‘Notes’ section for details.

	Test method	Typical value		
		XY (Flat)	YZ (Side)	Z (Up)
Tensile (Young's) modulus	ASTM D3039 (1 mm / min)	1962 ± 31 MPa	1931 ± 68 MPa	1699 ± 113 MPa
Tensile stress at yield	ASTM D3039 (5 mm / min)	38.1 ± 0.3 MPa	38.2 ± 0.4 MPa	No yield
Tensile stress at break	ASTM D3039 (5 mm / min)	33.9 ± 1.5 MPa	35.7 ± 1.0 MPa	19.0 ± 0.6 MPa
Elongation at yield	ASTM D3039 (5 mm / min)	4.1 ± 0.1%	4.1 ± 0.1%	No yield
Elongation at break	ASTM D3039 (5 mm / min)	4.6 ± 0.3%	4.5 ± 0.2%	2.0 ± 0.1%
Flexural modulus	ISO 178 (1 mm / min)	1430 ± 83 MPa	1470 ± 48 MPa	1317 ± 28 MPa
Flexural strength	ISO 178 (5 mm / min)	61.1 ± 3.2 MPa at 5.1% strain	60.2 ± 0.6 MPa at 5.3% strain	21.5 ± 1.8 MPa at 1.5% strain
Flexural strain at break	ISO 178 (5 mm / min)	No break (>10%)	No break (>10%)	1.5 ± 0.1%
Charpy impact strength (at 23 °C)	ISO 179-1 / 1eB (notched)	14.2 ± 1.2 kJ/m ² (Hinge) –	–	–
Hardness	ISO 7619-1 (Durometer, Shore D)	76 Shore D	–	–

Appendix 3. Mechanical Properties of PETG Material “Ultimaker”

All samples were 3D printed. See ‘Notes’ section for details.

	Test method	Typical value		
		XY (Flat)	YZ (Side)	Z (Up)
Tensile (Young's) modulus	ASTM D3039 (1 mm / min)	1939 ± 28 MPa	1874 ± 31 MPa	1711 ± 45 MPa
Tensile stress at yield	ASTM D3039 (5 mm / min)	46.2 ± 0.8 MPa	50.3 ± 1.0 MPa	–
Tensile stress at break	ASTM D3039 (5 mm / min)	38.5 ± 1.4 MPa	44.0 ± 3.7 MPa	19.0 ± 6.4 MPa
Elongation at yield	ASTM D3039 (5 mm / min)	5.9 ± 0.1%	6.0 ± 0.2%	–
Elongation at break	ASTM D3039 (5 mm / min)	7.6 ± 0.2%	6.4 ± 0.6%	1.8 ± 0.8%
Flexural modulus	ISO 178 (1 mm / min)	1882 ± 30 MPa	1681 ± 61 MPa	1489 ± 25 MPa
Flexural strength	ISO 178 (5 mm / min)	78.9 ± 1.0 MPa at 5.5% strain	75.8 ± 2.0 MPa at 5.5% strain	50 ± 3.5 MPa at 3.6% strain
Flexural strain at break	ISO 178 (5 mm / min)	No break (>10%)	No break (>10%)	3.6 ± 0.4%
Charpy impact strength (at 23 °C)	ISO 179-1 / 1eB (notched)	7.9 ± 0.6 kJ/m ²	–	–
Hardness	ISO 7619-1 (Durometer, Shore D)	76 Shore D	–	–

Appendix 4. Mechanical Properties of rPACF Material from “Reflow”

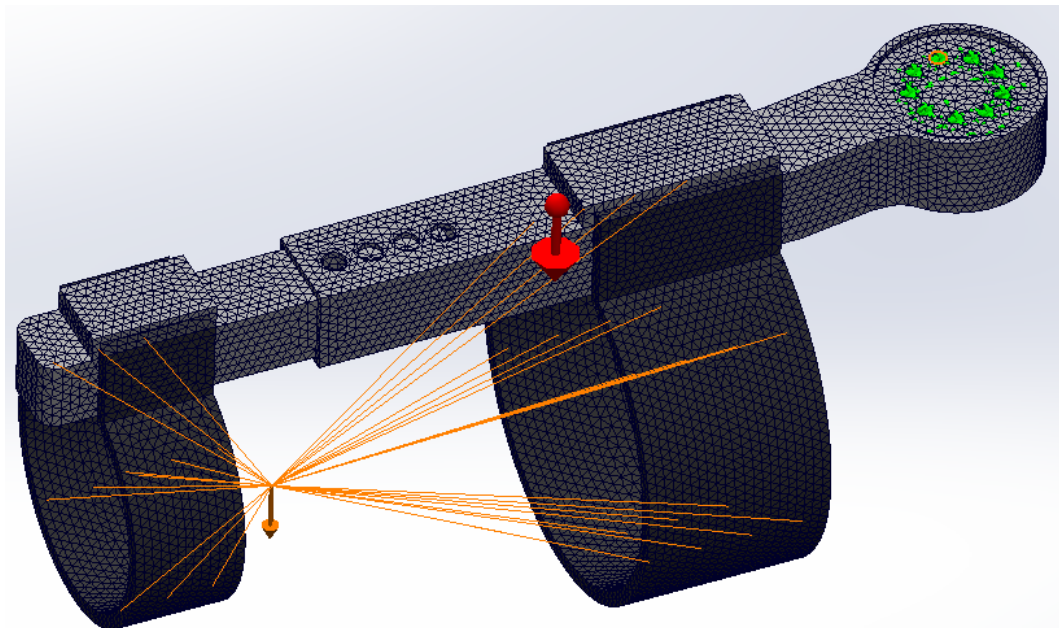
	unit	value	method
Tensile modulus	MPa	8838 ± 244	ISO 527 (10mm/min)
Tensile strength	MPa	127 ± 4.8	ISO 527 (10mm/min)
Tensile stress at break	MPa	127 ± 4.8	ISO 527 (10mm/min)
Tensile strain at break	%	7.7 ± 0.36	ISO 527 (10mm/min)
Flexural modulus	MPa	6600 ± 409	ISO 178 (10mm/min)
Flexural strength	MPa	165 ± 6.4	ISO 178 (10mm/min)
Flexural strength at break	MPa	165 ± 6.4	ISO 178 (10mm/min)
Flexural strain at break	%	3.2 ± 0.1	ISO 178 (10mm/min)
Compression strength	PSI	24311.7 +/- 1099.1	ISO 604 (10mm/min)
Charpy impact strength (at 20°C - unnotched)	kJ/m2	23.8	ISO 179

Appendix 5. Mechanical Properties of PET CF Material from “ Ultimaker”

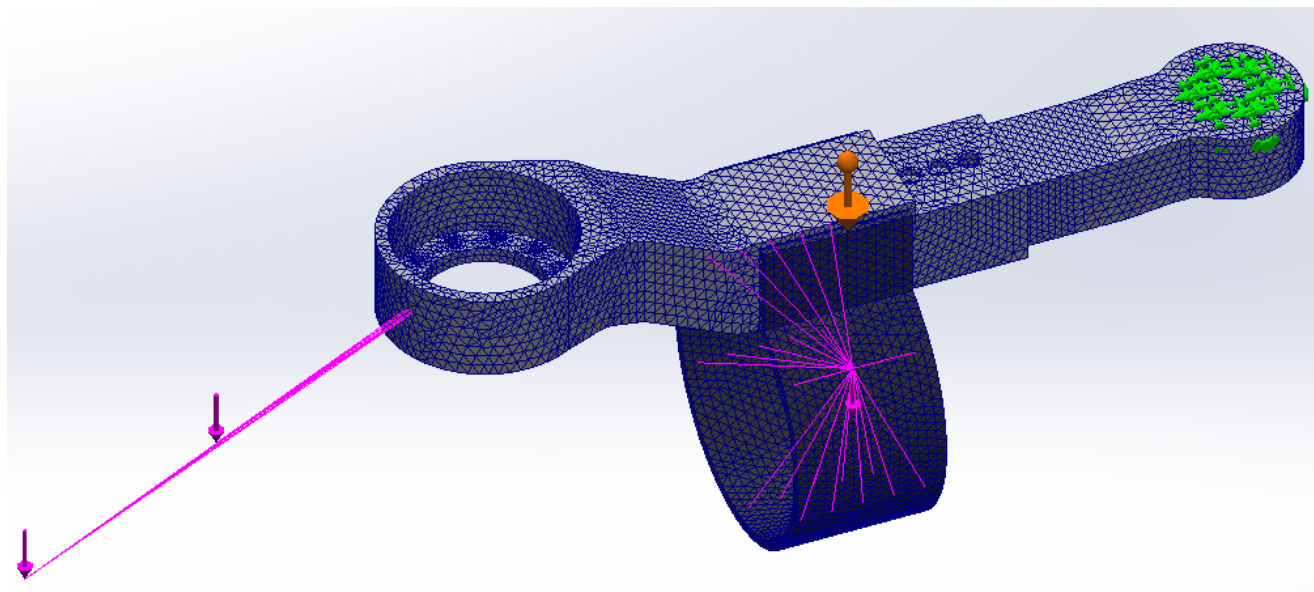
All samples were 3D printed, see notes section.

	Test Method	Typical value XY (flat)	Typical value YZ (side)	Typical value Z (up)
Tensile (Young's) modulus	ASTM D3039 (1 mm / min)	4342 ± 89 MPa	8568 ± 130 MPa	2420 ± 120 MPa
Tensile stress at yield	ASTM D3039 (5 mm / min)	50.6 ± 0.6 MPa	75.2 ± 0.8 MPa	-
Tensile stress at break	ASTM D3039 (5 mm / min)	49.3 ± 0.6 MPa	72.3 ± 1.0 MPa	26.3 ± 1.4 MPa
Elongation at yield	ASTM D3039 (5 mm / min)	3.9 ± 0.1%	3.5 ± 0.1%	-
Elongation at break	ASTM D3039 (5 mm / min)	5.5 ± 0.6%	5.9 ± 1.3%	1.9 ± 0.1%
Flexural modulus	ISO 178 (1 mm / min)	5743 ± 150 MPa	7667 ± 90 MPa	2675 ± 33 MPa
Flexural strength	ISO 178 (5 mm / min)	102.8 ± 2.6 MPa at 4.4% strain	122.3 ± 2.2 MPa at 4.0% strain	41.9 ± 3.2 MPa at 1.5% strain
Flexural strain at break	ISO 178 (5 mm / min)	No break (>10%)	No break (> 10%)	1.5 ± 0.1%
Charpy impact strength (at 23 °C)	ISO 179-1 / 1eB (notched)	8.6 ± 0.5 kJ/m²		
Hardness	ISO 7619-1 (Durometer, Shore D)	76 Shore D		

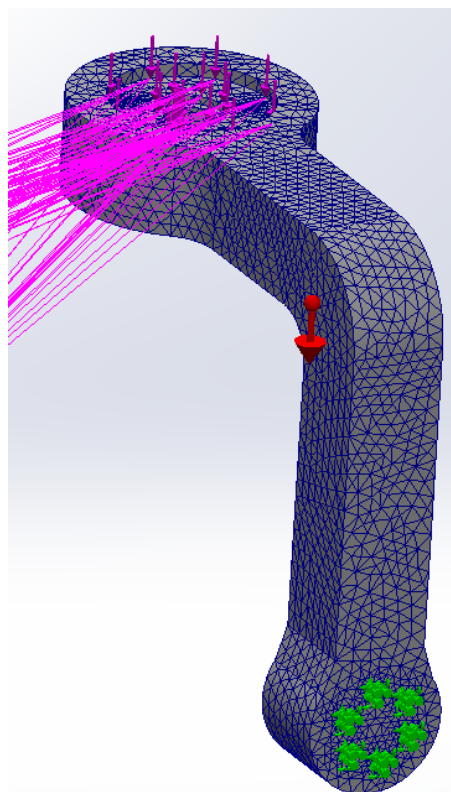
Appendix 6. Finite Element Mesh of Forearm Frame



