# VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ
BRNO UNIVERSITY OF TECHNOLOGY

## FAKULTA STROJNÍHO INŽENÝRSTVÍ
FACULTY OF MECHANICAL ENGINEERING

## ÚSTAV KONSTRUOVÁNÍ
INSTITUTE OF MACHINE AND INDUSTRIAL DESIGN

# DESIGN PRACOVNÍHO EXOSKELETONU
DESIGN OF A WORKING EXOSKELETON

**DIPLOMOVÁ PRÁCE**
MASTER'S THESIS

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**BRNO 2020**

# Specification Master's Thesis

| | |
|---|---|
| Department: | Institute of Machine and Industrial Design |
| Student: | **Bc. Dominika Kasarová** |
| Study programme: | Applied Sciences in Engineering |
| Study branch: | Industrial Design |
| Supervisor: | **Ing. David Škaroupka, Ph.D.** |
| Academic year: | 2019/20 |

Pursuant to Act no. 111/1998 concerning universities and the BUT study and examination rules, you have been assigned the following topic by the institute director Master's Thesis:

## Design of a working exoskeleton

**Concise characteristic of the task:**

Exoskeletons are used to increase the physical performance of the human body. Currently, the first affordable types are appearing on the market, which assume wider commercial use, especially for manual professions. Due to the necessary dimensional variability, it is appropriate to address the design so as to allow adaptation to other users who also use the device. In order to maintain hygiene, material in contact with the body of user, will be replaceable and the intensity how the exoskeleton helps with the work movement will be adjustable.

Type of work: developmental – design
Thesis output: publication result (J, D)
Project: specific university research

**Goals Master's Thesis:**

The main goal of this work is the design of a working exoskeleton for manual workers in the automotive industry. The device must be designed to regulate the amount of provided assistance directly while using – without the need to remove the device from the user's body.

Sub–objectives:

– identification of the needs of the market environment,

– identification of user requirements for exoskeleton,

– identification of suitable materials,

– design of adaptable contact surfaces acoordingly to anthropometric parameters of the user,

– design of the part attachement system for replacement due to hygiene reasons.

Required outputs: accompanying report, summary poster, technical poster, ergonomic poster, design poster, photography of the mock–up, physical model.

Extent of work: approx. 72,000 characters (40 – 50 pages of text without images).

Work harmonogram, thesis template and structure of accompanying report are obligatory:

http://ustavkonstruovani.cz/texty/magisterske–studium–ukonceni/

**Recommended bibliography:**


BOHNACKER, Hartmut, Benedikt GROSS, Julia LAUB a Claudius LAZZERONI, c2012. Generative design: visualize, program, and create with processing. New York: Princeton Architectural Press. ISBN 978-161-6890-773.

MORRIS, Richard. The fundamentals of product design. Lausanne: AVA, c2009. ISBN 978-2-9403-3-17-8.

LIDWELL, William a Gerry MANACSA. Deconstructing product design: exploring the form, function, usability, sustainability, and commercial success of 100 amazing products. Beverly, Mass.: Rockport Publishers, c2009. ISBN 15-925-3345-0.

LIDWELL, William, Kritina HOLDEN a Jill BUTLER. Univerzální principy designu: 125 způsobů jak zvýšit použitelnost a přitažlivost a ovlivnit vnímání designu. Brno: Computer Press, 2011. ISBN 978-80-251-3540-2.

GENGNAGEL, Christoph, et al. Computational design modelling proceedings of the Design Modelling Symposium Berlin 2011. Berlin: Springer, 2011. ISBN 978-364-2234-354.

TEDESCHI, Arturo. AAD_Algorithms-aided design: parametric strategies using grasshopper. Brienza, Italy: Le Penseur Publisher, 2014. ISBN 978-88-95315-30-0.

Deadline for submission Master's Thesis is given by the Schedule of the Academic year 2019/20

In Brno,

L. S.

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| prof. Ing. Martin Hartl, Ph.D.<br>Director of the Institute | doc. Ing. Jaroslav Katolický, Ph.D.<br>FME dean |

# ABSTRAKT

Tato diplomová práce se zabývá návrhem exoskeletonu pro horní část těla, který je zaměřen především na práci s rukama nad hlavou. V první části je provedena důkladná analýza jak stávajících produktů, tak i potenciálních produktů v budoucnosti. Zkoumáním kinematiky lidského těla a technologických možností, je pomocí designérských postupů navržen produkt, který zohledňuje ergonomické, technické a hygienické požadavky. Je řešena otázka individuální adaptability, prostorového neomezení tak, aby produkt byl uživatelsky přívětivý a na trhu konkurenceschopný.


# KLÍČOVÁ SLOVA


Design, exoskeleton, práce s rukama nad hlavou, únava, lidské tělo, svalově-kosterní potíže



# ABSTRACT

This diploma thesis deals with the design of an exoskeleton for the upper part of the body, which is primarily focused on overhead work. The first part of the thesis contains a thorough analysis of both existing products and potential product in the future. The kinematics of the human body and technological possibilities are investigated, and subsequently, using Design Thinking methods the product that considers ergonomic, technical and hygienic requirements is designed. Furthermore, individual adaptability and spatial non-limitation is solved, thus the final product is user-friendly and competitive on the market.


# KEYWORDS


Design, exoskeleton, overhead work, fatigue, human body, musculoskeletal disorder

# BIBLIOGRAPHIC CITATION

KASAROVÁ, Dominika. *Design pracovního exoskeletonu.* Brno, 2020, 107 s. Vysoké učení technické v Brně, Fakulta strojního inženýrství, Ústav konstruování. Vedoucí diplomové práce Ing. David Škaroupka, Ph.D.

# ACKNOWLEDGEMENT

I would most like to thank my mother for her sacrifice and support throughout my studies, without which this work would not have taken place. Thanks also to all the people who participated in the creation of this work, for inspiring opinions and comments, especially to the supervisor of the thesis David Škaroupka.


# PROHLÁŠENÍ AUTORA O PŮVODNOSTI PRÁCE

Prohlašuji, že diplomovou práci jsem vypracoval samostatně, pod odborným vedením Ing. Davida Škaroupky, PhD. Současně prohlašuji, že všechny zdroje obrazových a textových informací, ze kterých jsem čerpal, jsou řádně citovány v seznamu použitých zdrojů.

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Podpis autora

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# 1 INTRODUCTION

The beginning of the development of robotics is associated with the emergence of industrial robots and can be considered as a period between historical attempts to construct a mechanical human double and the current development of humanoid robotics and active exoskeletal systems. Even though the fabrication is robotized nowadays, machines cannot completely replace a man, his or her quick thinking, the ability to subjectively evaluate an unexpected situation resulting in finding a quick solution, or his or her motor skills. On the other hand, more and more demands are placed on a human's physical performance, which causes health problems that express themselves over time and contribute to shortening active life.

In the past, aids have been used to relieve stress or to help people with disabilities to walk, primarily in the military or in medicine. After several years of research, exoskeletal systems based on these predecessors are being used in industry, in order to reduce the burden on workers that perform exacting tasks and strenuous operations, and to protect their health.

Exoskeleton is a wearable mobile machine which is attached to the body with straps. Exoskeletons differ in their construction in terms of supporting body part and intended activities and are designed to maintain the greatest possible mobility and comfort of the user.

Exoskeletons penetrate not only into work, but also into everyday life, where they become a kind of assistant, helping us with common activities at home, work, training or rehabilitation. From this point of view, it is possible that in a few years we will consider them as a normal part of life, or a kind of accessory, so their appearance should be visually pleasing and attractive.

The most common cause of occupational diseases are musculoskeletal problems, when mainly the shoulders, neck and back are overloaded. The work is focused on the design of a working exoskeleton for industrial workers, which facilitates overhead work, prevents excessive fatigue during working hours, and thus prevents the emergence of inaccuracies in the assembly while performing the tasks.

# 2 CURRENT STATE OF KNOWLEDGE

## 2.1 Historical analysis

The earliest known exoskeleton-like device was a set of walking, jumping and running assisted apparatus developed in 1890 by Nicholas Yagn. It used energy stored in compressed gas bags to assist in movement, and mitigate impacts, thus preventing muscle strain caused by bending legs or lifting the body. [1] In 1917, the American inventor Leslie C. Kelley developed a so-called pedomotor that provided two sets of artificial ligaments acting in parallel to the wearer's principal motor muscles and movements. The device was powered by steam generated in small steam engine worn on wearer's back. [2]

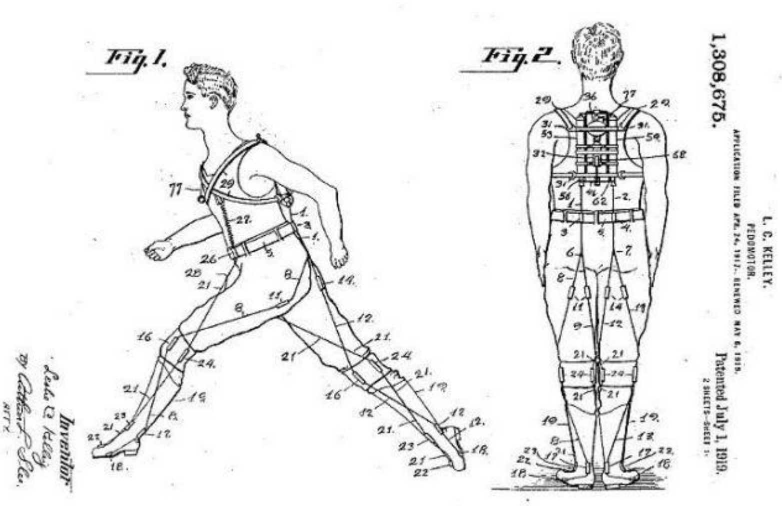



***Fig. 2-1*** Pedomotor [2]

For decades, engineers and sci-fi enthusiasts have dreamed of an exoskeleton that could boost human strength, turning an average person into a real-world Iron Man. But few people know that in the 1960s, General Electric set out to bring this vision to life. In the project lead by Ralph Mosher the suit called Hardiman was designed to mimic the user's natural movements, enabling him to lift up to 680 kg. This impressive power came at a price – the suit itself weighed 700 kg and included 28 joints and two grasping arms connected by a complex hydraulic and electronic network. Ultimately, Hardiman's size, weight, lack of stability and power supply issues kept it from ever being developer beyond an experimental prototype. [3] [4]

***Fig. 2-2*** Hardiman [3]

The beginning of the development of humanoid robotics coincided with the beginning of the development of the world's first active exoskeletons. World's first active exoskeleton pneumatically powered and partly kinematically programmed, for producing near-anthropomorphic gait was developed at the Mihailo Pupin Institute in 1969, under the guidance of Prof. Vukobratovic. Also, the first theory of these systems was developed in the same institute, in the frame of active exoskeletons. Hence, it can be said that active exoskeletons were the predecessors of the modern high-performance humanoid robots. The present-day active exoskeletons are developed as the systems for enhancing capabilities of the natural human skeletal system. [5]

Due to technical limitations, little experience and knowledge in that period, it took several decades for the technology to evolve to the point so that exoskeletons could appear on the market.

At the beginning of the 21st century, the first exoskeleton products made their way to the market and were accessible to an increasing number of users. One of the first applications was gait rehabilitation in stroke and spinal cord injured patients. Besides medical and military applications, several companies started developing exoskeletons for industrial use and just recently the first systems were introduced. Especially for this application, passive systems are increasingly favoured, as actuators are not necessary to relieve the exoskeleton user of a payload or bodyweight. For certain applications, even single articulated exoskeletons are sufficient to provide support. This results in devices that are lighter and cheaper than their actuated counterparts.

***Fig. 2-3*** Robotic exoskeleton [7]

In pursuit of reducing constraints that can be caused by the size, weight and rigid structure, the concepts of exosuits has emerged in the past couple of years. These soft, robotic devices are primarily made of fabric and can be worn like clothes. They provide support by actuated cables that are integrated into the fabric, or by soft and lightweight actuators at the joints. [6] The expected future technological achievements in the field of special and composite materials, the development of new hybrid-type actuators or artificial muscles, new breakthroughs in the field of artificial intelligence and neural networks will certainly lead to a remarkable development of humanoid robotics as a whole, and hence, new interesting results can also be expected in the domain of active exoskeletal systems. [5]

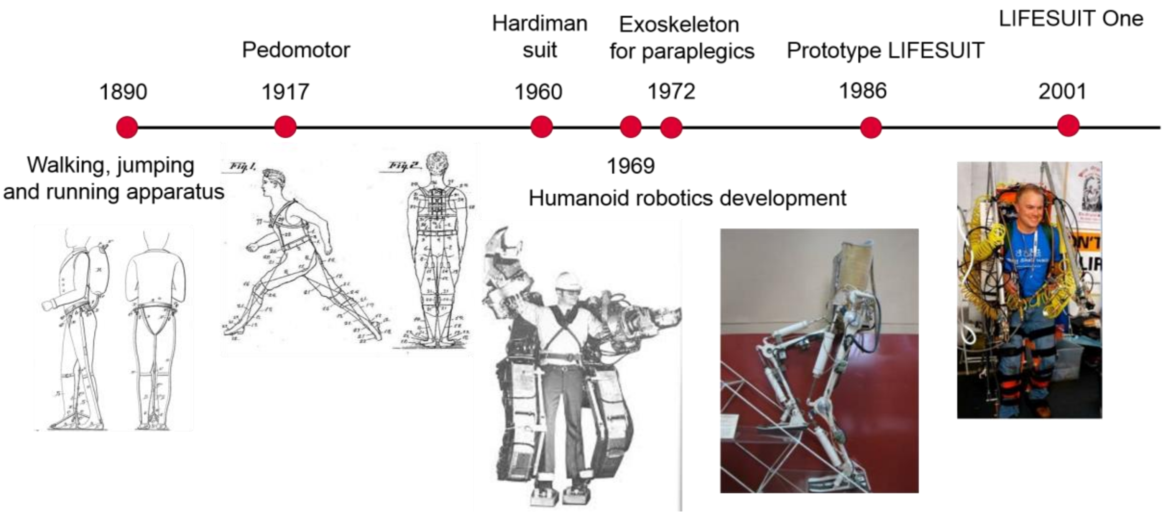



***Fig. 2-4*** Historical development

## 2.2 Design analysis

In the past, exoskeletons were used mainly in the military or for rehabilitation purposes. Today, they are being integrated into industry to facilitate work and enhance performance. Design analysis examines and evaluates current solutions of competing products, production technologies and trends. Discovering problems and mapping opportunities is fundamental for further targeting and developing the product.

### 2.2.1 Exoskeleton classification

Exoskeleton systems can be divided into many different categories, types or classifications based on a series of criteria:

***Body parts that are actuated or powered by wearable device***

- Full body
- Upper extremities: arms and torso
- Lower extremities: legs

***Power of device***

- Powered exoskeletons

  Using batteries or electric cable connections to run sensors and actuators

- Passive exoskeletons

  Do not have any electrical power source and can be used for:

  - Weight re-distribution using spring and locking mechanism
  - Energy capture to improve walking efficiency
  - Dampening, shock absorbing and vibration reducing
  - Locking so that user is allowed to sit or crouch in the same position for a prolonged period of time

***Mobility of the device***

- Fixed: the device is tethered, attached to a wall or suspended from the air by fixed hook and harness
- Supported: the exoskeleton is attached to an overhead rail; it is supported by a moving frame or an adjacent wheeled robot
- Mobile: the user and exoskeleton can move around freely

***Control(user-machine-interface)***

- Joystick
- Buttons or control panels
- Mind-controlled
- Sensors
- No control

***Materials***

- Rigid materials such as metal or carbon fiber
- Flexible materials in the entire construction (soft exoskeleton or exosuit)

[8][9]

### 2.2.2 Current exoskeleton market

Evaluation is based on an approach offered by the book Deconstructing Product Design. Critical analysis and additional qualitative rating across four dimensions – aesthetic, function, usability and commercial success - provides an objective framework for comparison of products. This interpretation offers systematic evaluation and mutual comparison of products. Product are valued from one to five points, where five is the most favourable for each criterion.


Aspects as form or visual attractivity are assessed within aesthetic criterion. However, this criterion can be more subjective, design that exhibits appealing elements and follows contemporary trends has higher potential to become more competitive.

Functionality, space limitation, construction assessment is included in function, usability represents simplicity of the use, accessibility or effectivity. Commercial success describes its sales capability and competitiveness. [10]

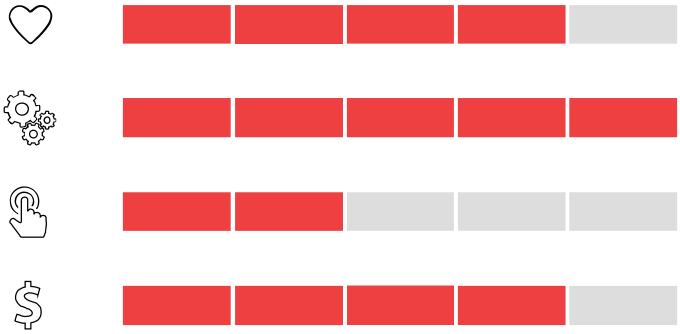
### Chairless chair

A folding wearable chair can help to avoid fatigue, lower back pain or uncomfortable positions. The main application is for the manufacturing companies, where workers are required to stand for long period of time and traditional sitting methods are not suitable, causing obstacles in the work area. The system works as being locked while a sitting position is maintained, and it unlocks when the user stands up.

Chairless chairs are special skeleton fastened with straps to the wearer's body, waist and legs. The main part is a plastic or fabric seat behind the legs on which the wearer can sit when needed. The user can often choose between two sitting positions. The pressure is distributed over the shin and thigh reducing muscle fatigue. All of these exoskeletons are passive, so they do not need any power supply.

Known exoskeletons on the market include LEX, Noonee and Archelis. All these products show elegant and simple design. Exoskeleton LEX provides minimalistic solution without a need of ankle straps and folding system allows the user to move freely. Noonee belongs to most widespread exoskeletons of this type in industry. [11] [12] [13] [14]

***Fig. 2-5*** Chairless chair [11] [12] [13] [14]



### Upper body exoskeleton

Upper body exoskeletons provide back support to the workers as they bend down to perform a lift and, again, ensure they are lifting in the right manner. They reduce the burden on the back, shoulder and neck muscles while bending down or working overhead and reduce repetitive-stress injuries, evenly distributing energy to the outside of the hips. The exoskeleton can be either passive or active. The supporting device is comprised of harness worn similarly as backpack. Wearable device uses either passive spring mechanism or system of pulleys that are located and covered in arm segment. Also, different levels of support can be quickly tuned. Waist, shoulder and arm straps are usually adjustable to different proportions of the wearer. An anthropometric profile and adjustable sizing allow for natural movement and intuitive awareness of the wearer's position within tight spaces. [15] [16] [17]

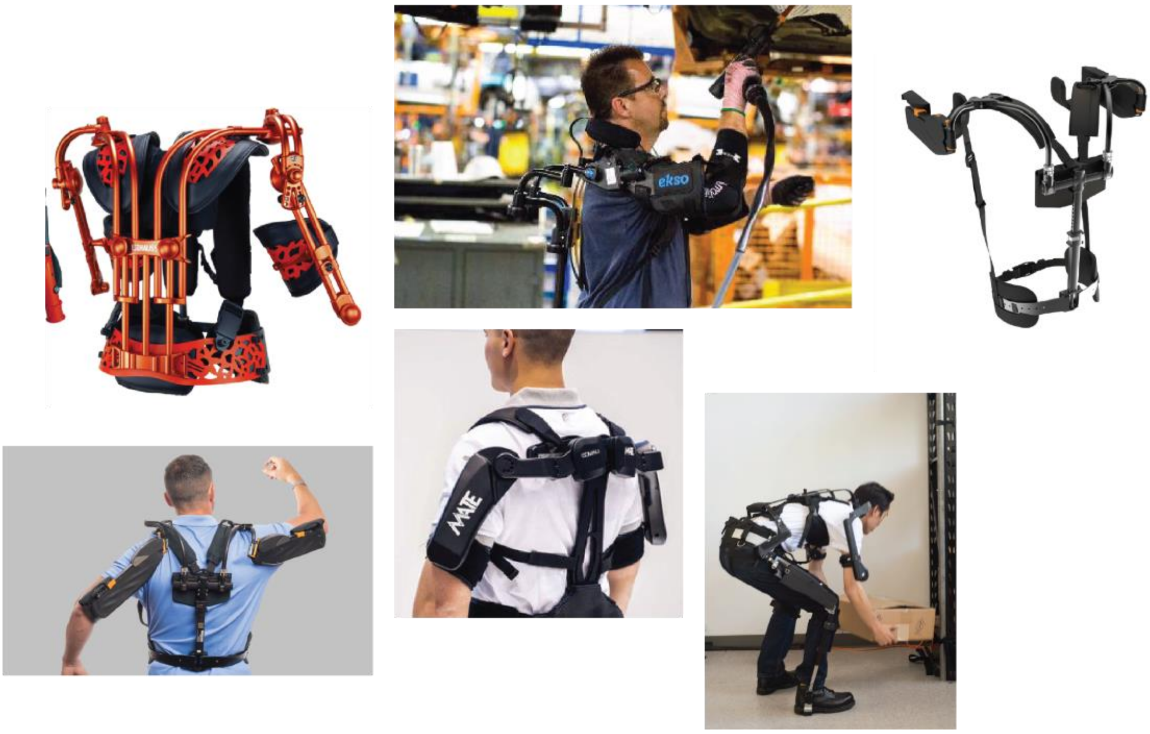
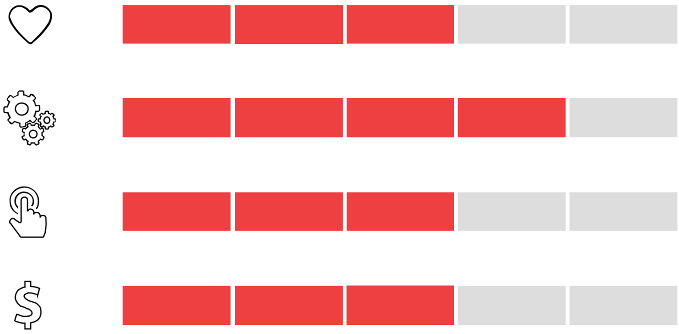



***Fig. 2-6*** Upper body exoskeletons [15] [16] [17]



Tool holding exoskeleton

A tool holding exoskeleton assists in carrying heavy tools and relieves from long-term stress. They reduce worker fatigue while improving safety and prevent injuries. Exoskeleton holds the weight of a heavy tool and redirects it straight into the ground. The exoskeleton frame bypassing the wearer's body is attached by straps to the body, waist and legs. The main frame produced of metal allows wearer to move and change positions freely. The tool is usually held in a gimbal to allow for rotation and flexibility. The gimbal is then connected to a spring-loaded arm. A gimbal mechanism allows for full motion of the implement while a counterweight in the back keeps the wearer balanced and steady. [18] [19] [20]

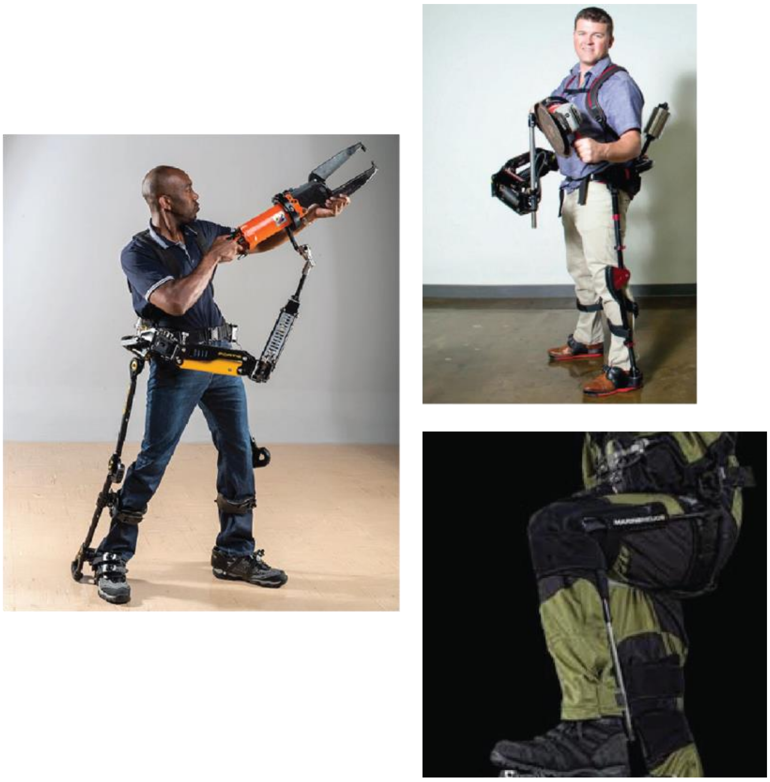
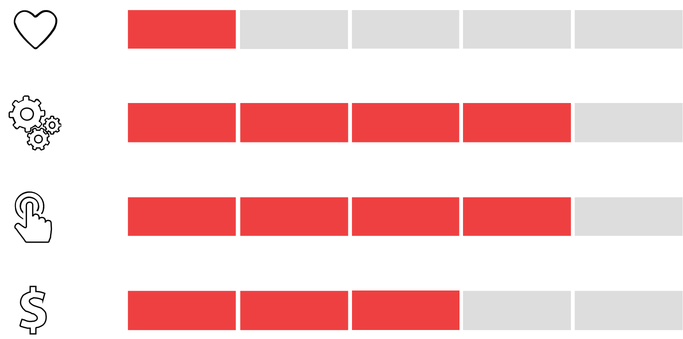


***Fig. 2-7*** Tool holding exoskeletons [18] [19] [21]



### Exosuit

Exosuit is a next generation of soft wearable robotics that use innovative textiles to provide a more conformal, unobtrusive and compliant means to interface to the human body. As compared to a traditional exoskeleton, these systems have several advantages: the wearer's joints are unconstrained by external rigid structures and worn part of the suit is extremely light. These properties minimize the suit's unintentional interference with the body's natural biomechanics and allow for more synergistic interaction with the wearer. Exosuits can be either passive or active. New sensor technologies are being developed so that they can detect key event in the gait cycle and can be easily integrated in the garment. These wearable sensors can be used as part of the control strategy or alternatively to monitor and record the movement of the wearer. [22] [23] [24]

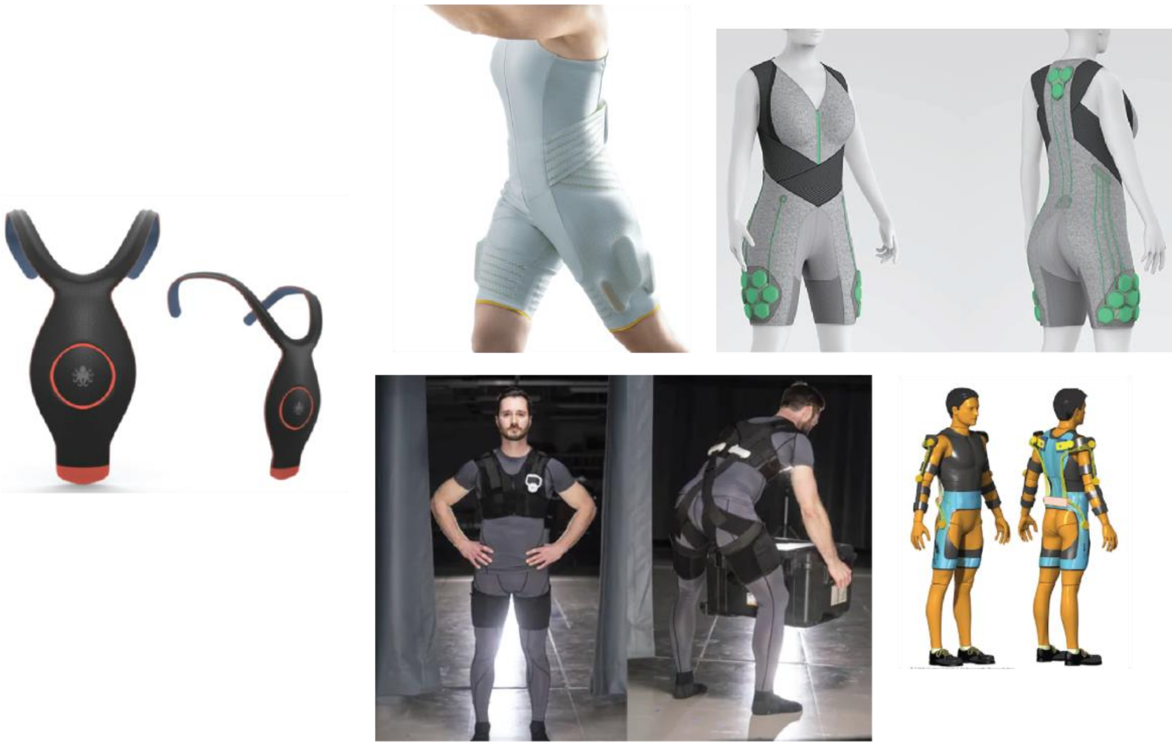
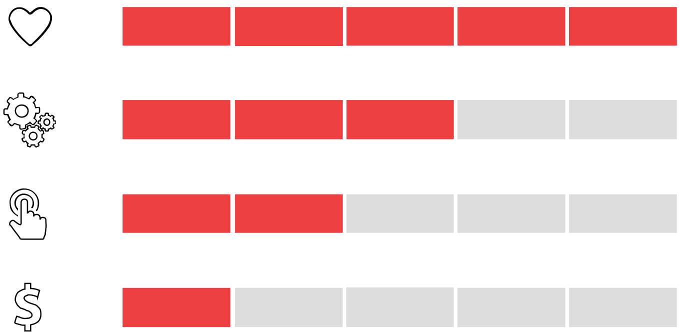