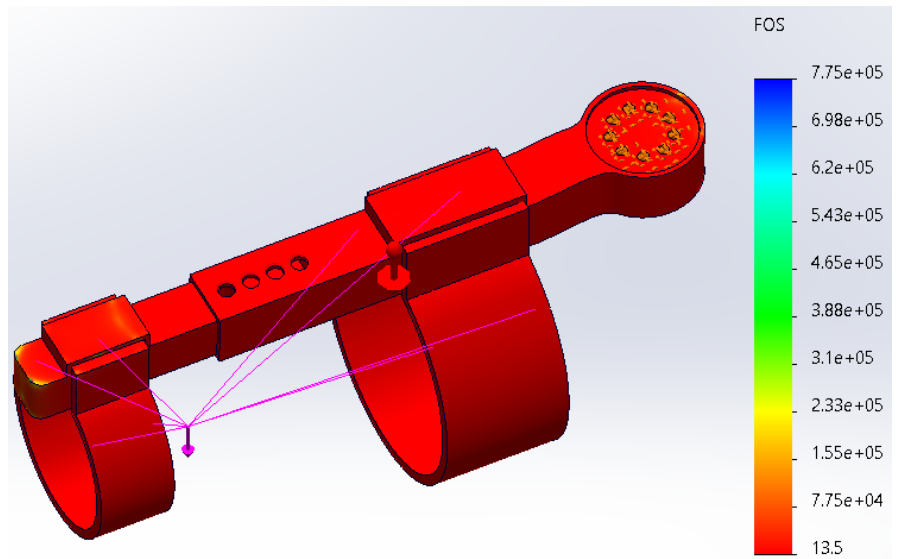
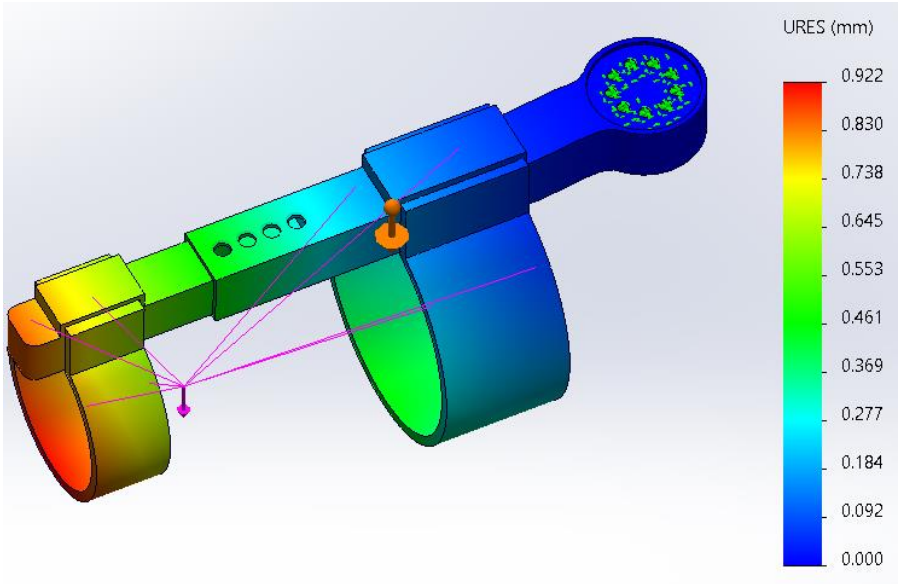
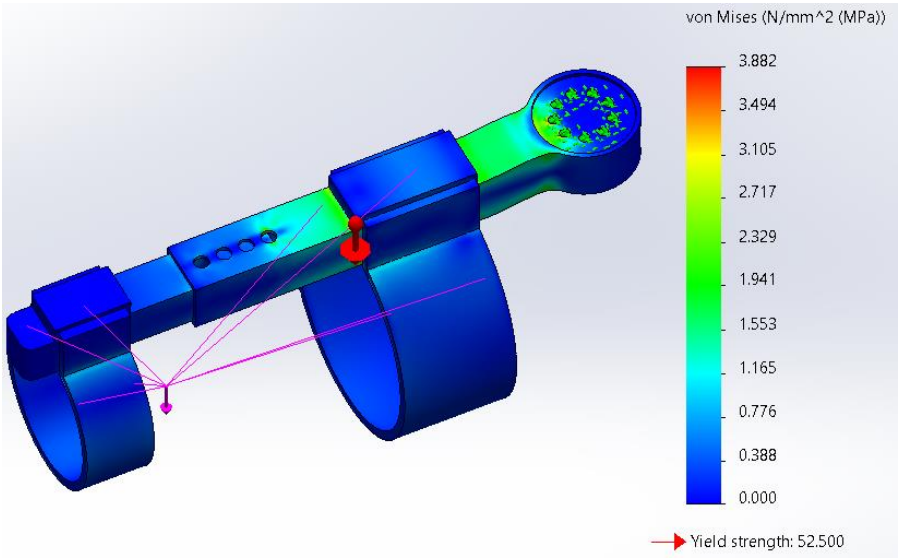
Appendix 7. Finite Element Mesh of Upper Arm Frame



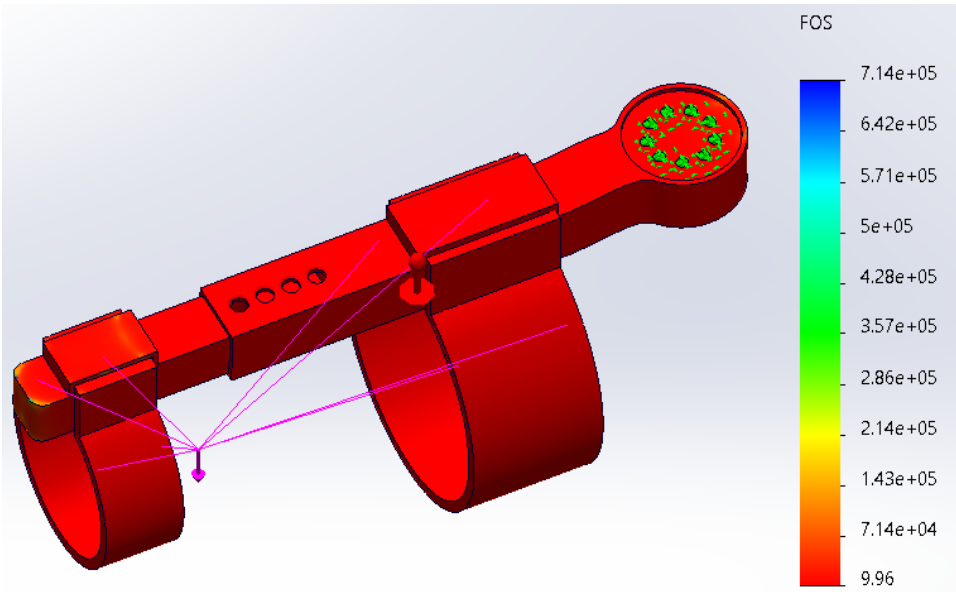
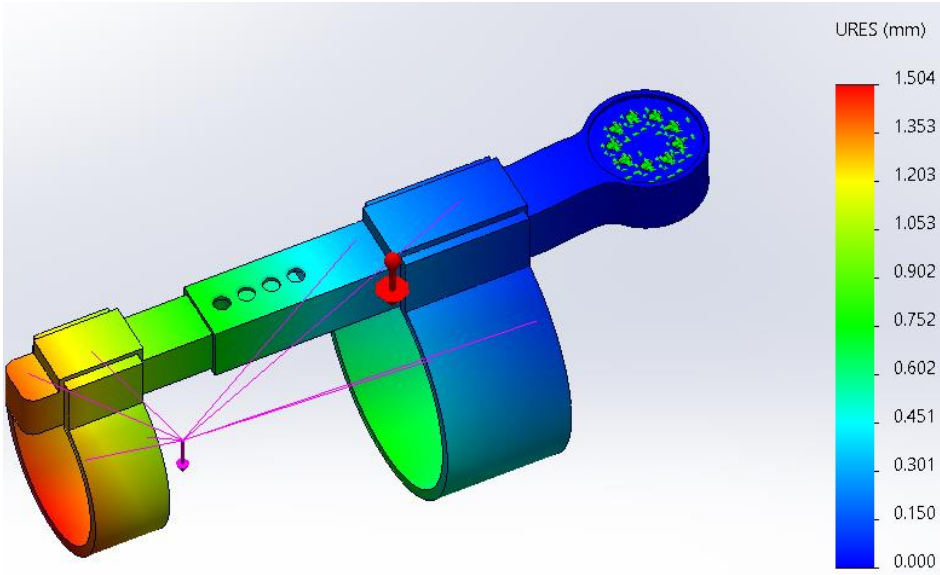
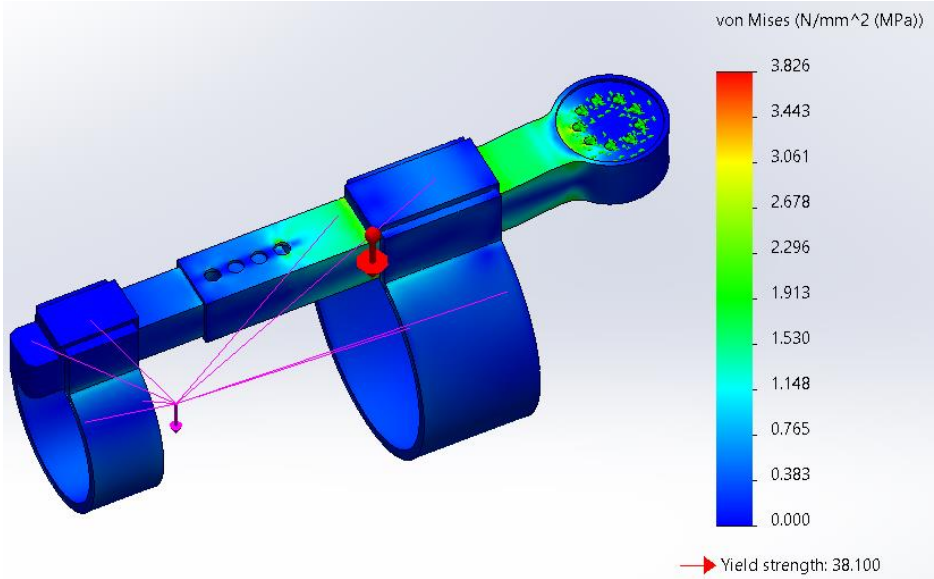
Appendix 8. Finite Element Mesh of Shoulder Frame



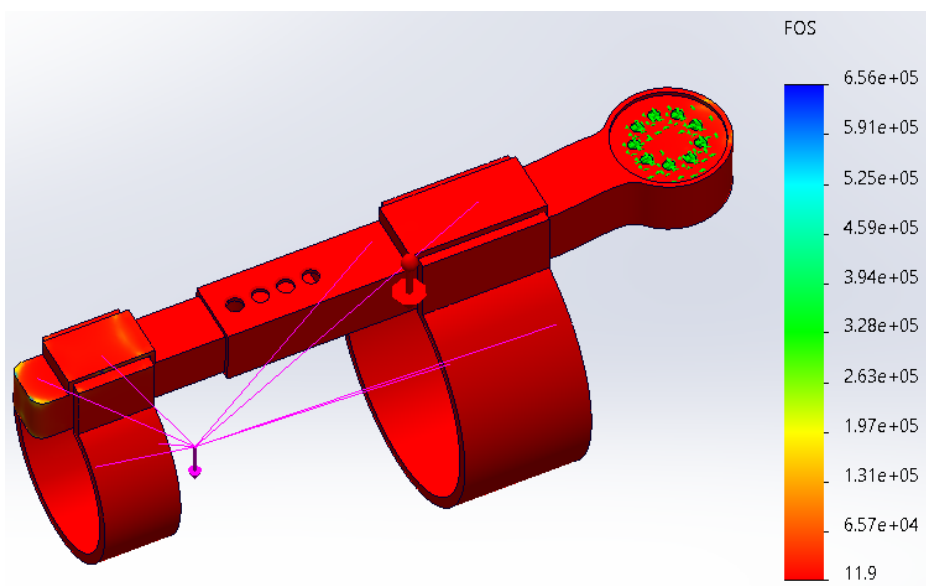
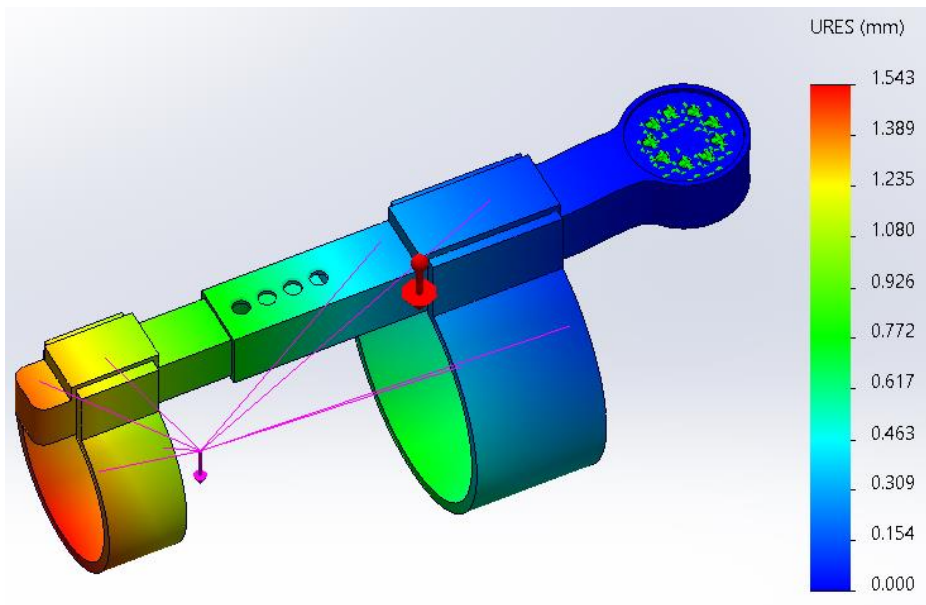
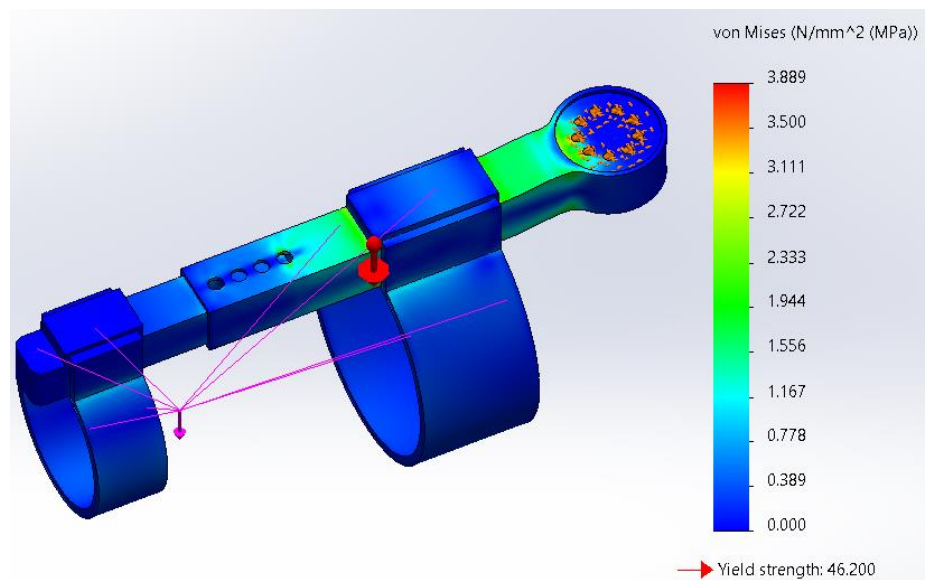
Appendix 9. Static Simulations of Forearm Frame with PLA Material