***Fig. 2-8*** Exosuit [22] [23] [24] [25]



## Power glove

In Europe, North America, and Japan alone, more than 50 million people have a weak hand grasp due to illness, injury, stroke or old age. Power glove is type of soft exoskeleton, worn as typical glove, with the main goal to augment wearer's grip and dexterity, prevent fatigue and hand injuries. It is made of soft flexible fabric, making it light and comfortable to wear compared to classical rigid frame exoskeleton devices. The exoskeleton is usually comprised of sensors, power supply and connection system. Current manufacturers are using different technologies. RoboGlove, originally developed by NASA, comprises actuators and tendons embedded into the glove that are comparable to the nerves, muscles and tendons in a human hand. The Japanese company Daiya developed a pneumatic hand exoskeleton, in which inflatable membrane and controller is integrated into the glove. When the side of the hand opposite the thumb touches the table, the power glove inflates providing assistance in grasping. [26] [27] [28] [29]

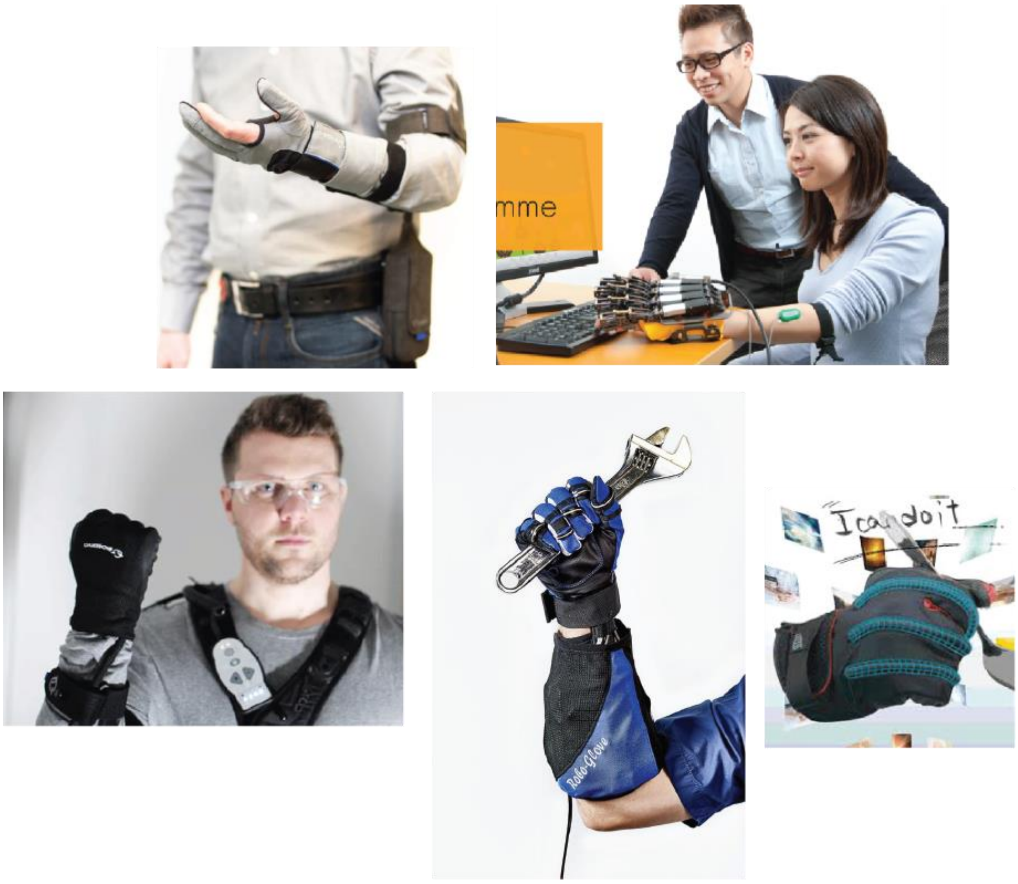
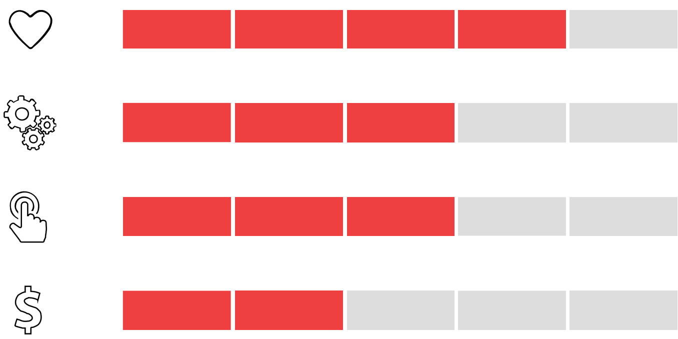


***Fig. 2-9*** Power glove [26] [27] [28] [29]

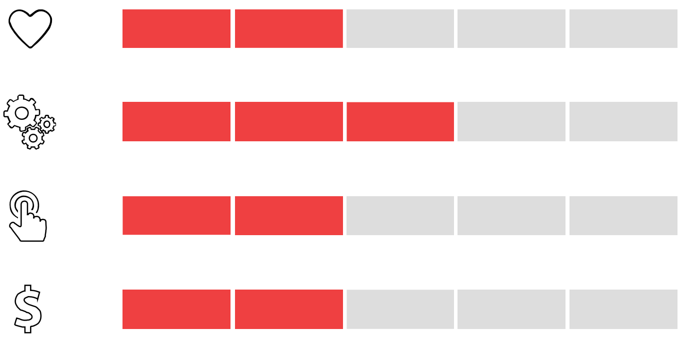


## Back support

The back-support device is designed to prevent back injuries, keep wearer's body in the correct posture so that the wearer's performance is also enhanced. Current devices provide two axes of movement, one for bending at the waist, and another for supporting the thighs. The pack works as a counterweight and keeps the wearer steady when lifting heavy objects. Devices are powered hydraulically or pneumatically.

Muscle Suit by Innophys can be controlled in two ways. The user can either touch and control surface using their chin or blow into a tube. This creates a hands/free control system for a powered exoskeleton. Unlike other exoskeletons, FLx ErgoSkeleton does not try to assist or augment the user physically but instead focuses exclusively on keeping the user safe. It keeps the position of the human body as to always stay within a safe body posture while lifting or moving heavy objects. [30] [31] [32] [33]

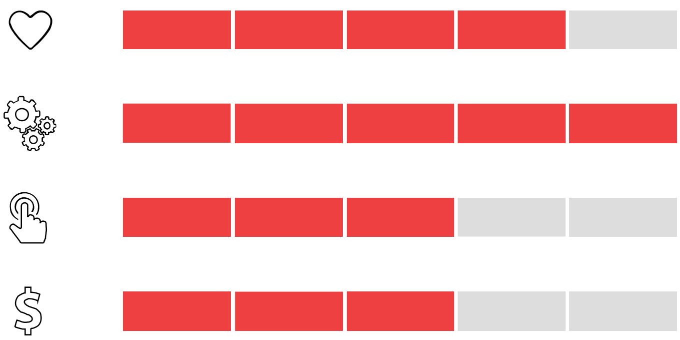

***Fig. 2-10*** Back support [30] [31] [32] [33] [34]



### Sport

Robotic exoskeleton, designed for sport, focuses mainly on skiing and enables seasoned skiers to continue to enjoy the sport free of discomfort. It improves knee stability and provides structural support for knee joints and squads. The lightweight exoskeleton frame is closely surrounding the legs and is attached with thigh and shin strap. The braces are then connected to the ski boots to transfer the weight to the skis. Sensors and software on the exoskeleton anticipate user intent and automatically adjust torque at knee via pneumatic actuators. Skier usually is wearing a power backpack. Device by SkiMojo as the only one can be worn discreetly under ski trousers. [35] [36] [37] [38]

***Fig. 2-11*** Exoskeleton for sport [36] [37] [38]



#### Summary

Designer analysis has shown that the exoskeleton is a device that surrounds the body of the user. It is essentially the frame construction, attached to the body straps. The device is a part of a person, it allows him to move in a desired direction. Exoskeletons are a relatively new technology that has evolved over several decades from robust and heavy mechanisms into a compact, light and simple construction, which strives to ensure the greatest possible comfort for the user without space limits. Many companies are starting to launch their exoskeletons in new markets; however, the current exoskeletons are rich in shortcomings in terms of hygiene, replacements of textile parts, space constraints, and stability on the wearer’s body. Nevertheless, there are also concepts of so-called soft suits, which are themselves apparel, but these devices have not been tested sufficiently, and technology of artificial muscles used for actuation is still subject to research.

## 2.3 Technical analysis

Working exoskeleton is defined as wearable external mechanical device. It is a device that supports and improves human performance by increasing strength, stamina and other physical abilities of a healthy and fit individual. It can be used to lift and carry heavy objects and to support heavy tools.

### 2.3.1 Exoskeleton components

Although the market offers various designs of robotic exoskeletons that may have different use, there are many aspects similar to all of them. In the following sections, significant parts of exoskeleton designs, including actuators, sensors, control strategy and materials, are being discussed.

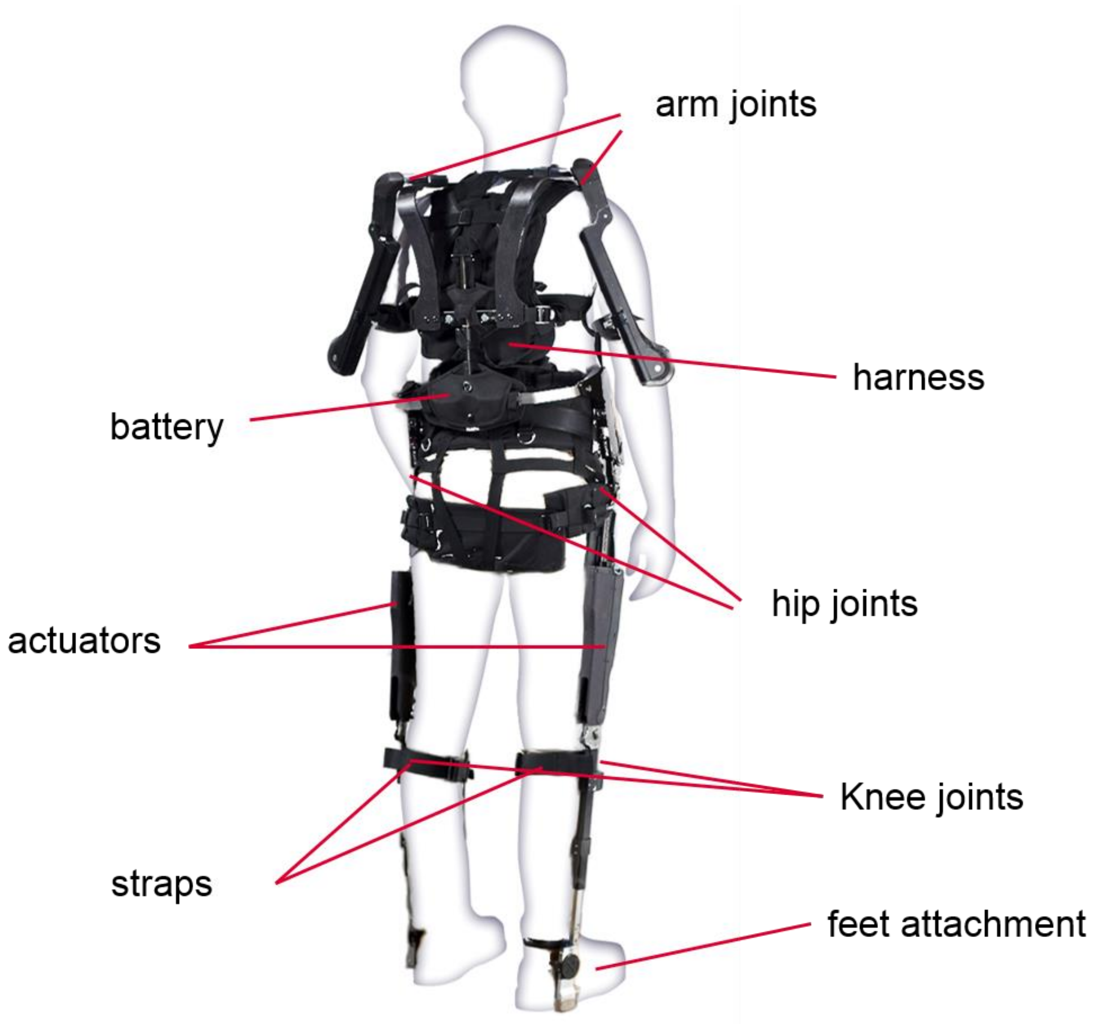



***Fig. 2-12*** Exoskeleton parts

### 2.3.2 Actuators and energy production

Historically exoskeletons have been limited by the weight, size, and power efficiency of the motors they use. Engineering teams went through several iterations of design with different types of actuation. The goal of the actuator is to provide torque to the device at a joint of interest. This means that actuator must overcome the weight and resistance of the exoskeleton and allow user to move easier than without actuation. However, the advent of new technologies has allowed for more functional designs that are portable and not as reliant on the large, bulky actuators seen with early exoskeletons. Majority of the exoskeletons utilize electric servo motors as a main source of actuation. Less common are hydraulic and pneumatic actuators. [39]

## DC motor

Electric servo motors provide the best position-based controllers that are often favoured by robotics researchers. Servo motors are self-contained electric devices that provide rotation or shifting parts of a machine with great precision. They can be divided into various categories according to their construction and energy supply. Two basic types are AC and DC motor. AC motors are based on induction motor designs that consists of electromagnetic winding around the outside - stator, which is supposed to produce rotating magnetic field using applied alternating current. Inside the stator, a loop of wire, a coil, a squirrel cage or some other freely rotating metal part, that can conduct electricity, is located. [40] [41]

### *Servomotors*

Electric servo motors provide the best position-based controllers that are often favoured by robotics researchers. Servo motors are self-contained electric devices that provide rotation or shifting parts of a machine with great precision. They can be divided into various categories according to their construction and energy supply. Servomotor consists of electric motor (AC or DC, depending on specific motor application) and built-in rotational encoder. External electronic driver monitors shaft position via built-in rotational encoder and based on that, sends electric commands to the motor.