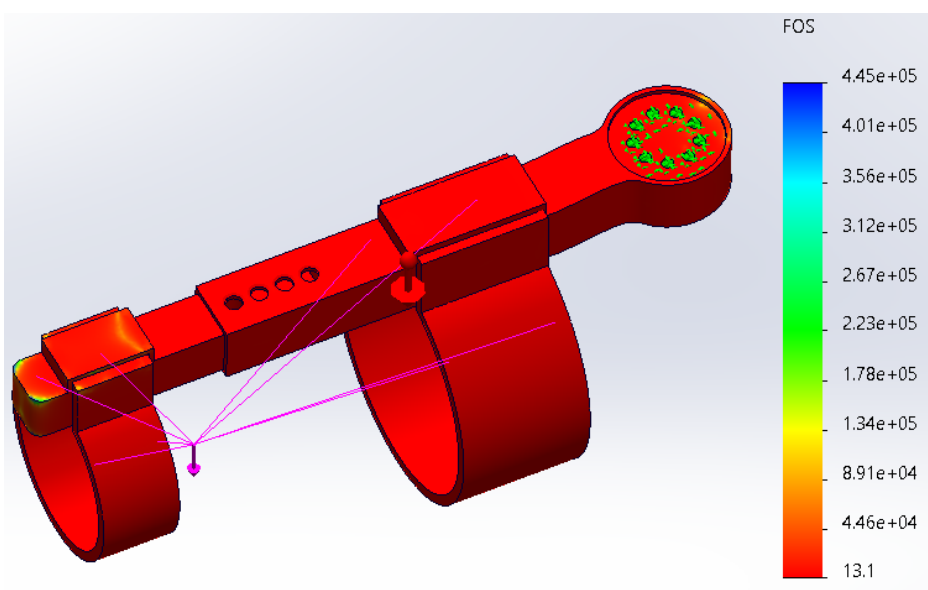
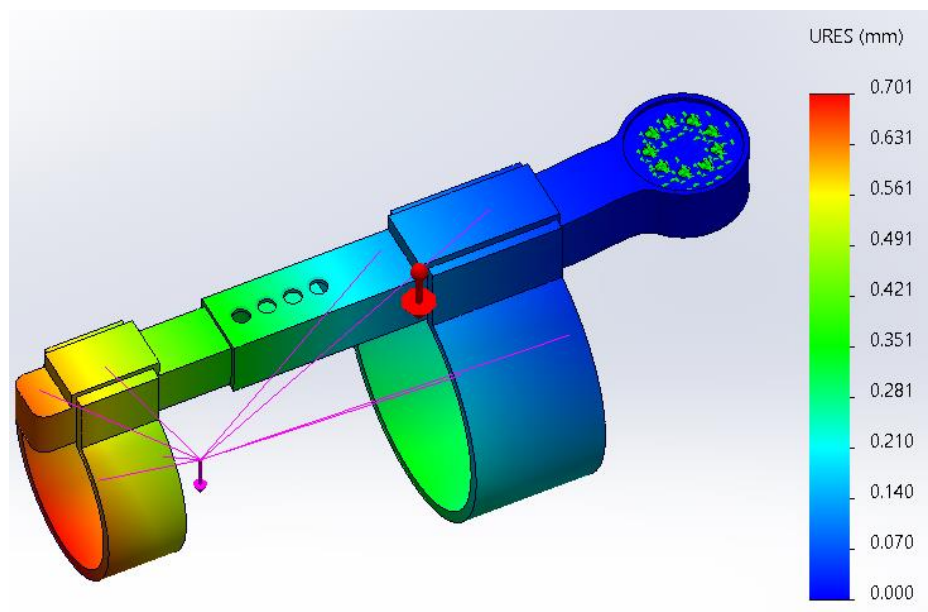
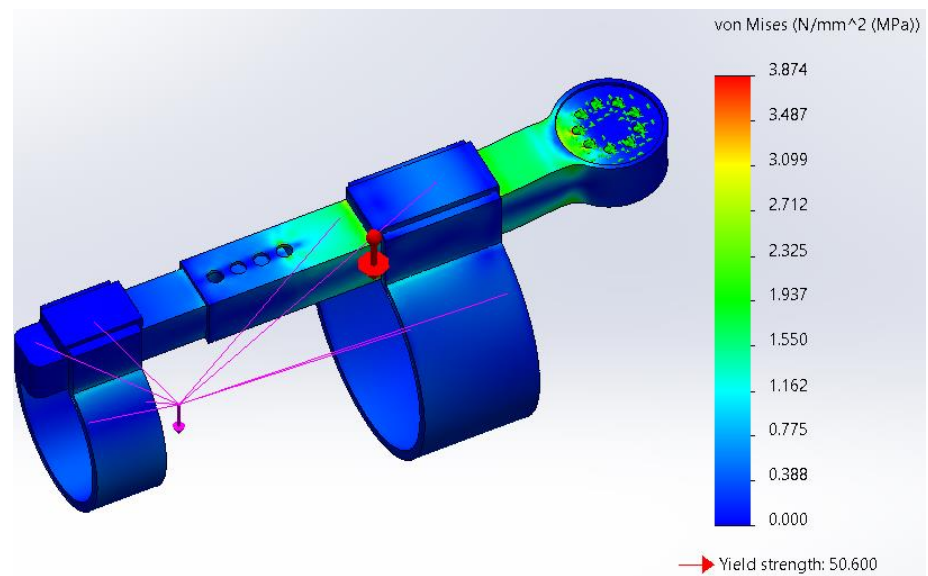
Appendix 10. Static Simulation of Forearm Link with ABS Material



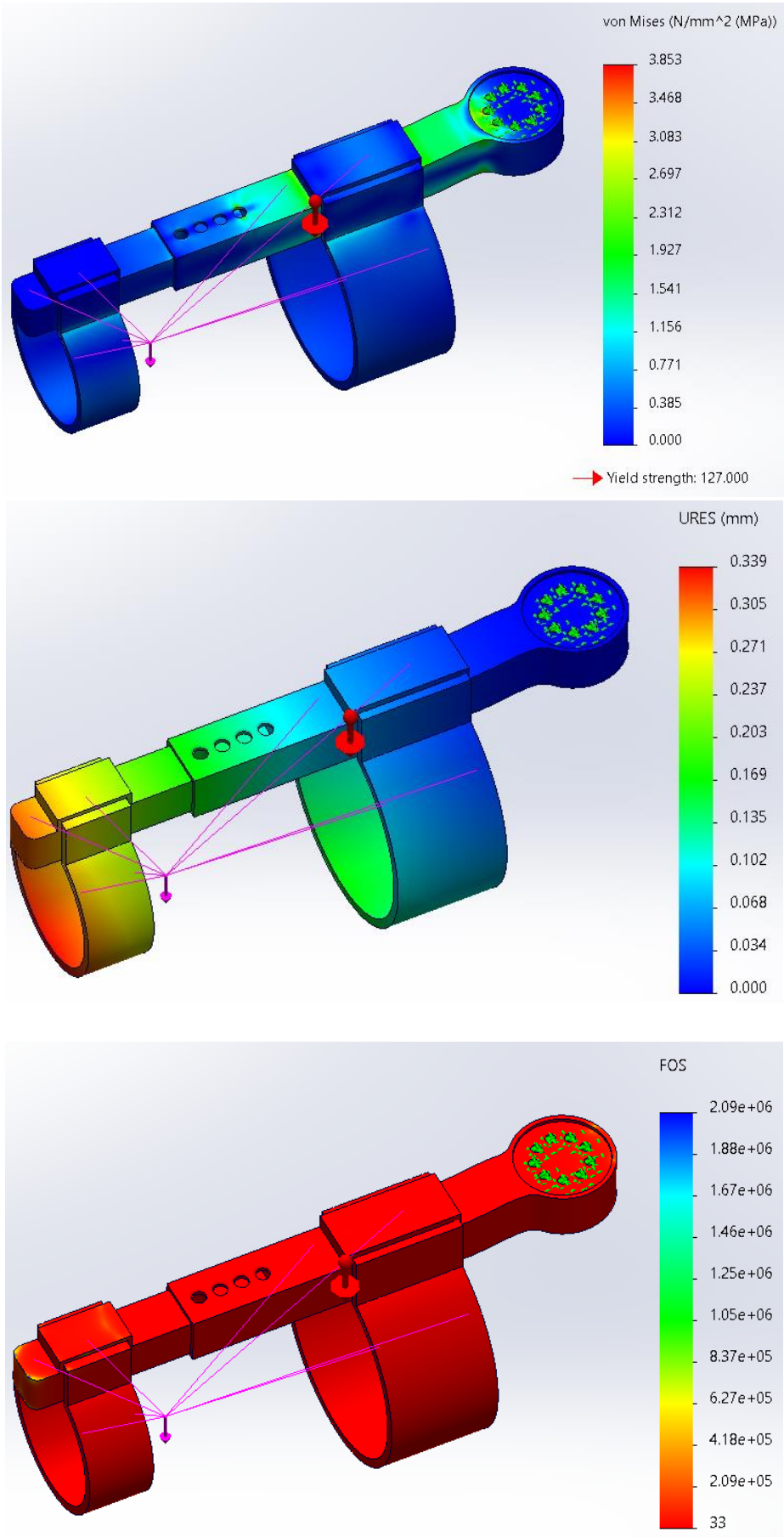
Appendix 11. Static Simulation of Forearm Link with PETG Material