Two basic types are AC and DC motors. AC motors are based on induction motor designs that consists of electromagnetic winding around the outside - stator, which is supposed to produce rotating magnetic field using applied alternating current. Inside the stator, a loop of wire, a coil, a squirrel cage, or some other freely rotating metal part that can conduct electricity is located.

DC motors are divided into two categories - brushed and brushless. In a brushed DC motor is stator comprised of permanent magnets fixed in place that forms the outside static part of the motor. The rotor consists of a coil of wire and commutator. Electric current is transmitted via brushes into a rotor. When a direct current is applied to the coil, temporary magnetic field around it is created that causing the coil to rotate. Using commutator enables keeping rotation in the same direction for as long as the current keeps flowing.

The most popular type of motor used in exoskeleton technology is a brushless DC motor due to its high torque-to-weight ratio. In DC brushless motors the rotor consists of series of permanent magnets arranged around the entire circumference of the rotor. According to the design, brushless motors can be either "in-runner" (rotor is inside the stator) or "out-runner" (rotor is out of the stator)" Stator consists of an even number of separate coils wound around a metal core. By gradually switching on and off of the current on the coils, rotating magnetic field that subsequently rotates the rotor is generated. [40] [41] [42] [43]

*Fig. 2-13* Servo motor for exoskeletal joint - MAXON [44]

Despite its more complex construction, including built-in rotational encoder and control unit, a servomotor offers excellent speed and position control, long life, and high torque density. To biggest benefits are:

- High torque with compact size
- Extended battery operating time
- Long lifetime
- High efficiency with low power consumption, weight and volume
- Ability to work under load (e.g. sitting position, walking on staircase)

[43]

### Hydraulic actuators

Hydraulic actuators are usually used when a large amount of a motive force is required. Most common hydraulic activators are piston type. It consists of a cylinder, piston, spring, hydraulic supply and return line, and stem. The piston slides vertically inside the cylinder and separates the cylinder into two chambers. The upper chamber contains the spring and the lower chamber contains hydraulic oil. The hydraulic supply and return line are connected to the lower chamber and allows hydraulic fluid to flow to and from the lower chamber of the actuator. The stem transmits the motion of the piston to a valve. [45] [46] [47]

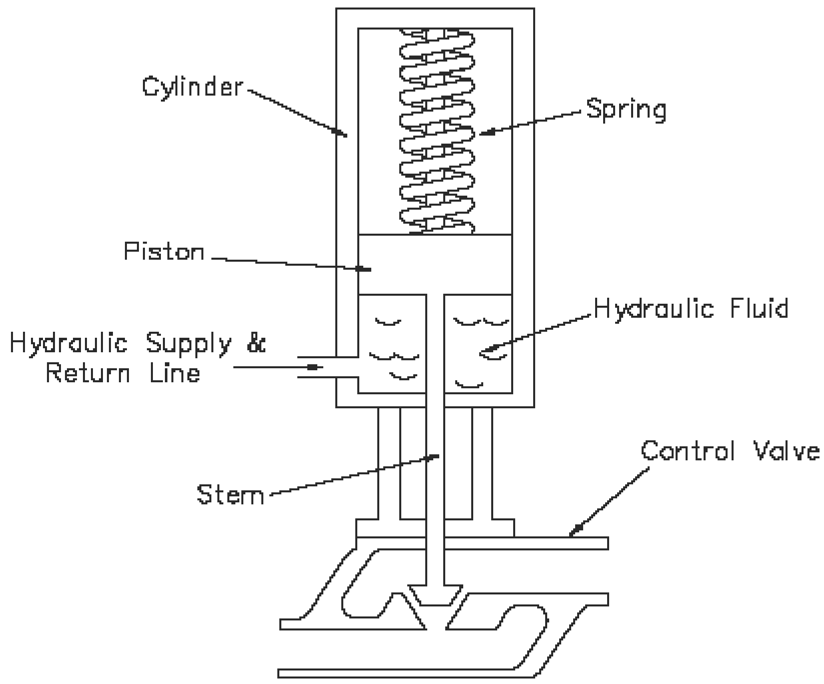



***Fig. 2-14*** Hydraulic actuator principle [46]

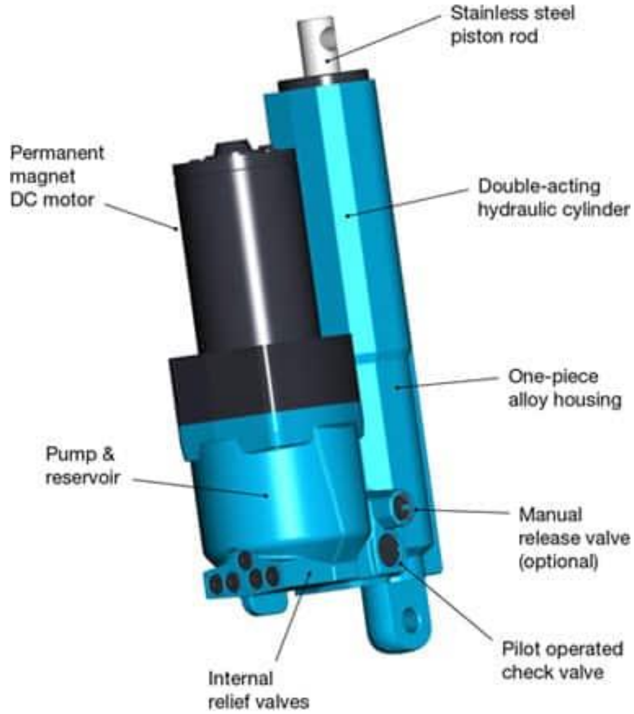



***Fig. 2-15*** Hydraulic actuator [45]

Another type of hydraulic actuators used in exoskeletons are based on human muscle, only instead of using contracting muscle tissue it uses a rubber tube bound by woven high-tensile fibres, which contracts in length as it is pressurized with hydraulic fluid. The combination of rubber and fabric gives it a structure like that of the human artery, so it responds dynamically as pressure is applied and released, allowing it to move smoothly and precisely. In addition, it has a very high strength-to-weight ratio, muscles are very tough and resistant to impacts and vibrations. [47] [48]

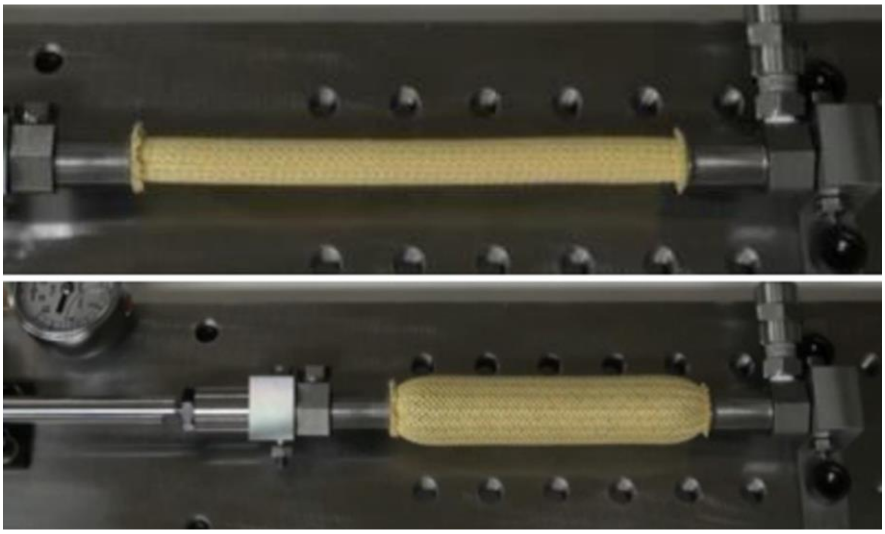


***Fig. 2-16*** Hydraulic actuator [47]

### McKibben artificial muscles

Artificial McKibben muscles are an example of technology simulating real action of muscle elements of living organisms. These devices, being powered by a specific medium – liquid or gas, mimic the processes of contraction and relaxation of muscles, causing the formation of the corresponding axial stresses. Latest conducted research focuses on chemically activated pneumatic muscles.

Their main advantage is high power to weight ratio and power to volume ratio, what is five time higher than those offered by electric motors. Another advantage of artificial muscles is that they can work, as so called “soft actuators”, which means a higher level of security for the user in the event of structural damage of the exoskeleton, and the low impedance of the actuator itself. [49]

The muscles consist of an inflatable inner bladder inside a braided mesh, clamped at the ends. When the inner bladder is pressurized and expands, the geometry of the mesh acts like a scissor linkage and translates the radial expansion into linear contraction. Standard McKibben muscles contract in a linear motion up to a maximum of typically 25%, though different materials and construction may yield contractions around 40%. [50]

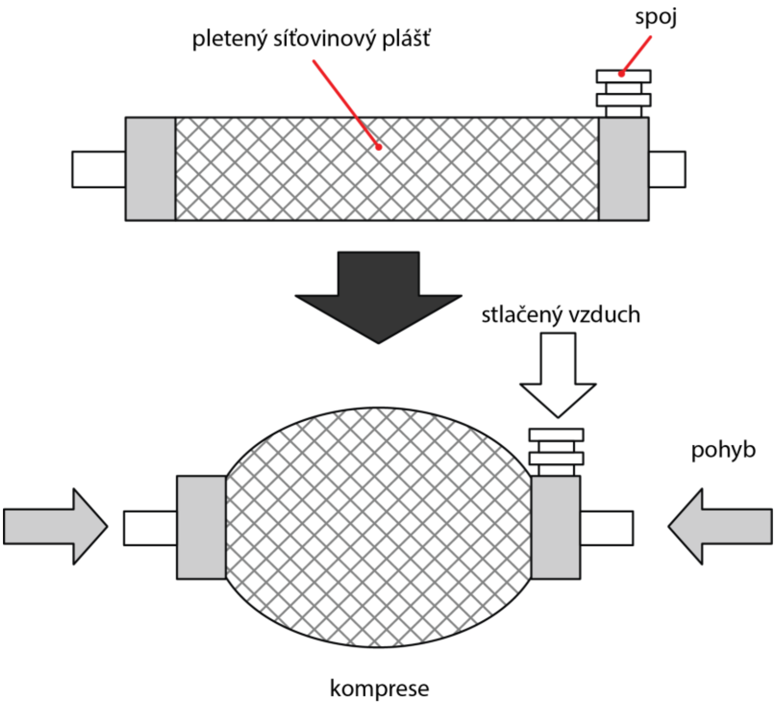



***Fig. 2-17*** Principle of McKibben muscle

***Fig. 2-18*** McKibben muscle [52]

The main drawbacks of this technology are difficulties to accurately control the muscle work, due to the nonlinearity caused by the compressibility of the working medium and the flexibility of the coating. Moreover, compressed air requires adequate supply of this medium, and this in turn requires a compressor and air handling unit, or air container, what makes the actuation system heavy and bulky and unsuitable to be utilized as microactuators or in portable applications where a compact size and weight minimization are desired. [49] [51]

### Shape memory alloy

The search for a new designs or technology implementation for exoskeletons contributed to the development of innovative materials, such as shape memory materials (SMA), or dielectric materials. SMAs are metallic alloys with the ability to return to a predetermined shape when heated. After an apparent plastic deformation, the SMAs undergo a thermo/elastic change in crystal structure when heated above its transformation temperature range, resulting in a recovery of the deformation. In SMA, a change between a mother phase and a product phase is produced. This transformation phase causes the crystallographic movement of the alloy structure, producing a macro scale effect known as shape memory. [49] [53]

Most remarkable applications can be found in the field of actuators for deployable structures and in aerospace mechanisms. In the forms of fibres, it becomes a contractile material that can be programmed, just like natural muscles fibres, either as a fast response fibre, or as a slow response fibre. The principle of contraction is based on the transformation phase of the material, and the principle of activation is thermal, that can be induces electrically through joule effect, or by other heating means. Above a certain temperature, the transformation occurs. This transformation temperature can be selected during the manufacturing process. [53] [54] [55]

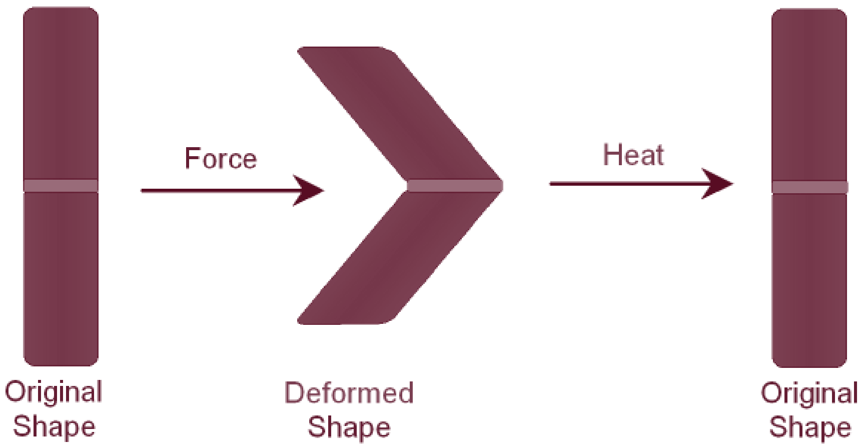



***Fig. 2-19*** Shape memory alloy principle [56]

### Dielectric elastomers

Dielectric elastomer actuators (DEA) are a class of electroactive polymers which work based on inducing of deformation with and electric field. A common design of DEAs is to sandwich a soft insulating elastomer membrane between two compliant electrodes. When a voltage is applied between the electrodes, the arising electric field causes a decrease in thickness and increase in area of the membrane. [57]

Results in field of dielectric muscles research show extraordinary efficiency, but a small amount of change of length and a non-linear value of contraction force do not yet allow their use as actuators in the major joints of the limbs. Dielectric elastomers show unique properties such as good actuating pressure, strain, efficiency, fast response, high energy density. [49] [58]

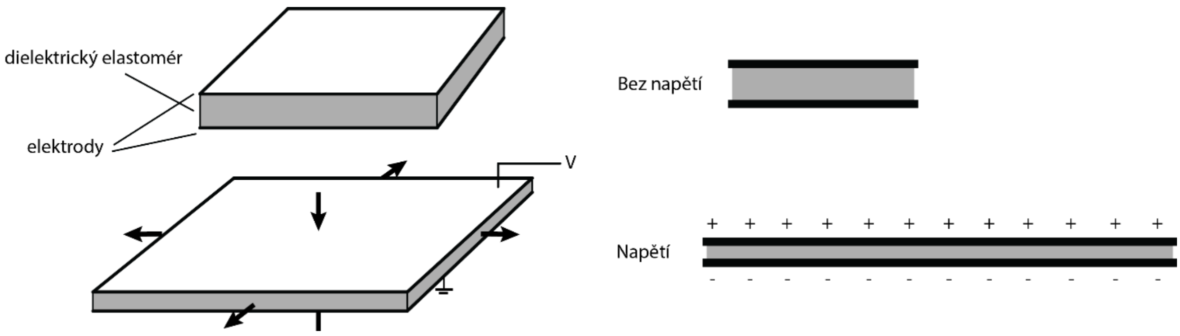



***Fig. 2-20*** Dielectric actuator principle [58]

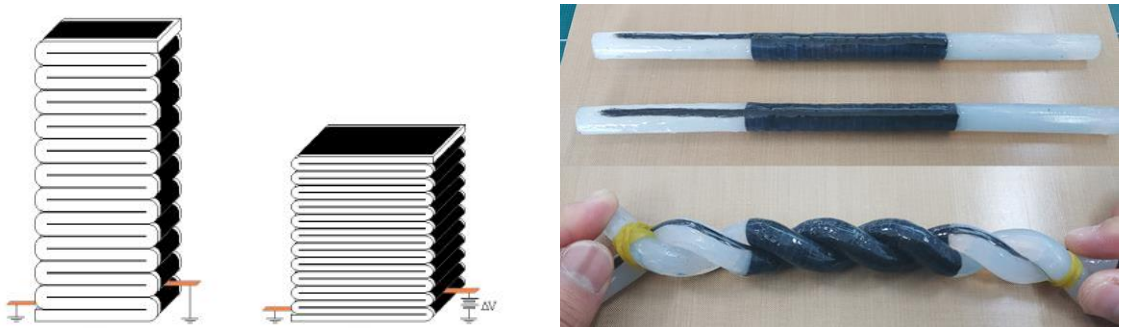


***Fig. 2-21*** Dielectric actuator [58]

### 2.3.3 Sensors

In order to provide an appropriate amount of actuation to an exoskeleton, sensors are required to regulate the force, torque, or position of the device. It is necessary to prescribe an overarching strategy for how it is to be controlled. The inputs to this control strategy are the desired actions to perform. The desired action, in turn, is dictated by the state of the system and estimated intention of the user. There are variety of sensors used to acquire this information.

***Position sensors***

The vast majority of exoskeletons use methods of detecting the joint angles and the position of the various links with respect to the exoskeleton base. There are a variety of different choices to establish this information including encoders on the motors, encoders or potentiometers placed at joints, flex sensors, and linear variable differential transducers among others. Position sensors are required to obtain the physical configuration of the exoskeleton and are therefore critical to many control strategies. Joint position is also important to ensure that the limits of the exoskeleton's range of motion are within safe and acceptable range for the user. [59]

***Force/torque sensors***

Numerous applications require knowledge of the force/torque experienced by exoskeleton. This information can be used to enable admittance or force control, provide information about the muscle progress, and for interactive use as a teleoperation or virtual reality haptic device. Inclusion of force/torque sensors are varied, with some systems omitting them, others building them into the fundamental structure of the device, and others placing them at human-robot interface. Force sensors can come in the forms of a force sensitive resistor, a load cell, or a pressure sensor. Many controllers rely on accurate measurements of exoskeleton dynamics in order to work smoothly. [39] [59]

***Non-mechanical sensors***

Neural or neuromuscular sensors are not as common, but they can provide information for the controller about user's intent prior to development of large limb forces. Electromyography (EMG) and electroencephalography (EEG) systems measure muscle and brain activity over time by measuring electric potentials on the surface of living tissue. Nervous stimuli and muscle contractions can be detected by measuring the ionic current flow in the body. This is accomplished using a biopotential electrode. There is a natural electromechanical delay in human muscles, meaning that the muscle electrical activity occurs prior to force development. Thus, muscle activity has been a major area of investigation for exoskeleton control, but tends to suffer from problems with reliability, noise, and movement. [39] [60]

### 2.3.4 Control

The control system is the core of the exoskeleton robot. If control system cannot fleetly process information transmitted by sensor and drive power system, man and exoskeleton cannot match up well. Acceleration sensors, force sensors, encoders, and so on a large number of sensors can real-time monitor of the state of motion of the human. [61]

There are different types of control systems applied according to the structure of the exoskeleton frame and intended function of the device that directly affect the type of controller that will be most successful.

One of the exoskeleton control system categories is model-based control system. In general, according to the model used, the control strategy for the skeleton can be divided into two types: the dynamic model and the muscle model-based control. The dynamic one uses model of the human body as rigid links joined together by joints. In contrast to dynamic model, the muscle model is based on prediction of the muscle forces that are developed by the muscle of the human limb joint as a function of muscle neural activities and the joint kinematics. [62]

### 2.3.5 Materials

To construct an exoskeleton requires a proper material selection, as it is an important aspect influencing the bulk, weight, and comfort. The frame must be able to provide a structure to which the actuators can attach and transfer power. As well as provide a comfortable interface for the user’s body. The framing should be as lightweight as possible while still allowing for torques to applied at the desired joints. The traditional concept of a robotic exoskeleton worn by a human often uses a rigid body connection to transfer power from the device to the human.

Many exoskeletons use rigid metal frames consisting of aluminium or aluminium alloy. Aluminium provides light, durable and functional properties. It is one of the lightest metals in the world, strong, extremely flexible and corrosion resistant due to very thin and very strong layer of oxide film. Since aluminium easily forms compounds with other chemical elements, a huge variety of aluminium alloys have been developed. Even a very small number of admixtures can drastically change the properties of the metal, making it possible to use in new areas. [63] [39]

Another frequently used material in exoskeleton technology is titanium. Titanium alloys are very strong, lighter in weight than steel, and corrosion resistant. Titanium is used in some prefabricated orthotic and prosthetic components when simultaneous strength and light weight are required. In conjunction with light weight composite shells and plates, metal components of exoskeleton are preferably chosen by titanium alloy to decrease the total weight of device. [64]

Carbon fibre is a polymer, that shows extraordinary properties. It is five-times stronger than steel and twice as stiff. Carbon fibre is made of thin, strong crystalline filaments of carbon that is used to strengthen material and it can be laid over a mould and coated in resin or plastic. Carbon fibres are often employed to achieve a more lightweight design, although these are more expensive and harder to mould and machine than metals. Soft exoskeletons consisting of flexible textiles are another new method of reducing the weight of the frame and use cable or other soft connections to transfer power. Fabrics represent a class of highly comfortable materials that have the potential for embedded function and are highly integrated into daily lives. [65] [66]

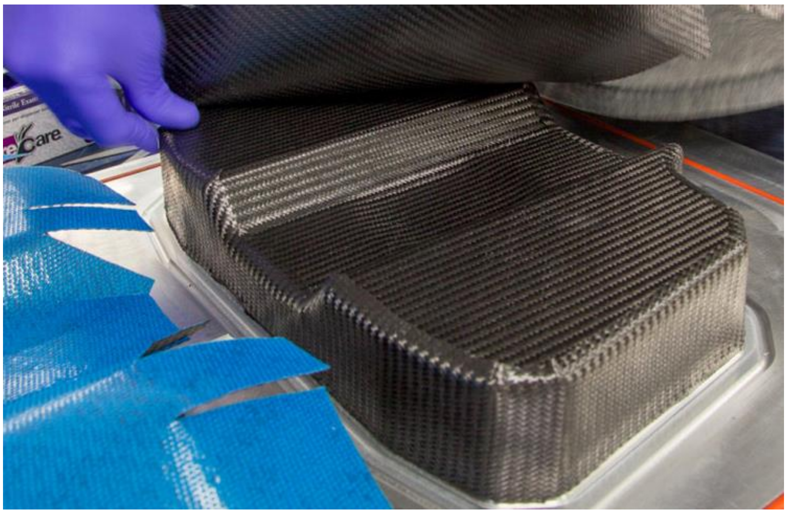


***Fig. 2-22*** Carbon fibre [65]

### 2.3.6 Ergonomics

Injuries caused by manual handling can have serious consequences for both employees and employers. They can occur virtually anywhere in the workplace, during heavy work, poor posture, repeated shoulder, leg or back movements. Many factors are important when handling objects that increase the risk of injury. These include the weight of the object, the frequency of manipulation, the distance, the location of the relocation, the human position, the environmental characteristics. Lifting a weight below the maximum limit does not always make the load safe. The weight of the load is not the only factor to be considered. There are several factors to consider when assessing whether a load is safe for an employee to lift at work. [67] [68]

The guidelines assume that the manual handling and lifting is taking place in reasonable working conditions. It is also assumed that the load is easy to hold and can be easily grasped with both hands. The guidance is also based on the assumption that the weight is being lifted by a reasonably fit, well-trained individual. Maximum workload is determined by hygiene regulations for manual load handling, which specifies a maximum load for men of 30 kg and for women of 16 kg. Whole version of the regulation can be found in § 29. Work in which the hands grip more than 60 degrees with the body is considered overhead work. [69] [70]


***Fig. 2-23*** Maximum load for manual handling [70]

### 2.3.7 Joints and kinematics

A human skeleton is composed of around 206 bones in adulthood. They form a strong structure, that allows movement. A joint is an attachment between bones in the body that link the whole skeletal system. There are three types of joints – fibrous, cartilaginous and synovial. For the next study of the thesis, the motion of synovial joints is important. [71] [72] [73]

Synovial joints allow a huge range of movements, which are defined by the arrangement of their surfaces and the supporting ligaments and muscles. There are many different classes of synovial joints in the body:

***Hinge***

Permits flexion and extension

***Saddle***

Concave and convex surfaces unite at saddle joints

***Plane***

Permit gliding or sliding movements

***Pivot***

Permits rotation; a round bony process fits into a bony ligamentous socket

***Ellipsoid***

Allows flexion, extension, adduction, abduction, and circumduction

***Ball and Socket***

Allows movements in several axis; a rounded head fits into a concavity

[71]

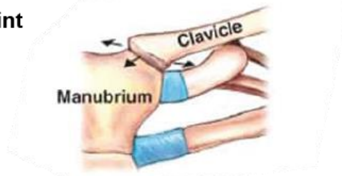
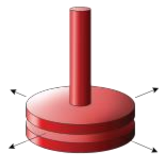
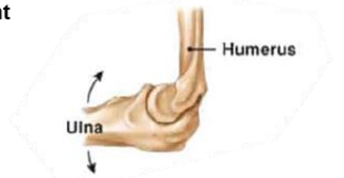
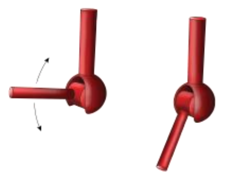
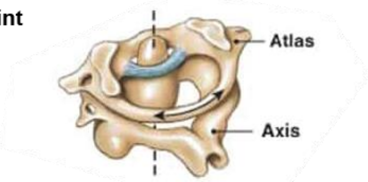
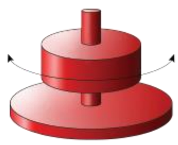
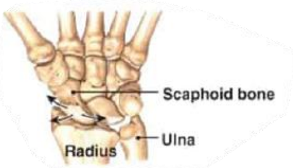
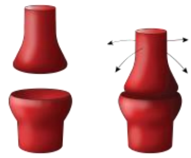
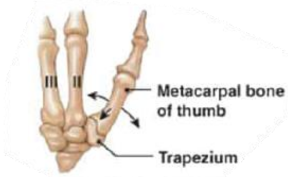
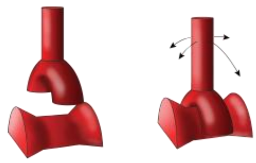
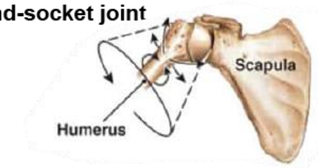
| Types of Synovial Joints | Models of Joint Motion | Examples |
|---|---|---|
| **Gliding joint**  |  | • Acromioclavicular and sternoclavicular joints<br>• Intercarpal and intertarsal joints<br>• Vertebrocostal joints<br>• Sacro-iliac joints |
| **Hinge joint**  |  | • Elbow joints<br>• Knee joints<br>• Ankle joints<br>• Interphalangeal joints |
| **Pivot joint**  |  | • Atlas/axis<br>• Proximal radio-ulnar joints |
| **Ellipsoid joint**  |  | • Radiocarpal joints<br>• Metacarpophalangeal joints 2-5<br>• Metatarsophalangeal joints |
| **Saddle joint**  |  | • First carpometacarpal joints |
| **Ball-and-socket joint**  |  | • Shoulder joints<br>• Hip joints |

***Fig. 2-24*** Types of synovial joints [72]

According to the physiological structure of human body, exoskeletons must be designed to cover the range of motion of the joints, so they will be unobtrusive during wearing. The human body is very complex, and the range of motion depends on the placing of the bone head in the socket, and the system of tendons and ligaments and their ability to contract. To better understand and describe the human body, certain number of degrees of freedom (DOFs) can be assigned to every joint according the D-H convection. [74] [75]

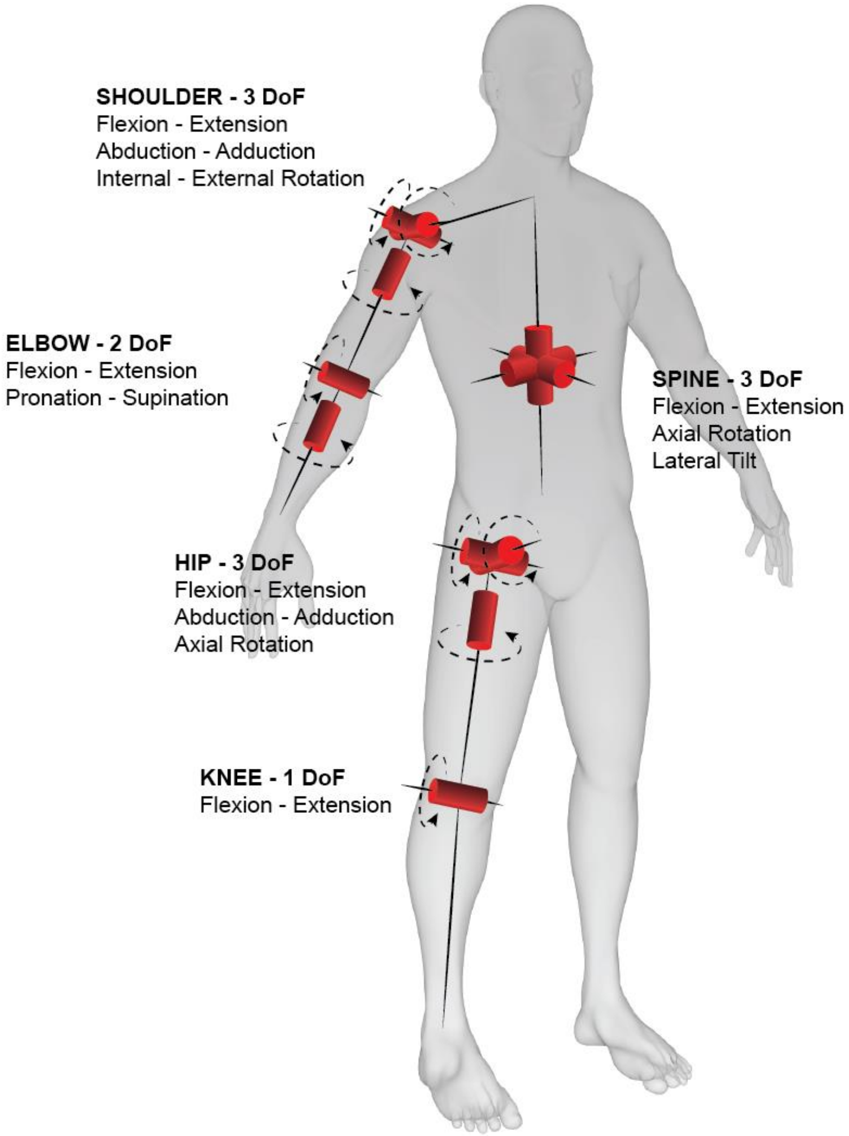



***Fig. 2-25*** DoFs of human joints [76]

The human upper limb can be divided into two parts: arm and hand. The arm is divided into the upper arm and the forearm. The shoulder joint has three degrees of freedom: horizontal and vertical movement, flexion and extension movement, internal and external rotation. Elbow joint has one degree of freedom for flexion and extension and the forearm has one degree of freedom for external and internal rotation. [75] [77]