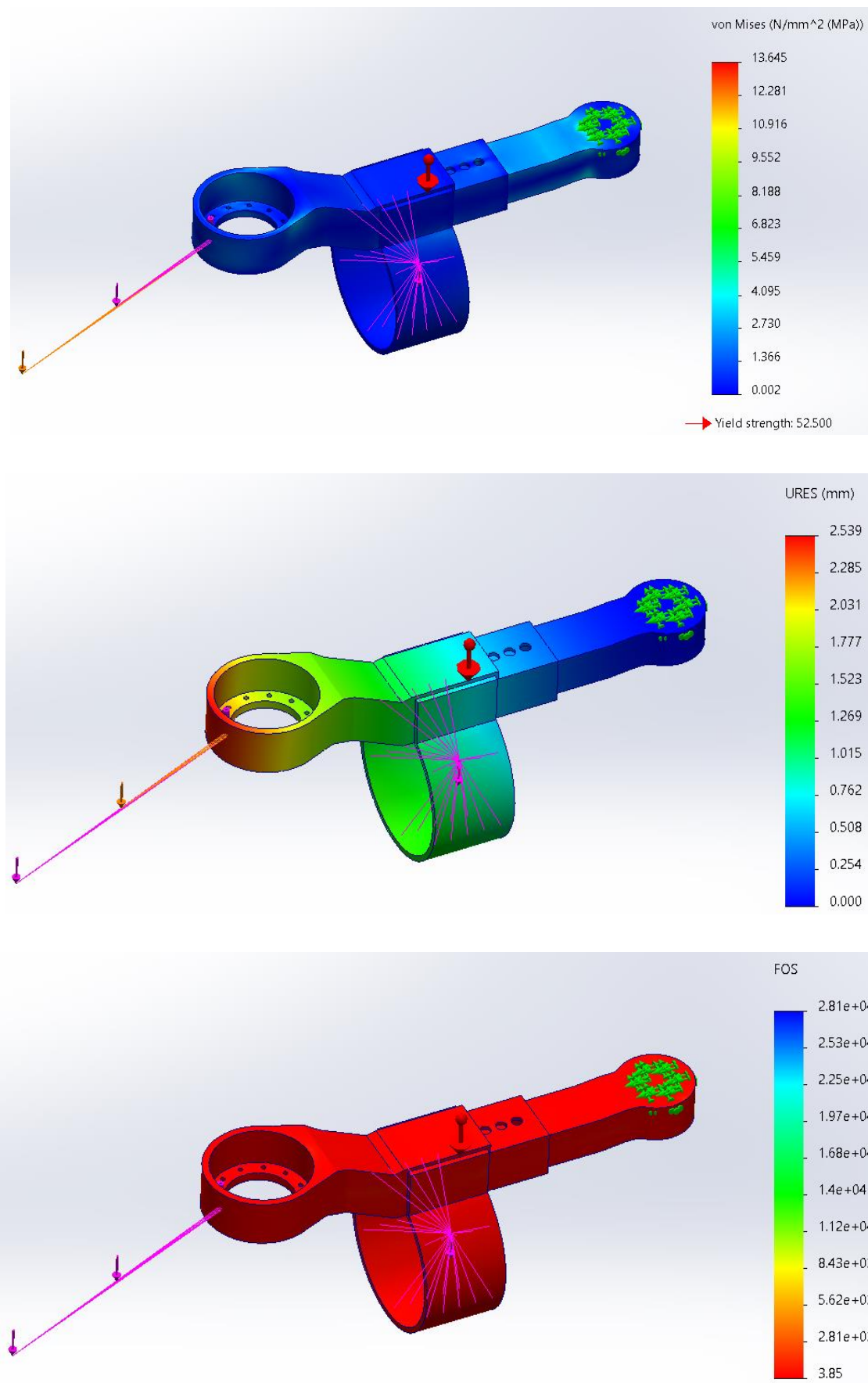
Appendix 12. Static Simulation of Forearm Link with PET-CF Material



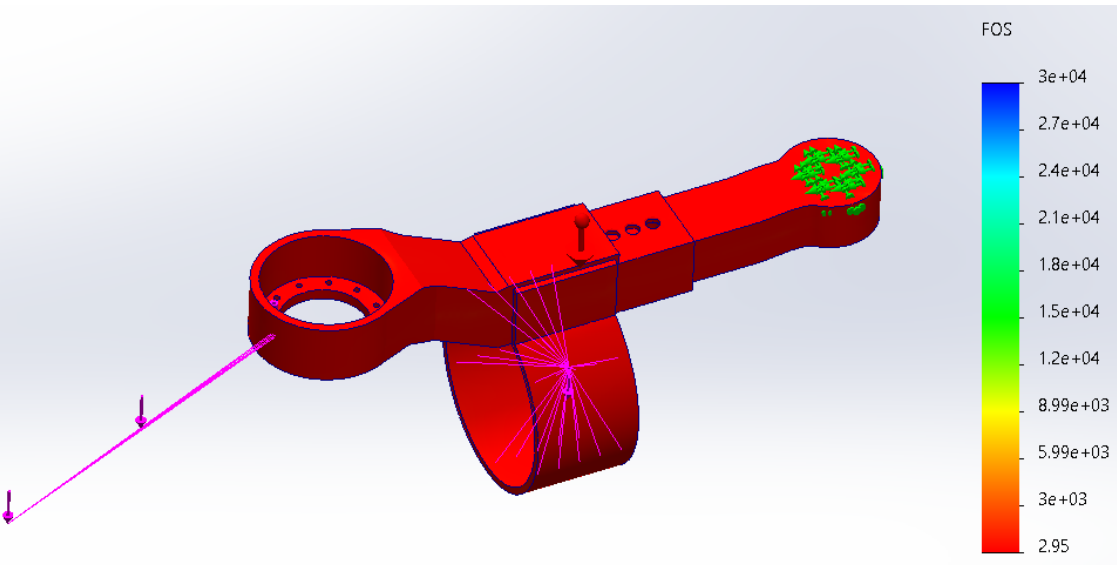
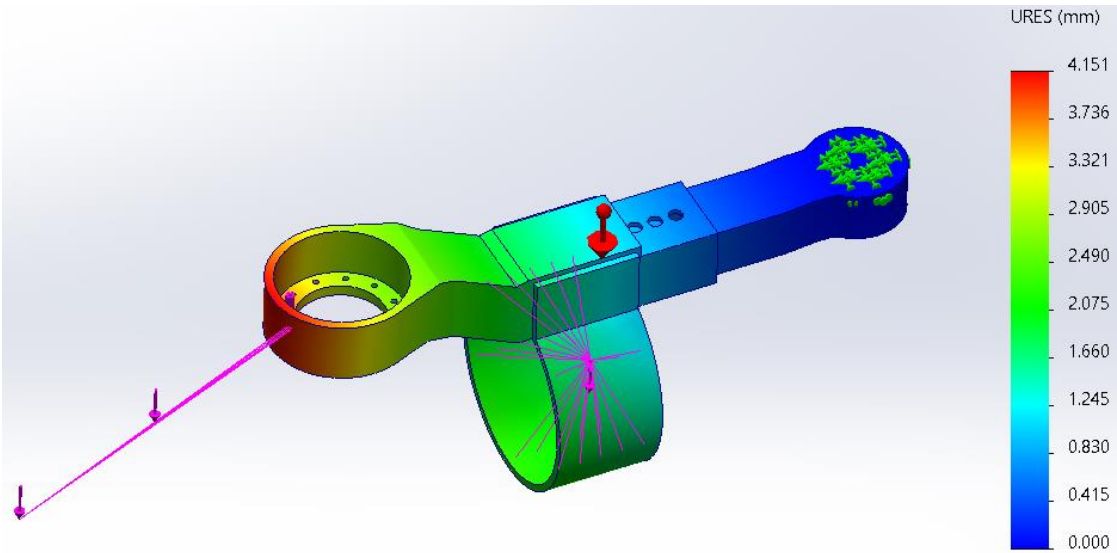
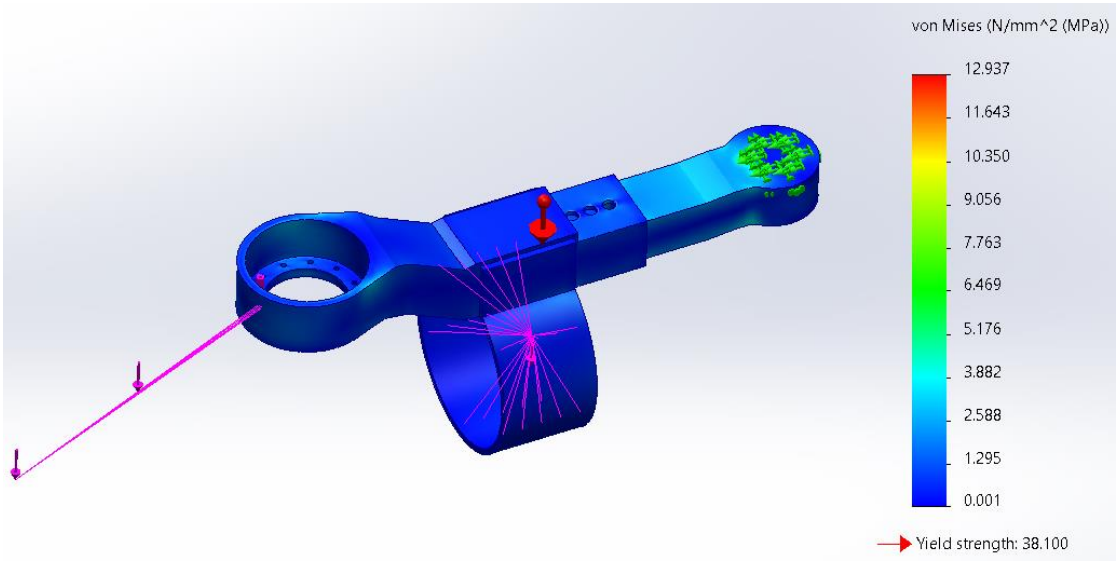
Appendix 13. Static Simulation of Forearm Link with rPACF Material



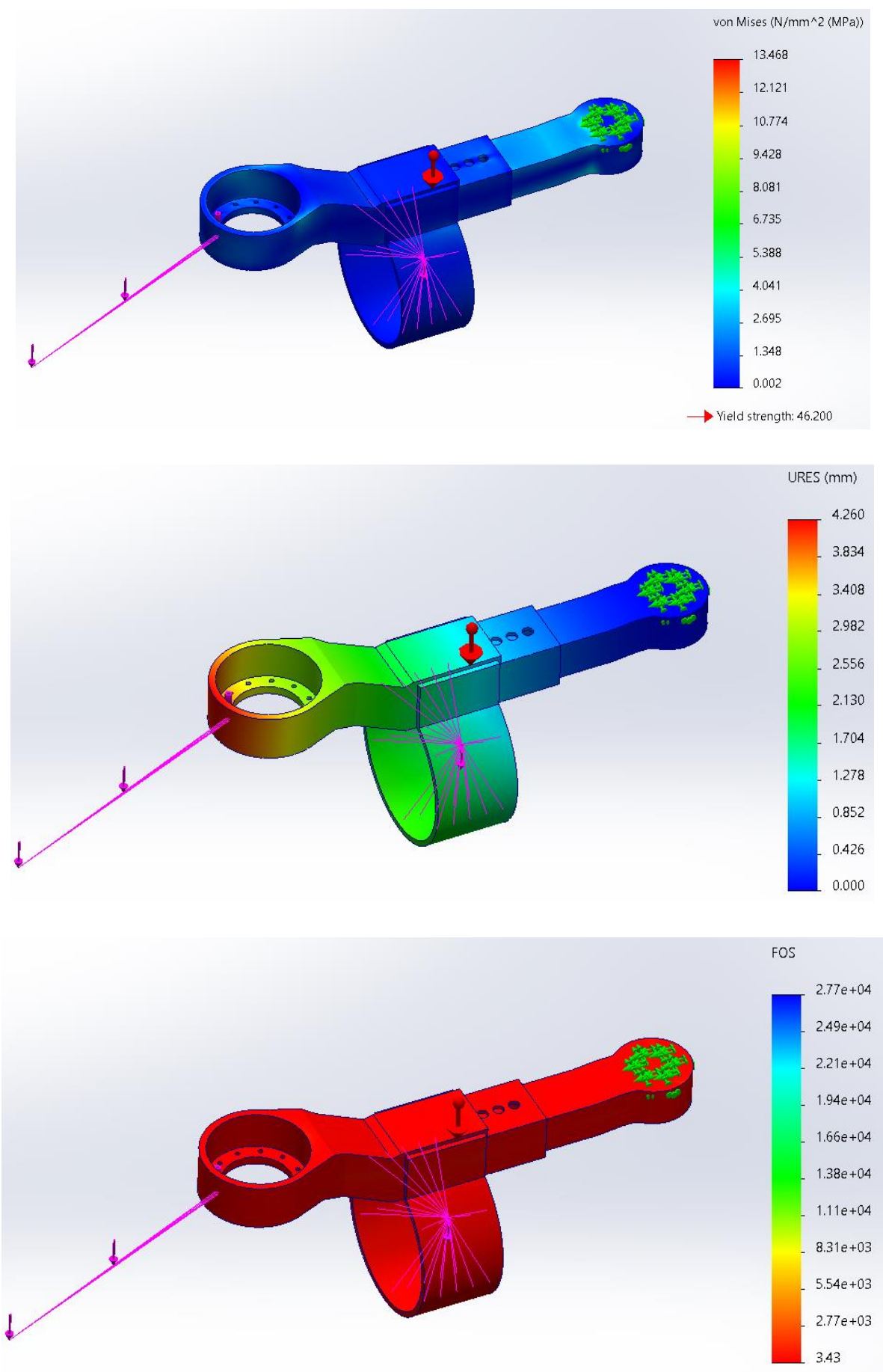
Appendix 14. Static Simulation of Upper Arm Link with PLA Material