Similarly, for the lower limb, hip joint has three degrees of freedom – flexion and extension, abduction and adduction, internal and external rotation, knee joint has one degree of freedom – flexion and extension, and ankle joint has two degrees of freedom – abduction and adduction, flexion and extension. [78]

## Summary

Exoskeletons are rather new technology spreading throughout the market. They have been produced using all sorts of accessible technological processes and materials. Their exact form depends on the purpose of each device, as every single device must follow human parameters, dimension, intended work or amount of load. Current devices use either passive or active mechanisms. However, new technologies such as artificial muscles, shape memory alloys or programmable materials are the subject of research, implementation and testing on real devices, they can be expected in near future.

# 3 PROBLEM ANALYSIS AND GOALS

## 3.1 Analysis, interpretation and evaluation of research

Exoskeleton have been used mainly in health care and the military in the past. Since they are nowadays available in the commercial market, they have been encountered in various industries and have penetrated the household and everyday life. With respect to utilization it is necessary to consider what the purpose of the proposed exoskeleton will be and then, adapt the size of the elements so that their placement does not affect the overall comfort and appearance of the device. In the past, many devices were massive and have been designed to encircle the entire body, so dressing and undressing was difficult. Today`s products focus more on specific activities, when a part of the body is stressed. Manufacturers are trying to achieve more compact shapes by reducing electronic elements and not functional contact surfaces.

Main parameters to be observed when designing exoskeleton are:

- Ergonomics
  - Dressing/undressing
  - Easy to adjust
  - Customization
  - Changing settings while working
  - Flexibility
- Safety
  - Preventing unwanted and dangerous movement
- Maintenance
  - Cleaning of the device, especially textile parts
  - Easy repair and replacement of damaged parts
- Technical parameters
  - Resistance
  - Low weight
  - Appropriate material use
  - Intuitive control
  - Sensors
- Price
  - Making product competitive in the market

## 3.2 Market segmentation

Market segmentation is the process of dividing a market of potential customers into groups, or segments, based on different characteristics. The segments created are composed of consumers who will respond similarly to marketing strategies and who share traits such as similar interests, needs, or locations. [79]

| TARGET GROUPS | Tasks | | The individual | The load | The environment | Future | |
|---|---|---|---|---|---|---|---|
| industry workers | mostly overahead work | carried out for too long, repeated | men, (about 10% women), all ages, | heavy tolls, assembling, mounting small components | limited space | many task requiring human power, accuracy, automation | > biggest room to improve and develop protective equipment |
| warehousmen | lifting heavy objects, translating obejcts | for too long, repeated | | various size of boxes | enough space | replaced with robots | |
| lumberjacks | bending, holding heavy tools | frequent | men, well trained | holding saw | enough space | | |
| bricklayers | bending, | repeated | men | | enough space | replace, other technologies not requiring human power | |
| doctors/surgeons | holding tools in one position, bending | varies | men | small tools | little working space, requires much concentration, good vision | robotic | |
| nurses | lifting pat ents | not often | women, all ages, all types of figures | patients vary in weight, height | limited space | lifting device | |
| airportbaggage handlers | bending, handling with heavy luggage | frequent | men | big, heavy | enough space | automation | |
| healthcare workers | lifting pat ents, bending | | | patients vary in weight, height | limited space | lifting device | |

***Tab. 3-1*** Market segmentation

To identify the target group, an analysis of potential target groups in the field of manual work was performed. Various criteria were evaluated, such as the tasks performed, their frequency, the demands placed on the individual, how heavy loads are handled, and how the environment in which they work is characterized. An important aspect is the development of occupations for the future.

The most common cause of workplace illnesses are musculoskeletal injuries, with up to 37% of the total work-related illnesses in the UK (2019. Findings from the Fourth European Survey on Working Conditions in 2005 revealed that around 23% of Czech workers reported to suffer from work related backache and 23.7% complained of muscular pains. According to statistics, it can be said that 24% In EU suffer from backache while 22% complain of other muscular pain. It is mostly caused of overloading of the upper body, shoulders and back. The cause of these diseases is long-term work with hands overhead, carrying and lifting heavy loads. As a result of this type of work industrial workers are the most affected group, where the upper body is most injury-prone by overloading and the health impacts are most critical. This group is the most represented for the use of exoskeleton and would benefit most in the future. [80] [81] [82]

| TARGET GROUP | Task | | The Individual | The load | The environment | Future | |
|---|---|---|---|---|---|---|---|
| industry worker | mostly overhead work | carried out for too long, repeated | men, (about 10% women), all ages | heavy tools, assembling, mounting small components | limited | many tasks requiring human power, accuracy, automation | >biggest room to improve & develop protective equipment |

***Tab. 3-2*** Selected target group

## 3.3 Observation (OVOC)

The observation and interview method were used to discover the problems concerning exoskeleton and its use. The observation took place at the Volkswagen plant in Bratislava in January 2019. There were tested thirty Ottobock exoskeletons during few months in 2018 on production line when assembling cables, undercarriage covers or at paint shop. In January 2019 another Laevo exoskeleton was tested for two days at the specific workplaces. Observation and testing of the device brought knowledge that will be further taken into consideration when designing and improving a new product.

### Process of testing

The VW plant has 14 800 (in 2018) employees where 61% of workplaces requires overhead work and 7.8% of the workplaces are considered as non-ergonomic. There are several mounting halls where operatives work three eight-hour shifts. Every two hours during the shift, workers change their position on different stands. Takt time is the time between the start of production of one unit and the start of production of the next unit. Takt time in the production line in VW is set to two minutes when the workers must perform the necessary assembly of precisely given components on the stand. In the one takt stand can work maximum four operatives. At the end of the shift 250 cars are produced at the one mounting line. [83]

### Currently used and tested exoskeletons in VW plant

**Ottobock Paexo**

Paexo reduces critical physical strain during work. It has a long-term preventive effect against musculoskeletal diseases in the shoulder area. It improves the quality of the work done, for example due to fatigue or convulsive posture. Weighing 1.9 kg, it is the lightest exoskeleton for work above head level. It can be customized individually, and the level of support is also variable and customizable. No electric drive is required as it is a passive exoskeleton. It can be used for more than eight hours a day. [84] [85]

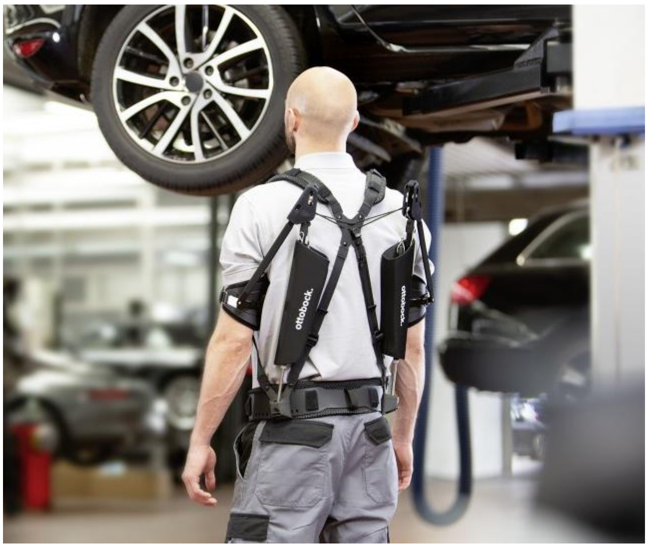



***Fig. 3-3*** Ottobock Paexo [84]

**Laevo**

Laevo is an exoskeleton that consists of a metal frame worn on clothes and which supports the back and spine during bending. Laevo uses a patented chest support and when bending forward, the entire weight of the upper body rests on this plate. The pressure that is usually on the back is conveyed by means of a metal frame through the chest to the legs and greatly reduces the risk of spinal injury. The Exoskeleton incorporates a hydraulic hip system that allows tilt with ease. The device weighs only 4.24 kg and costs less than 2200 pounds. [86] [87]

***Fig. 3-4*** Laevo Exoskeleton [86]

## 3.4 Summary and problem analysis

The exoskeletons were tested from 2 to 3 hours by 30 operatives during the common working hours. Device by Ottobock was applied on the workplaces where mainly overhead work occurs, for example when assembling cables, undercarriage covers or at paint shop. Laevo exoskeleton was tested at the different stands at the production line. At the end, workers completed a questionnaire.

The biggest effect of exoskeleton was in the position above 60˚. Average time when workers must have had their hands above the head level was 8s during one takt time. Although the exoskeletons show many advantages, testing revealed several deficiencies.

The main observed problems are:

- Long-term learning and training how to use the device
- Bad quality of the arm cuff
- Limited movability during working
- Too long straps made of scratchy material
- Not stable and fixed arm cuff – moving on the arm during working
- In warm months cuff created a pressure on the arm
- Few sizes


***Fig. 3-5*** Problems observed in the plant

Wearing exoskeleton is not intended to use whole working hours, it should be used when the workers start to feel fatigue after few hours at work, but it depends on the individuals and their estimation. Long term wearing can lead to muscle atrophy. In conclusion, exoskeleton would recommend 78% of tested workers for use in everyday life as the prevention of fatigue.

## 3.5 Substance and goals of work

The main goal of the thesis is a detailed analysis of the last stage of the development of working exoskeletons and on the ground of ascertained facts the design of a new type of exoskeleton, which will be intended especially for assembly purposes in automotive industry, enables the operator to work in overhead region and will enhances his or her performance and productivity.

The partial goals of the thesis are:

- Identification of market environment needs
- Identifying user requirements for exoskeleton
- Design of adaptable support surfaces regarding dimensional and shape parameters of the user
- Design a method of attaching the contact parts for hygienic replacement
- Ensure the amount of assistance can be adjusted during use without the need for removal of the device
- Identification of suitable materials

# 4 VARIANT STUDIES OF DESIGN

Bringing product from concepts and ideas to the tangible and successful one must undergo product development process. Product creation is a complex process consisting of design techniques and methods that help to understand the product, its deficiencies or positive characteristics, select the target group, include requirements determination, iteration and testing. In addition, good design increases the attractiveness of the product and influence the perception of the end user.

## 4.1 Process of development of the product

In consideration of results of the research and definition of problems were given criteria that must be retained in each design. The criterions evaluated are areas of free movements, user-device contact areas, technology of arm support, selection of joint connection, or method of hygienic maintenance.

Various concepts of auxiliary devices were created for work with hands overhead. They offer several solutions of attachment to the body and mechanisms of the device. Based on certain criteria such as construction, user mobility, feasibility, certain types were selected and are a model for further product development.

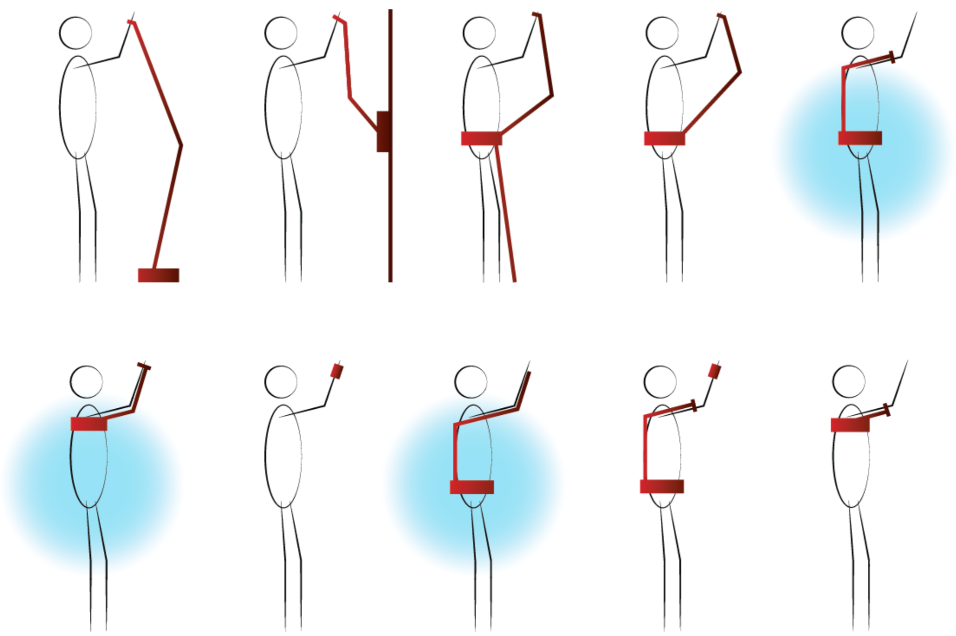


***Fig. 4-1*** Concepts of auxiliary device arrangements

Based on a selective evaluation, selected types of arrangements have great mobility, they are not conditioned by attachment to the wall, ground or other load-bearing structures. These are mainly devices mounted in the area of the hips and various types of attachment and support of either the shoulder or the entire forearm. The next stage of development is to determine the number of degrees of freedom needed to ensure the required movement with respect to the mobility of the human body.

The next important step was a definition of handling area. The minimum required space for comfortable and proper handling can be described as a notional half sphere. In this sphere the most important arm motions, such as arm flexion and abduction, are enabled. The angle from basic position is equal 180°. A larger range outside this area is advantage but not a necessity.

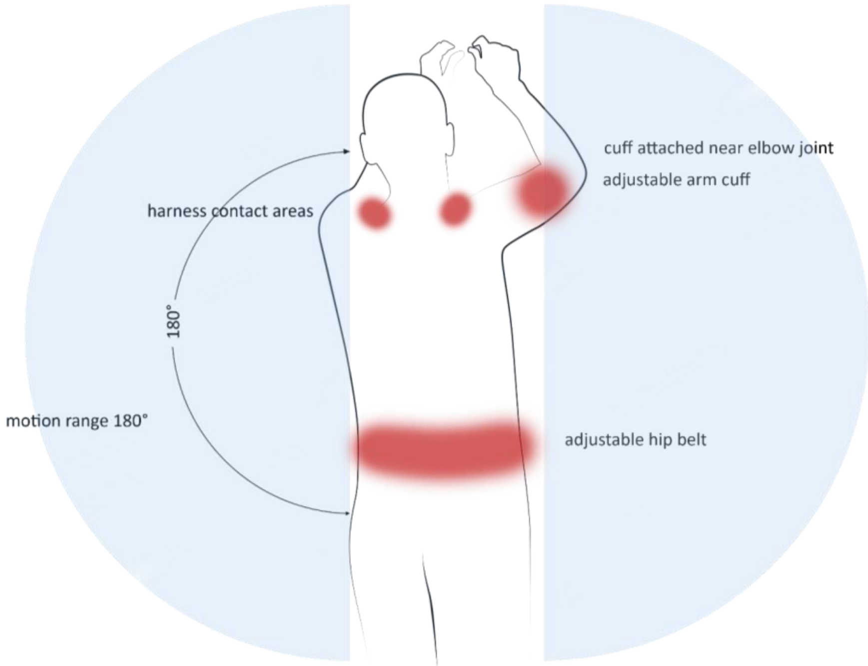



***Fig. 4-2*** Handling area

The critical places on the body that come into direct contact with the device are especially the areas of the hips, shoulders and arms. These places are exposed to higher loads and there might occur pressure, excessive swelling or scratching and discomfort. Therefore, there is a need to pay more attention to this place. Another aspect is the back support, which serves as the main carrier of the load towards the legs. This support contributes to both proper posture and, on the other hand, should be flexible and allow the user sufficient rotation and bending of the torso.

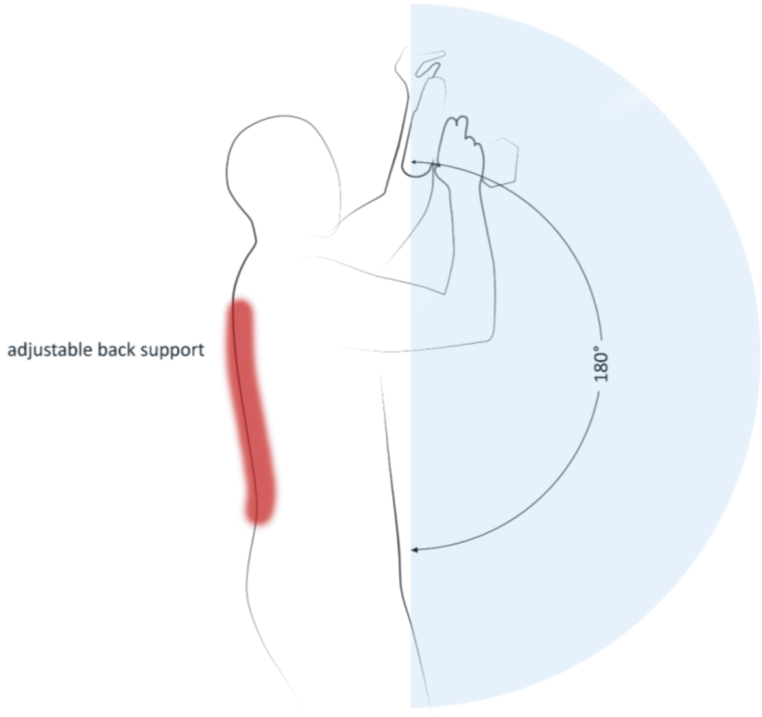



***Fig. 4-3*** Handling area

Based on the knowledge of kinematic analysis and arm motion, models describing the desired movement of the arm, especially its flexion, were created. From the previous requirements for spatial adaptability and mobility of the device, the variants that most meet these needs were selected. Further product development considers these results.

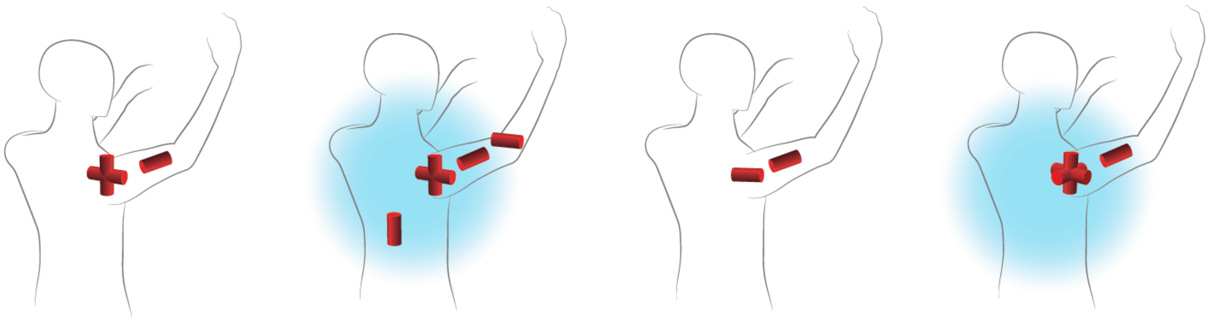


***Fig. 4-4*** Variants of joint arrangement

#### 4.1.1 Prototyping - joint arrangement testing

The kinematics of the joint and the mobility were tested by using a printed model, which allowed to test different combinations and arrangements of the joints and dimensions were easy to adjust. In particular, variants for one to three degrees freedom of shoulder joint were tested, as well as the use of an additional degree of freedom for inner and outer rotation or application of sliding mechanism of the shoulder cuff.

***Fig. 4-5*** Testing prototype

As a result of the testing, it was found that two shoulder joints are sufficient to ensure the required movement without restriction, but it should be necessary to allow rotation of the cuff and its sliding movement to compensate the length around the arm during the movement.

***Fig. 4-6*** Two joint arrangement

Three joints ensured better shoulder movement, they allowed to stretch the arm sideways in more comfortable way. However, it showed that adding 2 more degrees of freedom, sliding and rotation of the arm cuff, will be necessary to balance natural arm motion.

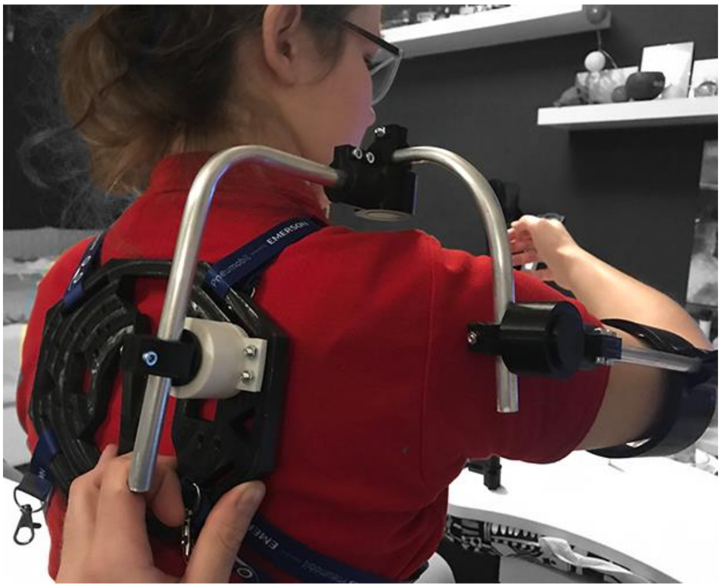


***Fig. 4-7*** Three joint arrangement

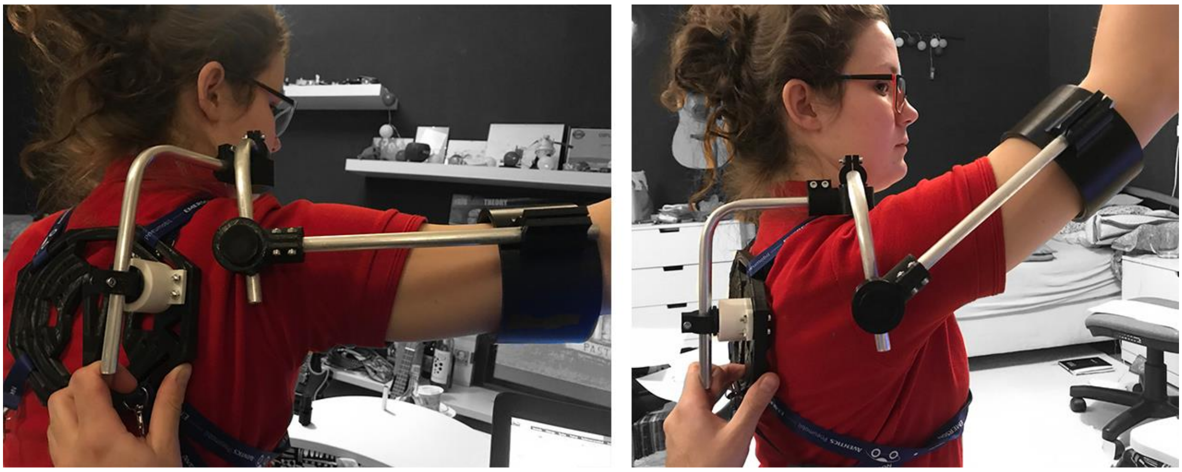


***Fig. 4-8*** Three joint arrangement

## 4.2 Variant studies

Based on the results from the study and testing the kinematics of arm movement and effort to preserve the greatest possible upper limb mobility, several designs were made. Following three variants were selected, based on evaluation according to criteria such as feasibility regarding current possibilities of technology, amount of freedom in the arm movement, or hygiene.

### 4.2.1 Passive exoskeleton - Variant 1

The first variant uses a solid structure copying the human body, through which all the load is transferred to the back unit and then to the lower limbs. The support mechanism uses the knowledge gained from testing different joint arrangements. In this case, the movement of the arm is ensured by means of two joints and a passive mechanism in the side joint assisting during arm flexion. This mechanism is either a gas spring or a torsion spring located directly in the joint.

The forces arising from the use of the device are directed to the back unit, which also serves as a support for proper back posture. However, this arrangement provides minimum of degrees of freedom, and even if the function of the device is fulfilled, there may occur some inconveniences during the usage.

The construction of the device is attached to the body with textile straps. The exoskeleton counts with using a piece of personal clothing underneath, which prevents contamination of the equipment and eliminates the need for frequent cleaning, especially that of the textile parts.

***Fig. 4-9*** Variant 1

### 4.2.2 Active exoskeleton - Variant 2

The basis of the second variant is again a solid construction, partly inspired by the first variant. The difference is adding one movement joint to the rear base, thus allowing a greater range of movement. This arrangement will allow more freedom and unrestricted movement that could occur in some intended positions. Related to this is the addition of rotation to the arm cuff, ensuring internal and external rotation of the shoulder joint. The geometry of the exoskeleton at different hand positions changes and the length of the construction expands. This fact of different length of arm is solved with incorporating a linear guide along the arm. This variant ultimately offers 5 degrees of freedom.

The support of the arm when working with the hands over the head is provided by an air spring with adjustable pressure. Since it is intended to be an active exoskeleton, the presence of a control element, sensor, battery and air source is required. This makes the device not only heavier but also requires a complex construction.

The exoskeleton is again attached to the body with a textile harness. Easier maintenance of the parts that are most often in contact with the body is carried out by removable straps. Adjustable straps allow the user greater size variability. Again, personal clothing is required to better protect the device from soiling.

***Fig. 4-10*** Variant 2

### 4.2.3 Flexible exoskeleton - Variant 3

The third variant is based on the use of flexible muscles and textile materials. The arm support is provided by artificial muscles based on pneumatic tubes sewn into the fabric. The inspiration for the arrangement of this technology along the shoulder are the main muscles in the upper limbs, which participate in the movement of the shoulder and forearm in desired directions.

These pneumatic muscles are guided along the active muscles, which enable the limb to move vertically as well as horizontally. Artificial muscles also require a source of energy and, in the case of pneumatic ones, a source of air. In this active variant, instead of a compressor and heavy batteries, replaceable compressed air bottles are used, which offer easy replacement if necessary. The pressure is regulated by an electromagnetic valve, so the assisted force can be adjusted.  In this way it is possible to achieve low energy consumption.

The soft exoskeleton is worn as clothing, it does not contain rigid parts that discourage movement and create discomfort. However, on the other hand, there is the issue of cleaning and maintenance of the device, as the technology is directly implemented in the suit. For further development it is necessary to set up a procedure, how the parts, which are exposed to the human body sweat, will be additionally treated.

The advantage of this variant is that it ensures the movement of the arm in the entire range of the real arm, it has no space restrictions and offers high user comfort. The disadvantage is the ongoing research of soft muscles which could be used today but has not been sufficiently tested yet. Furthermore, there is still the need of cleaning the exoskeleton after using in such a manner that these innovative technologies would not be damaged in any way during this hygienic maintenance.

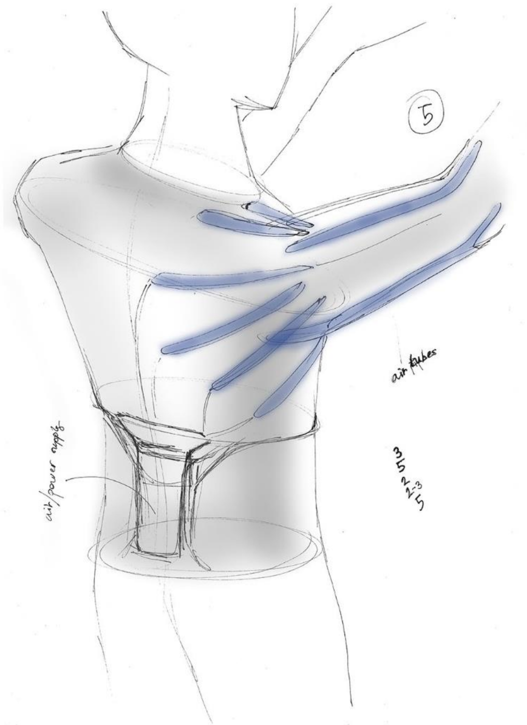



***Fig. 4-11*** Variant 3

## Summary

Variants of the study offer insights into different solutions for wearable devices. They can be passive or active and some future concepts show the possibility of using new artificial muscle technologies. After evaluating the positives and negatives, regarding the currently available technologies and the complexity of the implementation, it appears to be the most favourable variant of the passive exoskeleton. When it comes to joint mobility, the use of artificial muscles provides the best possible solution. On the other hand, it lacks the possibility of easy hygienic maintenance.