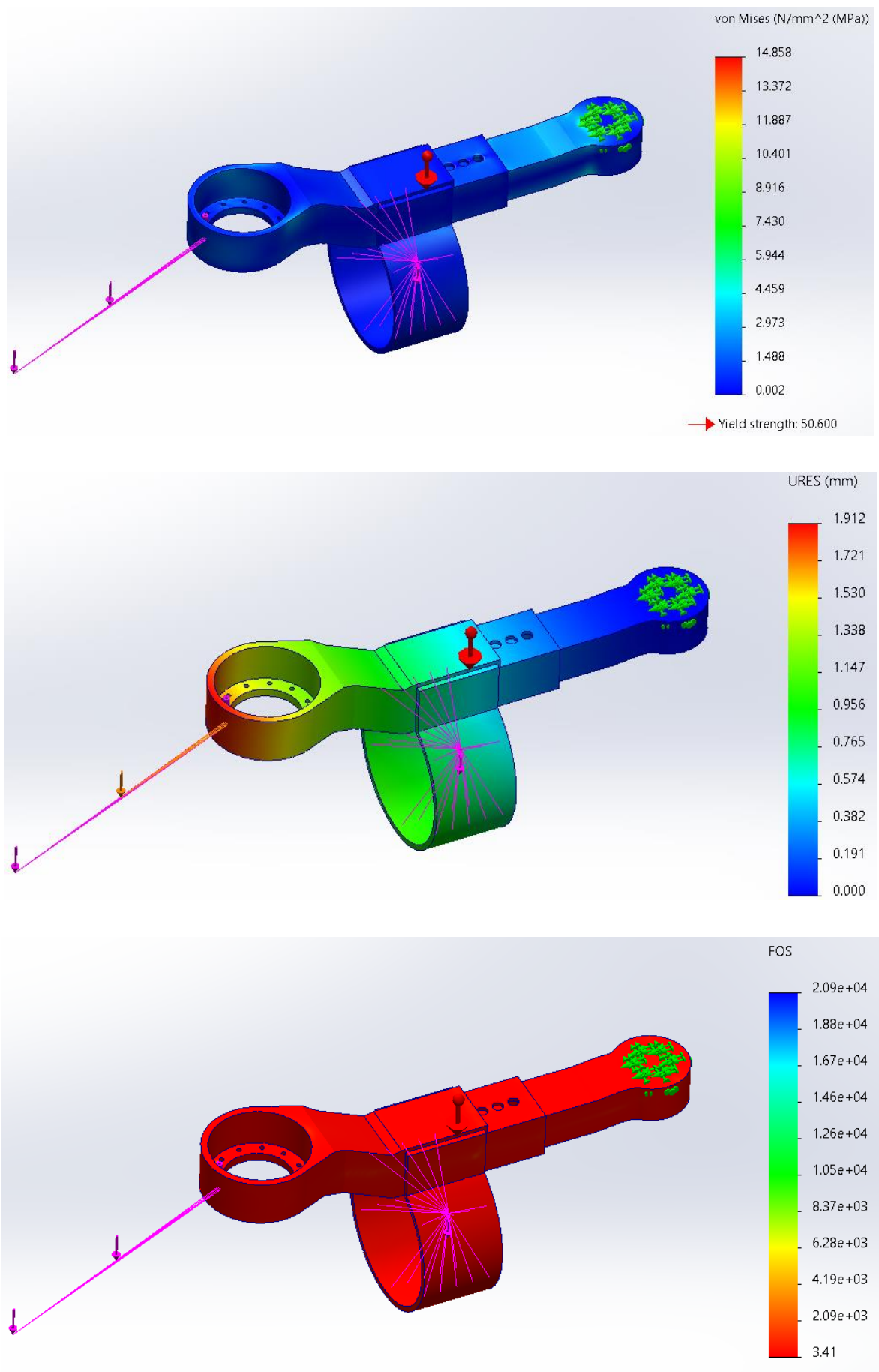
Appendix 15. Static Simulation of Upper Arm Link with ABS Material



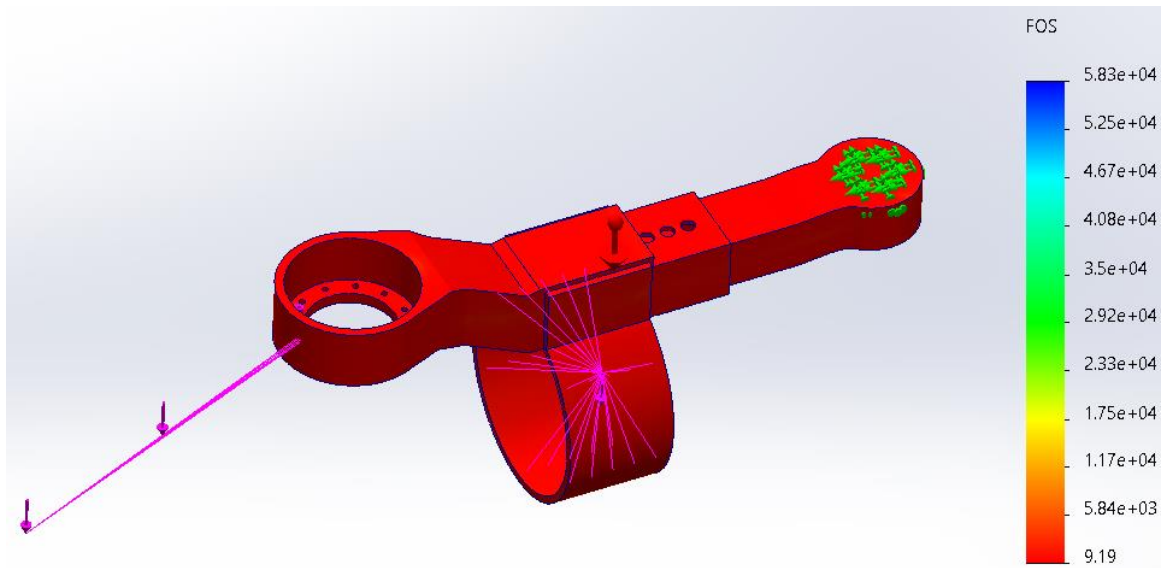
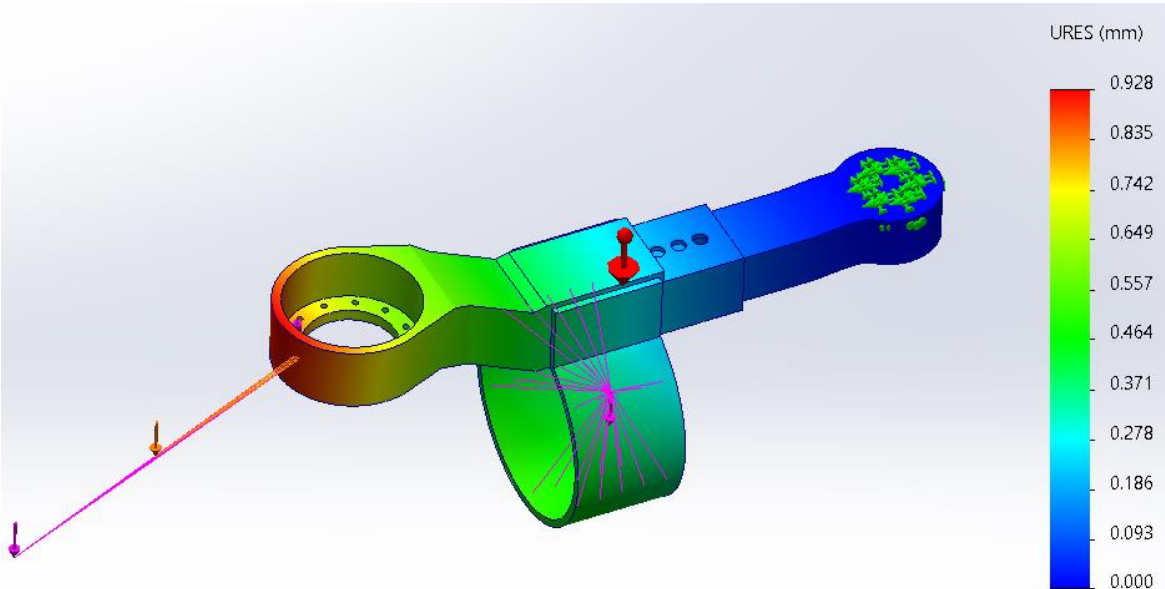
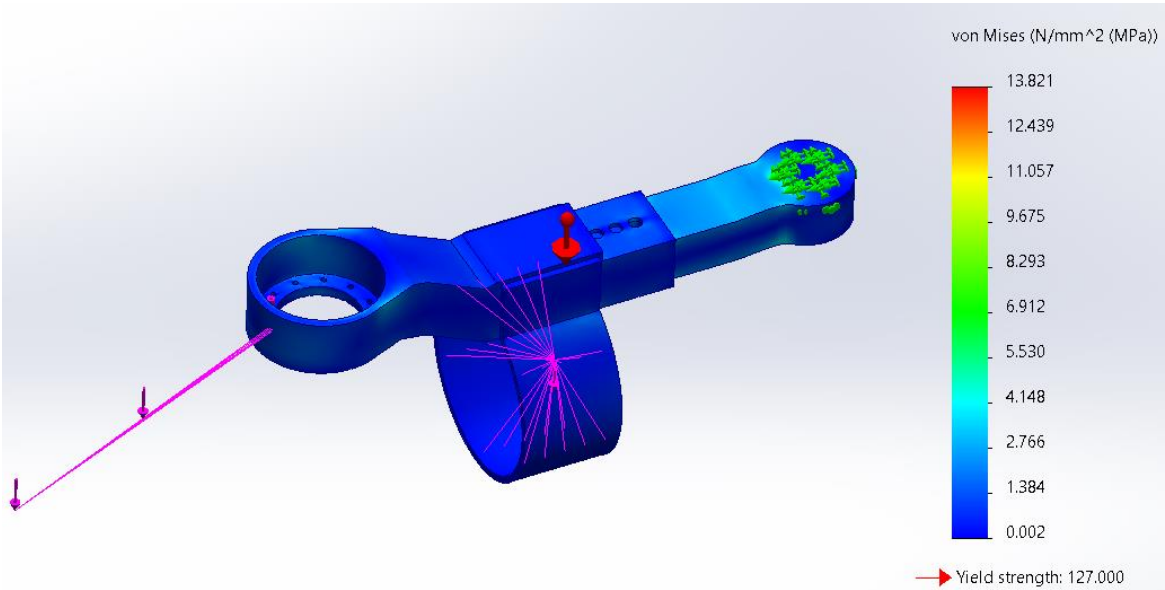
Appendix 16. Static Simulation of Upper Arm Link with PETG Material



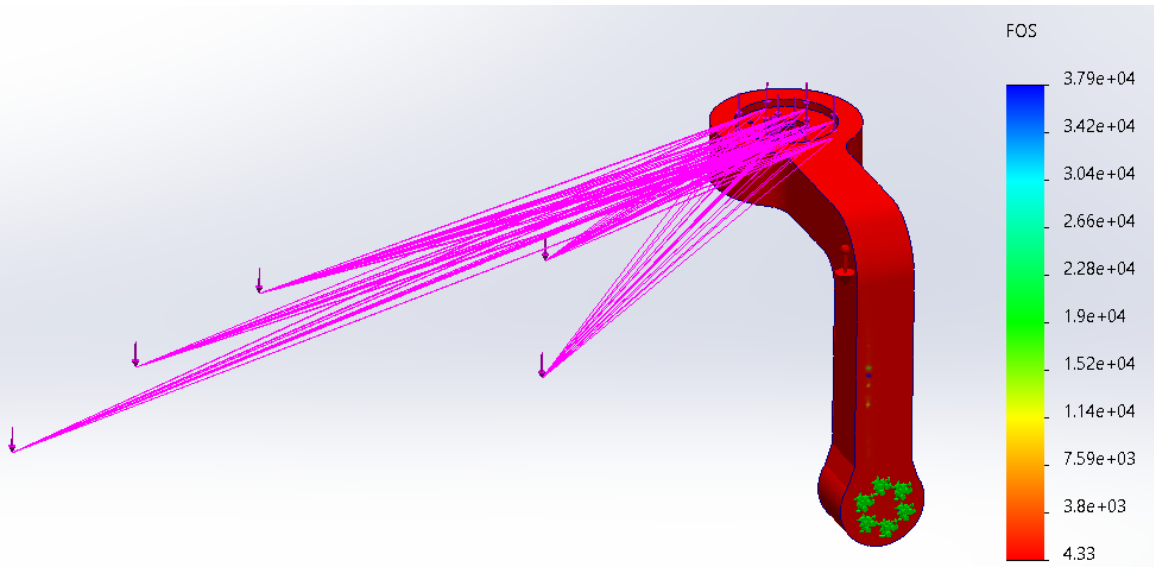
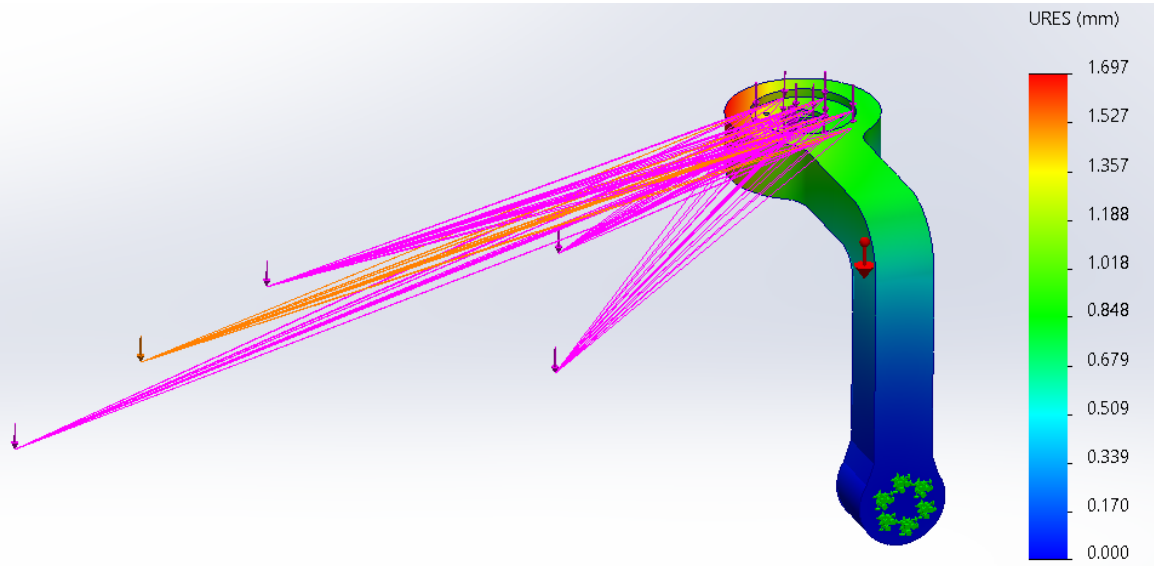
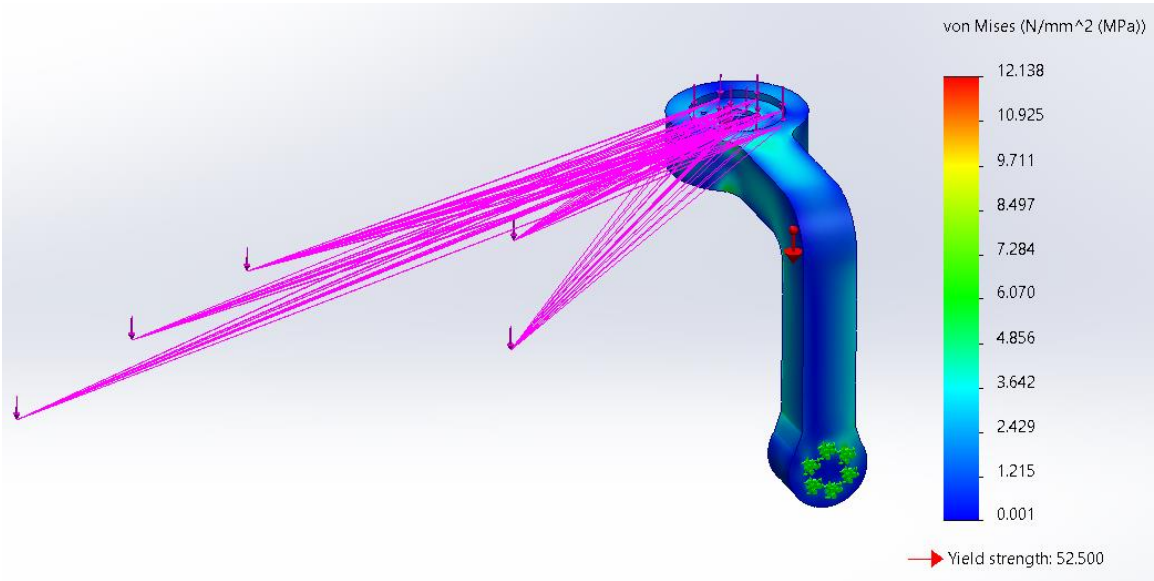
Appendix 17. Static Simulation of Upper Arm Link with PET-CF Material



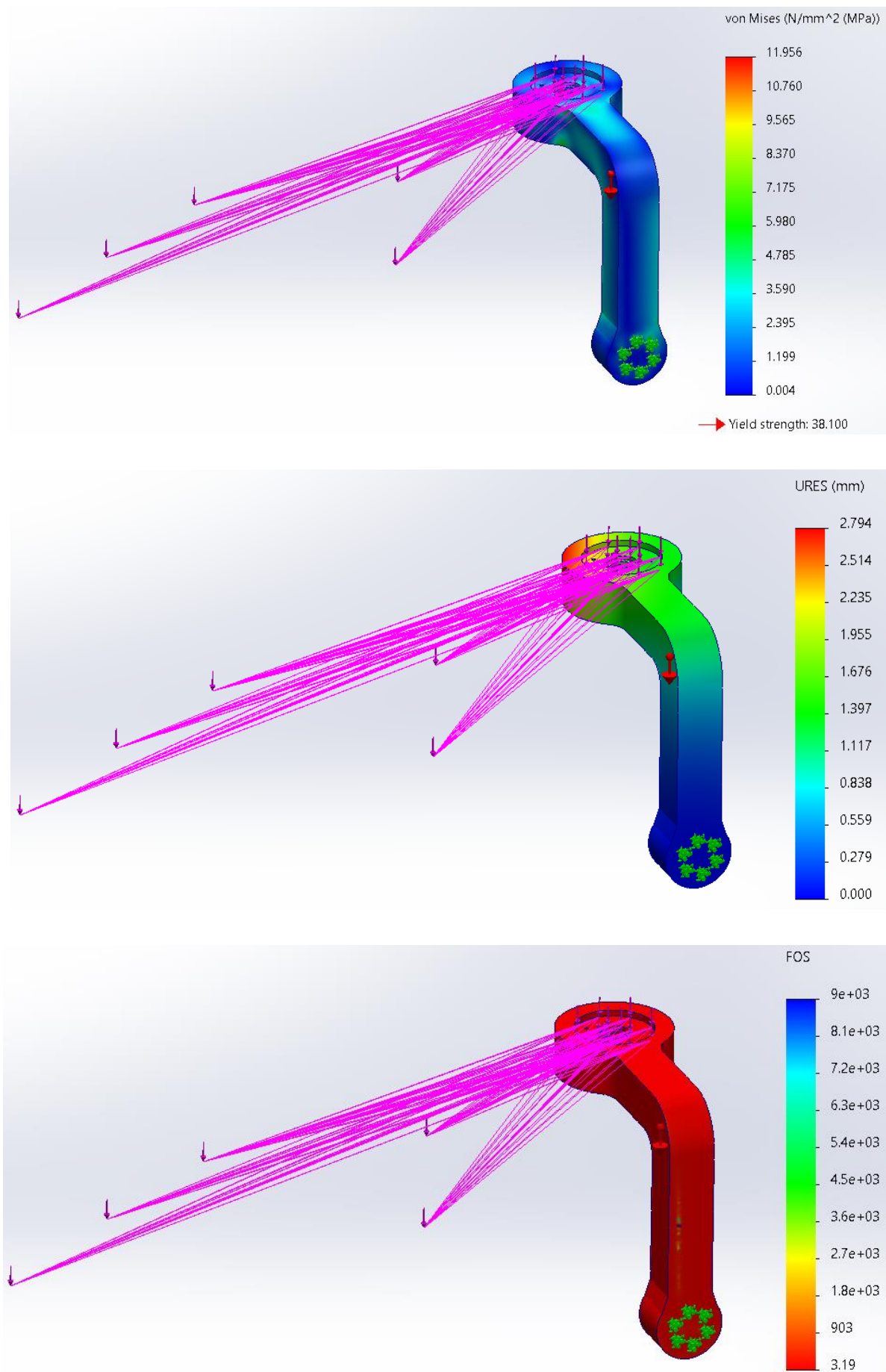
Appendix 18. Static Simulation of Upper Arm Link with rPACF Material



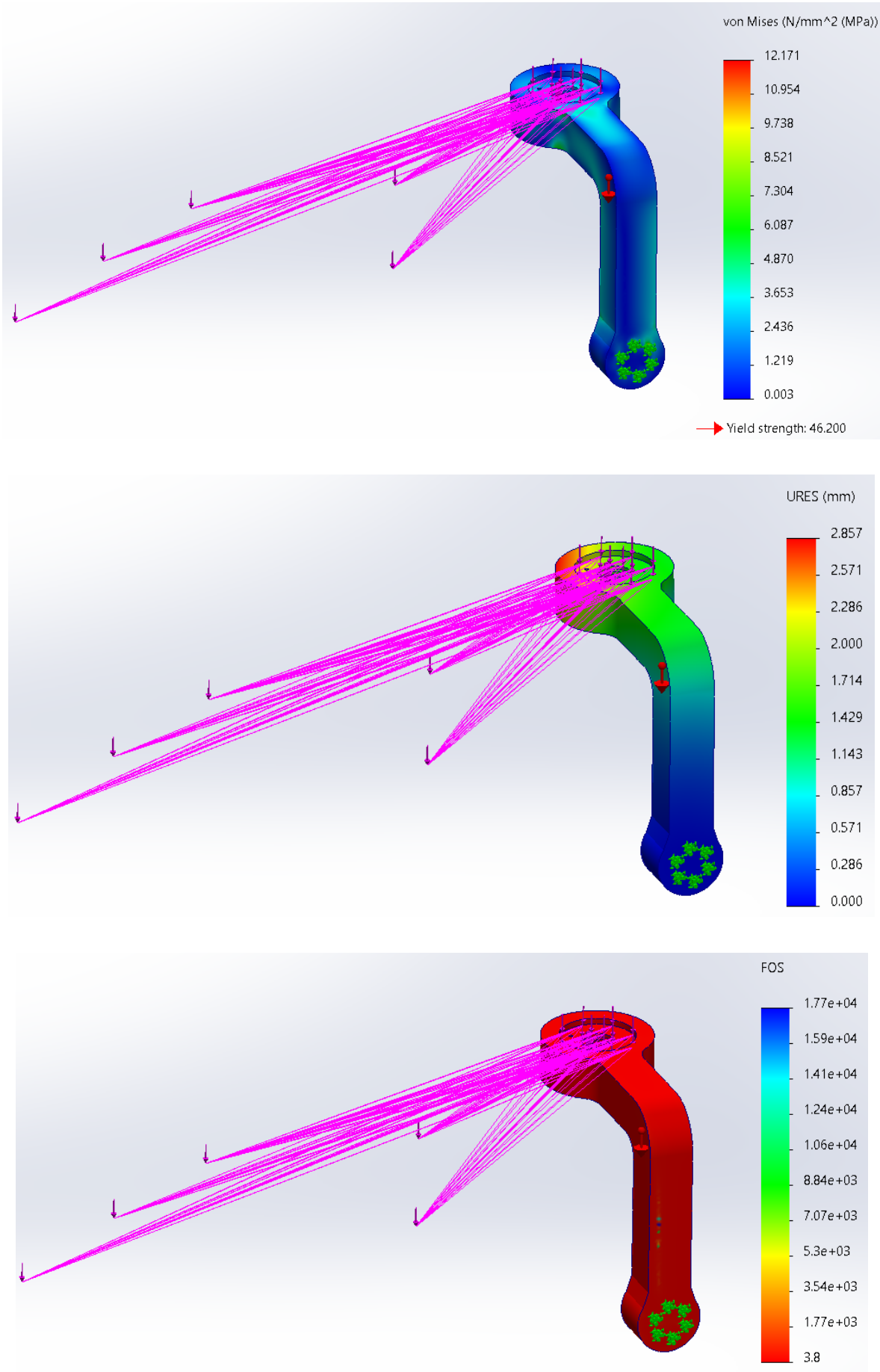
Appendix 19. Static Simulation of Shoulder Link with PLA Material



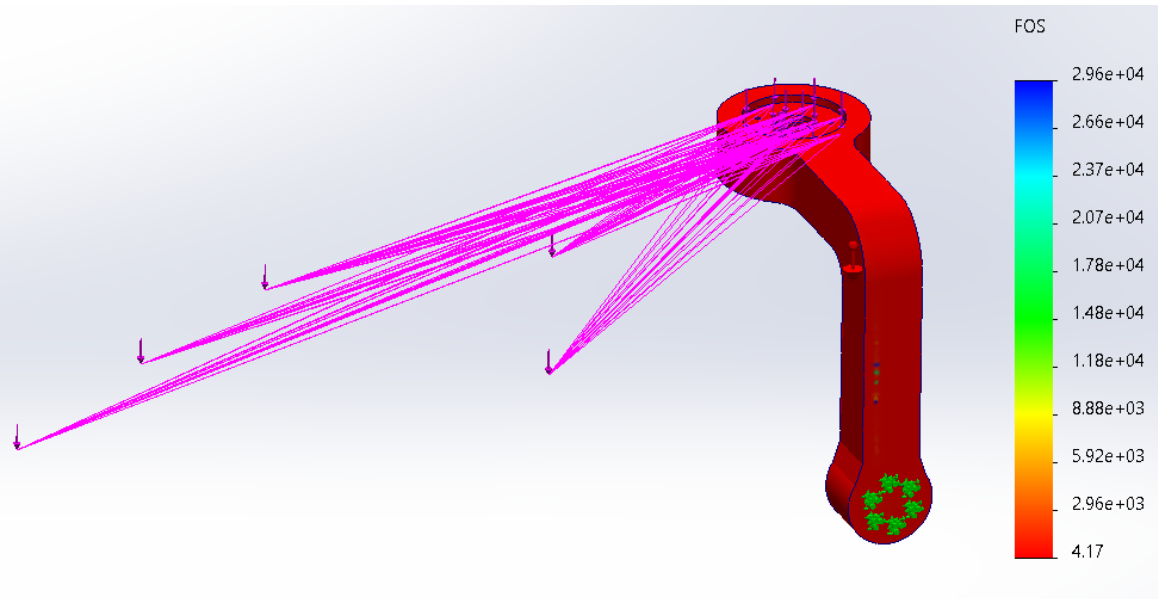
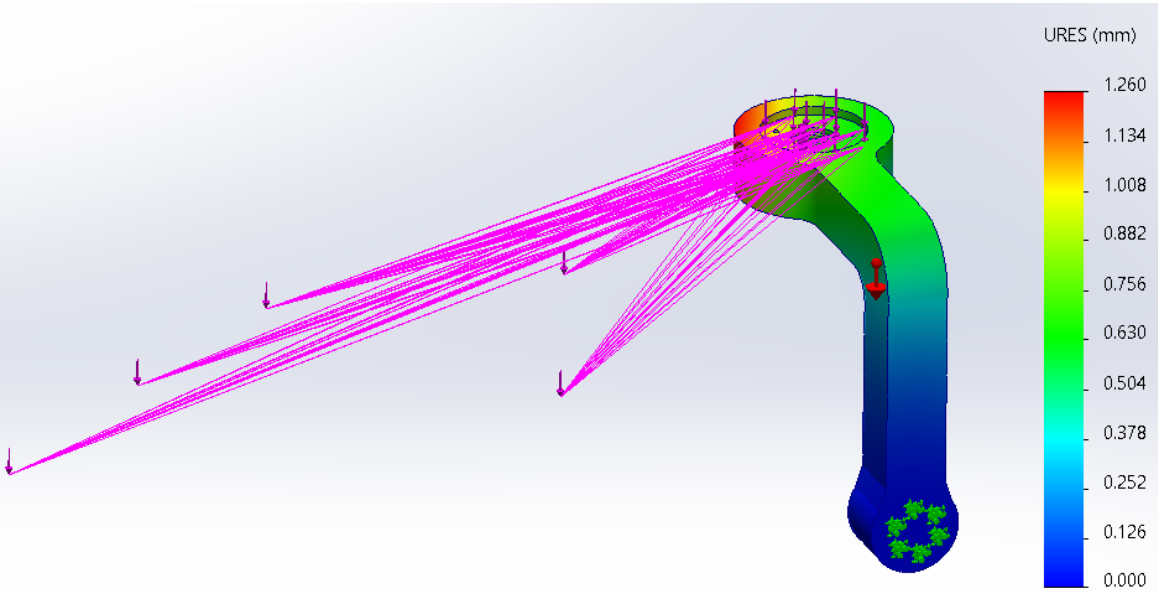
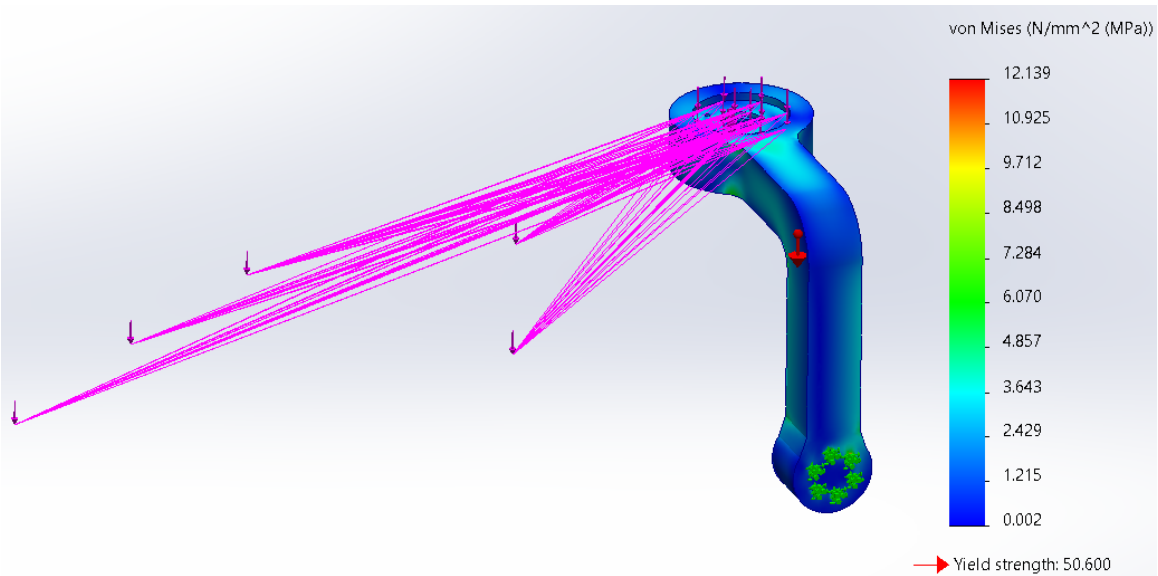
Appendix 20. Static Simulation of Shoulder Link with ABS Material



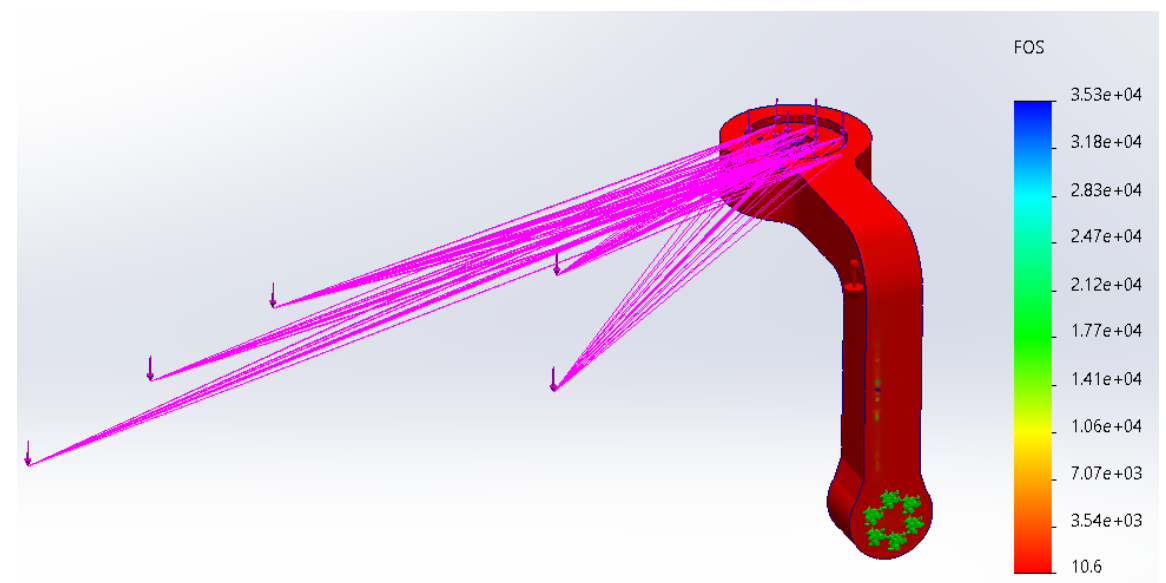
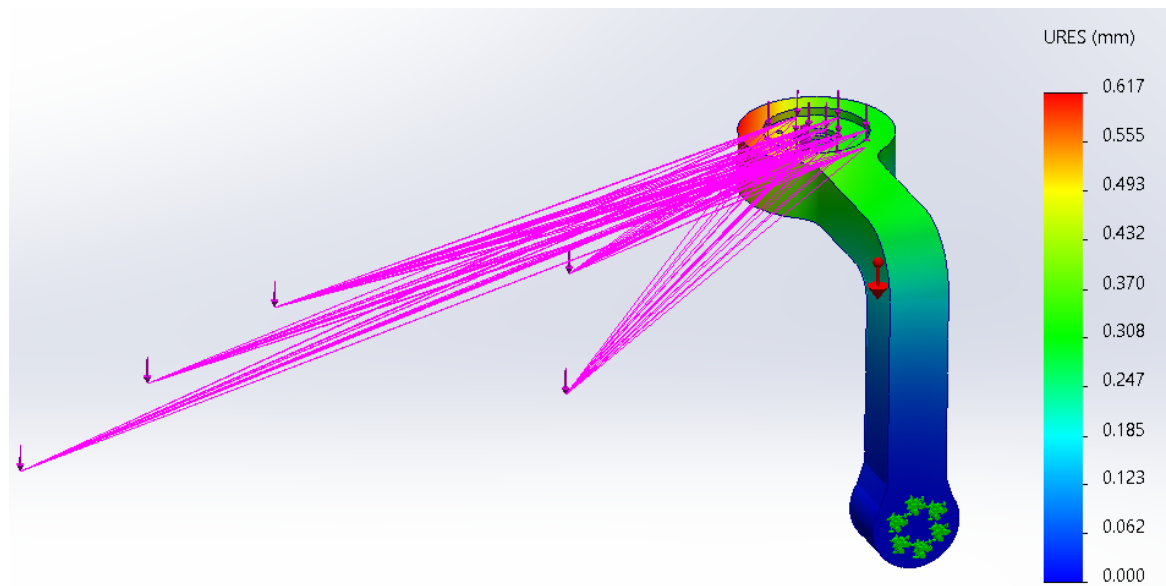
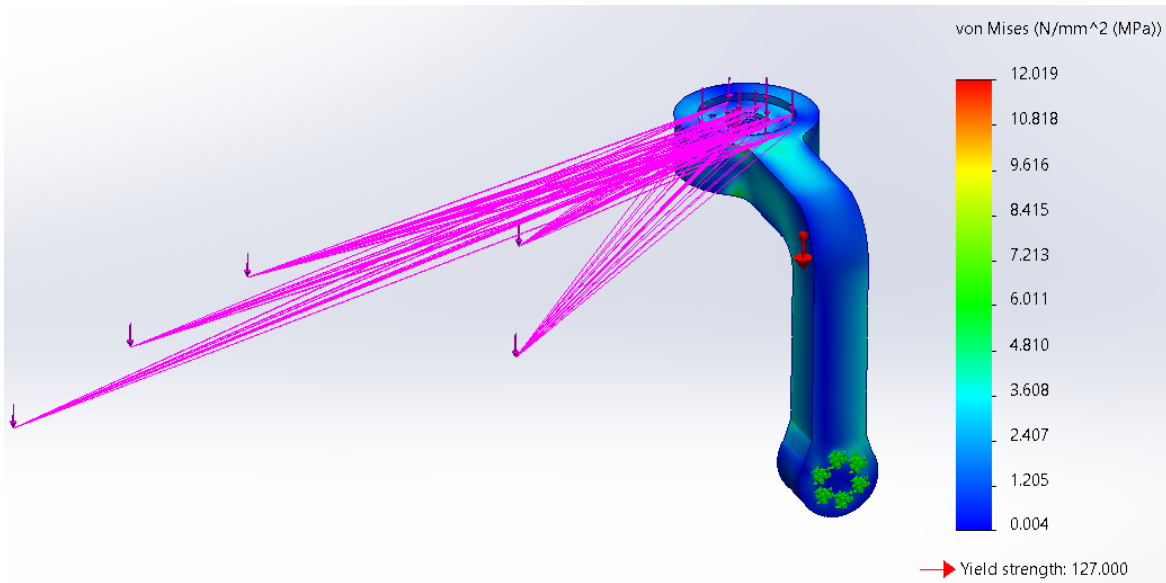
Appendix 21. Static Simulation of Shoulder Link with PETG Material



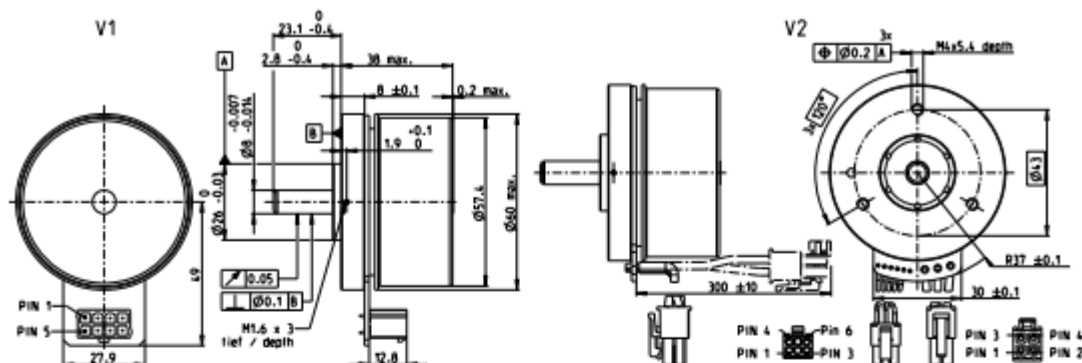
Appendix 22. Static Simulation of Shoulder Link with PET-CF Material



Appendix 23. Static Simulation of Shoulder Link with rPACF Material



EC 60 flat Ø60 mm, brushless, 100 watt



 Stock program
 Standard program
 Special program (on request)

Part Numbers

V1 with Hall sensors	625854	625855	625856
V2 with Hall sensors and cables	647691	647692	647693

V2 with Hall sensors and cables		647691	645604	647692				
Motor Data								
Values at nominal voltage								
1	Nominal voltage	V	12	24	48			
2	No load speed	rpm	3760	4300	4020			
3	No load current	mA	797	493	221			
4	Nominal speed	rpm	3210	3730	3460			
5	Nominal torque (max. continuous torque)	mNm	261	269	298			
6	Nominal current (max. continuous current)	A	8.72	5.14	2.61			
7	Stall torque ¹	mNm	3340	4300	4870			
8	Stall current	A	111	81.9	43.2			
9	Max. efficiency	%	84.1	85.3	86.4			
Characteristics								
10	Terminal resistance phase to phase	Ω	0.108	0.293	1.11			
11	Terminal inductance phase to phase	mH	0.0911	0.279	1.28			
12	Torque constant	mNm/A	30	52.5	113			
13	Speed constant	rpm/V	318	182	84.8			
14	Speed/torque gradient	rpm/mNm	1.14	1.01	0.837			
15	Mechanical time constant	ms	9.99	8.86	7.32			
16	Rotor inertia	gcm ²	835	835	835			

Specifications	Operating Range	Comments
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Thermal data	
17 Thermal resistance housing-ambient	2.6 K/W
18 Thermal resistance winding-housing	3.8 K/W
19 Thermal time constant winding	41.4 s
20 Thermal time constant motor	90 s
21 Ambient temperature	-40...+100°C
22 Max. winding temperature	+125°C

Mechanical data (preloaded ball bearings)	
23 Max. speed	6000 rpm
24 Axial play at axial load < 12.0 N	0 mm
> 12.0 N	0.14 mm
25 Radial play	preloaded
26 Max. axial load (dynamic)	12 N
27 Max. force for press fits (static) (static, shaft supported)	170 N
	8000 N
28 Max. radial load, 5 mm from flange	112 N

Continuous operation
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

Short term operation
The motor may be briefly overloaded (recurring).

Assigned power rating

2.0. Other specifications	2.0.1.1
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29 Number of pole pairs	7	
30 Number of phases	3	maxon Modular System Details on catalog page 46

30 Number of phases	3	maxon modular System	Details on catalog page 74
31 Weight of motor	355 g	Stator: Steel	Stator: Steel

Values listed in the table are nominal.

Connection M1 M2 (nominal AWG 24)

Planetary Gearhead Ø52 mm

Encoder MILE 512-4096 CPT

Connection V1	V2 (sensors, AWG 24)	1001 Nm		011-4000 en, 1
Pin 1	Hall sensor1	4-30 Nm		2 channels

Pin 2 Hall sensor 2 Hall sensor 2 Page 411 Page 462
Pin 3 V_{DD} 4.5...24 VDC Hall sensor 3 Recommended Electronics

Pin 3	V _{DD} 4.5...24 VDC Hall sensor 3	Recommended Electronics:
Pin 4	Motor winding 3 GND	Notes
Pin 5	Motor winding 3 GND	Page 46

Pin 5	Hall sensor 3	V _{H3} 4.5...24 VDC	ESCON Module 50/5	501
Pin 6	GND	N.C.		

Pin 6	GND	N.C.	ESCON Mod. 50/8 (HE)	502
Pin 7	Motor winding 1			
Pin 8	Motor winding 2		ESCON 50/5	503

Pin 8	Motor winding 2	ESCON 50/5	503
	V2 (Motor, AWG 16)	ESCON 70/10	503

Pin 1	Motor winding 1	DEC Module 50/5	505
Pin 2	Motor winding 2	EPSC4 Mod 50/5	510

Pin 2	Motor winding 2	EPOS4 Mod./Comp. 50/5	510
Pin 3	Motor winding 3	EPOS4 Mod./Comp. 50/8	511

Pin 4	N.C.	EPOS4 Mod/Comp. 50/6	512
Wiring diagram for Hall sensors see p. 89		EPOS4 Mod/Comp. 50/15	514

Connector	Part number	EPOS4 50/5	515
		EPOS4 30/15	515

Molex	46015-0806	43025-0600	EPOS4 70/16	516
Molex		39-01-3040	EPOS4 Disk 60/8	516

Molex	39-01-2040	EPOS4 Disk 60/12	516
Connection cable for V1		EPOS4 Disk 60/12	517

Universal, L = 500 mm	339380	EPOS2 P 24/5	520
— EPOS1, L = 500 —	354245		

²Calculation does not include saturation effect (p. 71/178)²Calculation does not include saturation effect (p. 71/178)

Appendix 26. Technical Data of “CSD-20-100-2A-GR” Harmonic Drive

CSD-2A Component Set

Size	Gear ratio	Rated torque at input speed 2000rpm		Limit for repeated peak torque		Limit for average torque		Limit for momentary peak torque		Maximum input speed (rpm)		Limit for average input speed (rpm)		Moment of inertia	
		Nm	kgfm	Nm	kgfm	Nm	kgfm	Nm	kgfm	Oil	Grease	Oil	Grease	I x 10 ⁻⁴ kgm ²	J x 10 ⁻⁵ kgfms ²
14	50	3.7	0.38	12	1.2	4.8	0.49	24	2.4	14000	8500	6500	3500	0.021	0.021
	80	5.4	0.55	16	1.6	7.7	0.79	31	3.2						
	100	5.4	0.55	19	1.9	7.7	0.79	31	3.2						
17	50	11	1.1	23	2.3	18	1.8	48	4.9	10000	7300	6500	3500	0.054	0.055
	80	15	1.5	29	3.0	19	1.9	55	5.6						
	100	16	1.6	37	3.8	27	2.8	55	5.6						
20	50	17	1.7	39	4.0	24	2.4	69	7.0	10000	6500	6500	3500	0.090	0.092
	80	24	2.4	51	5.2	33	3.4	76 (65)	7.7 (6.6)						
	100	28	2.9	57	5.8	34	3.5	76 (65)	7.7 (6.6)						

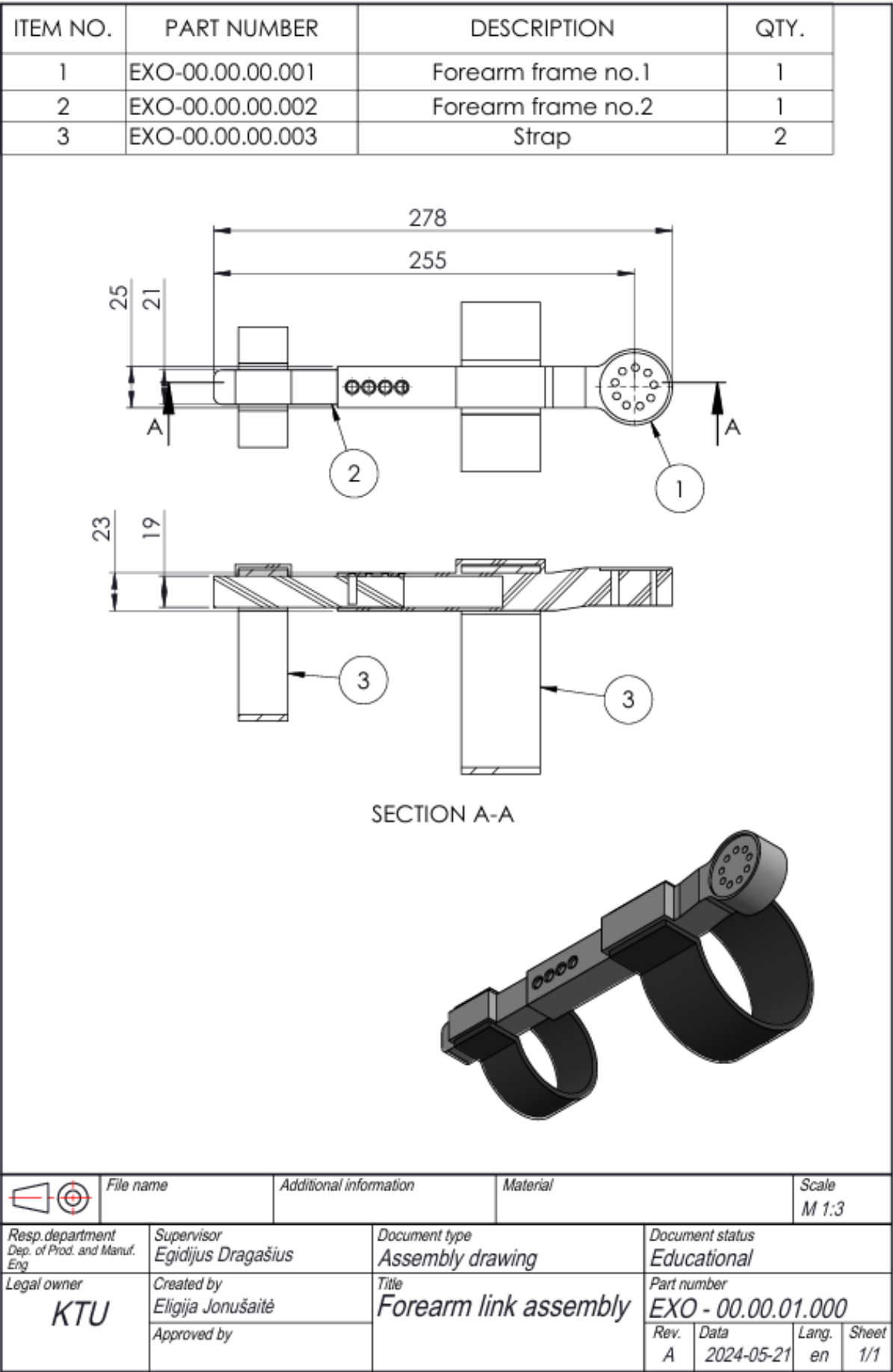
Appendix 27. Technical Data of “CSG-17-120-2UH-LW” Harmonic Drive

Rating Table

Table 2-1

Size	Ratio	Rated Torque at 2000rpm		Limit for Repeated Peak Torque		Limit for Average Torque		Limit for Momentary Torque		Maximum Input Speed		Max. Average Input Speed		Moment of Inertia	
		Nm	lb-in	Nm	lb-in	Nm	lb-in	Nm	lb-in	Oil	Grease	Oil	Grease	I x 10 ⁻⁴ kgm ²	J x 10 ⁻⁵ kgfms ²
14	50	7.0	62	23	204	9	80	46	407	14,000	8,500	6,500	3,500	0.033	0.034
	80	10	89	30	266	14	124	61	540						
	100	10	89	36	319	14	124	70	620						
17	50	21	186	44	389	34	301	91	805	10,000	7,300	6,500	3,500	0.079	0.081
	80	29	257	56	496	35	310	113	1,000						
	100	31	274	70	620	51	451	143	1,266						
	120	31	274	70	620	51	451	112	991						

Appendix 28. Assembly Drawing of Forearm Link Assembly



Appendix 29. Assembly Drawing of Upper Arm Link Assembly