# 5 SHAPE SOLUTION

The device becomes a part of the user's body, so the goal is to ensure that the product performs its function properly, but at the same time will be convenient during its using. This means the elimination of all the parts that could meet the environment in which the operator works and ensuring the best possible mobility.

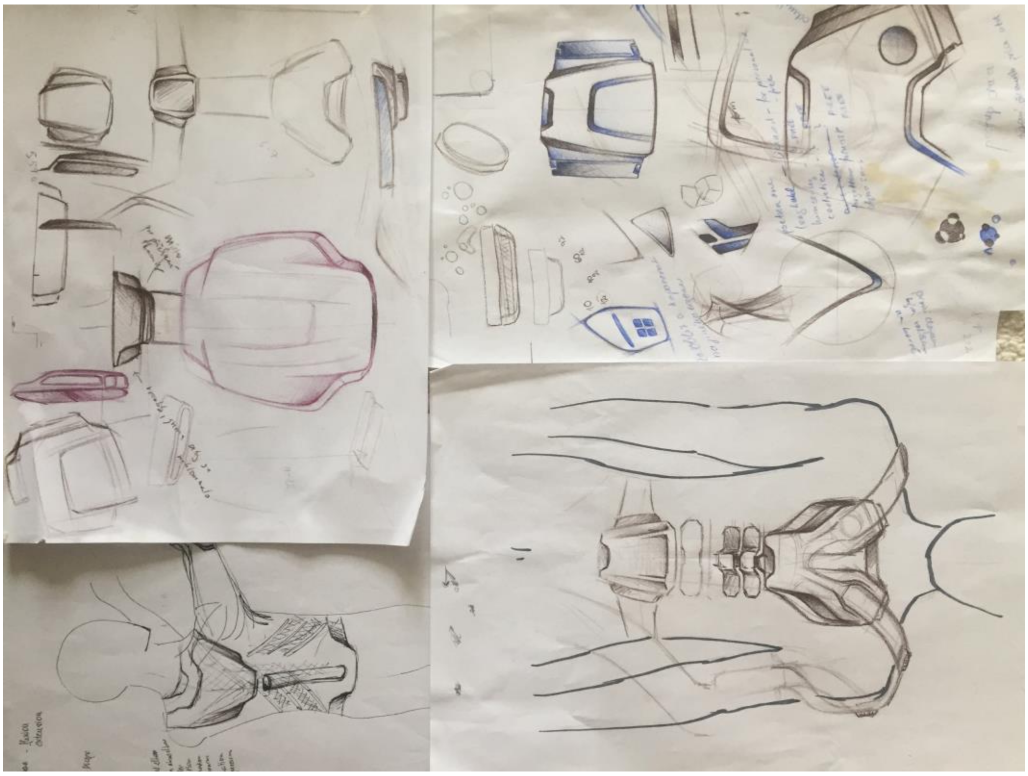


***Fig. 5-1*** Ideation

## 5.1 Proportion and composition

Based on an experimental study of joint mobility, the resulting product is based on the second variant with three joints. The third back joint provides more flexibility but is not necessary. The idea of the design was to create such a device that surrounds all the functional parts of the body that are used for a given task. Emphasis was also placed on stabilizing the device on the operator's body.

***Fig. 5-2*** Perspective view of the final design

*Static parts*

Final shape can be divided into several parts. First, static and moving sections on the exoskeleton can be distinguished. Static section contains back and lumbar part, connected with flexible unit that allows the user to bend without any restrictions. These parts are the carrier of the performing mechanism and the whole weight is transferred along them to the legs. As the device is inspired by humans, it shows overall symmetry. The static parts copy the shape of the back of a person. It can be seen that the upper back part is wider and covers the human's shoulder blades. It is narrowed downwards, what indicates the direction of force transmission to the legs.

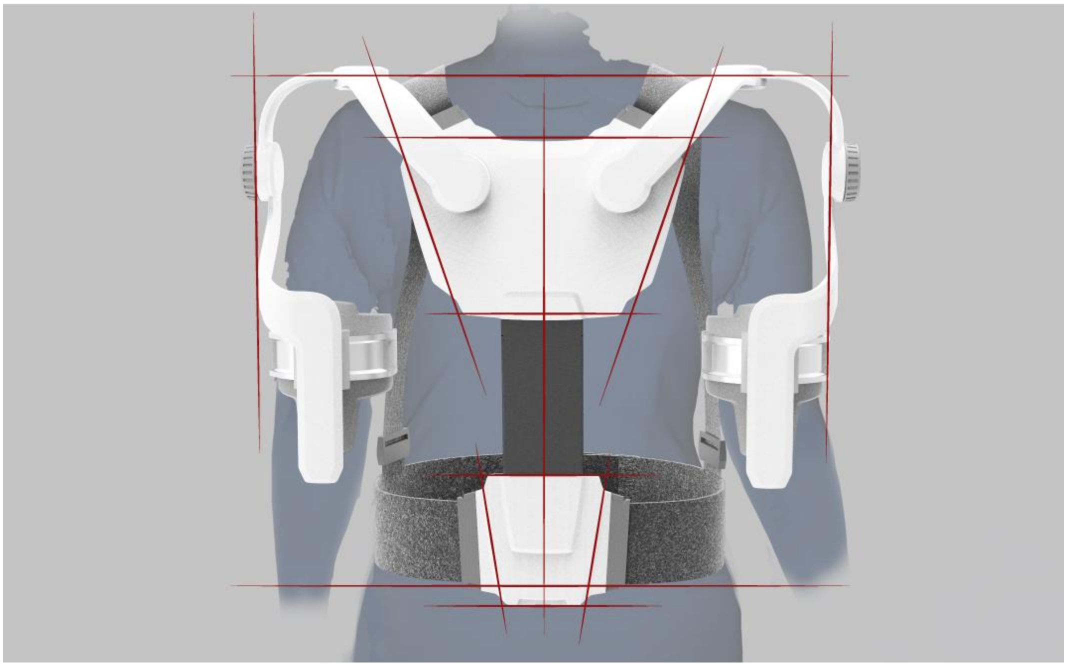


***Fig. 5-3*** Composition – back view

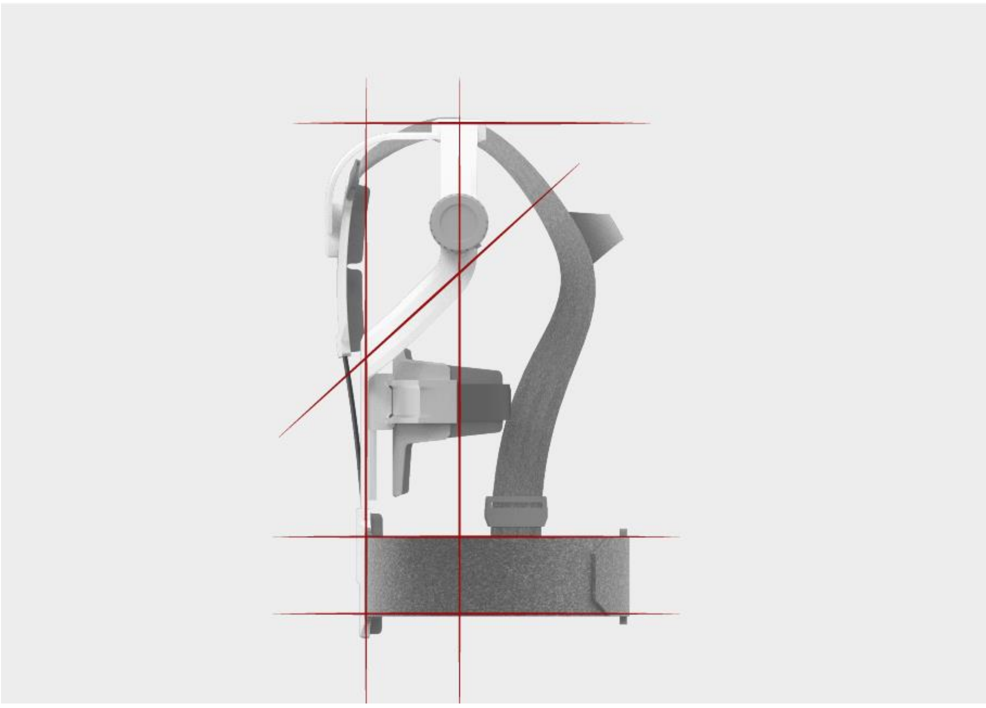


***Fig. 5-4*** Composition - side view

In the place of the shoulder blades, the posterior joints of the exoskeleton are connected. In these places, the back part is divided into two directions, from which the shoulder straps run. The buckles for fastening the strap are designed to correspond in shape and seamlessly follow the back unit. The chamfering of the edge surfaces has resulted in a lightening of this most massive part and a similar pattern is repeated throughout the device.

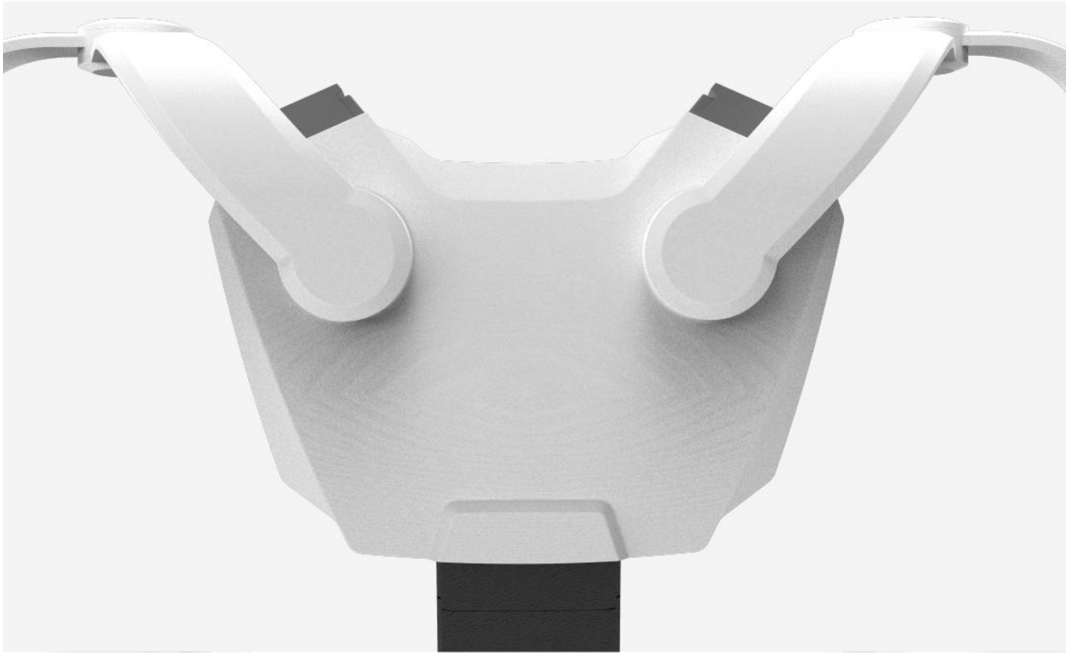


***Fig. 5-5*** Upper back unit

The lower and upper part is connected by a flexible unit based on a “silentblock”. On the back and lumbar parts, there is bulge, which indicates where the flexible unit is connected. The bulge is especially beneficial from a construction point of view, as it offers more space for mounting the unit and better stiffness of back and lumbar part.

The lumbar part is shaped similarly to the upper back unit and tapers slightly from top to bottom. This part is visually smaller due to the dimensions of the lumbar region and the fact that the body is narrower in this part. On the sides there is a bevel, smoothly passing into the detachable buckles. Similarly, as on the back unit, the integrity of the entire morphology is not disrupted.

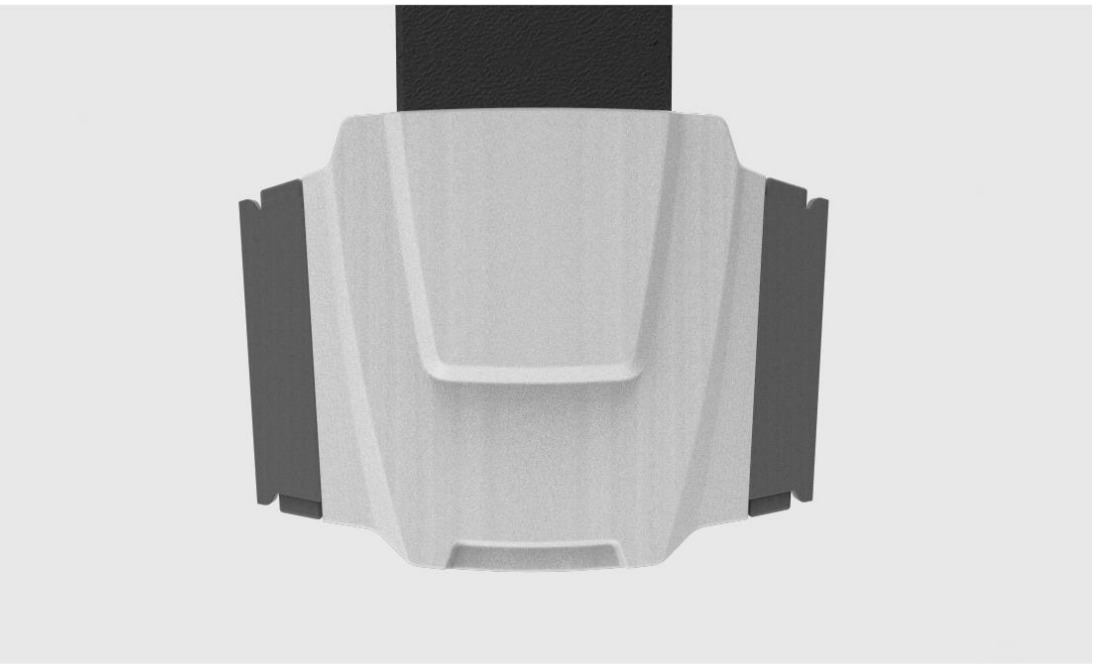


***Fig. 5-6*** Lumbar unit

The device is attached to the body with textile straps, which keep the entire device in a stable position, and are part of a system that transmits weight to the lower part of the body. They are connected to the device with buckles. Buckles are based on the design of the back and lumbar part and are a smooth and non-disruptive connector of these areas. The lumbar strap is an important part of the transmission, that helps to the correct distribution of forces to the lower limbs and relieves the back from the applied load. The shoulder straps fix the entire exoskeleton to the back to prevent unwanted deflection and movement of the device. For greater stability and wearing comfort, the shoulder straps are connected at the front and then attached to the hip belt.

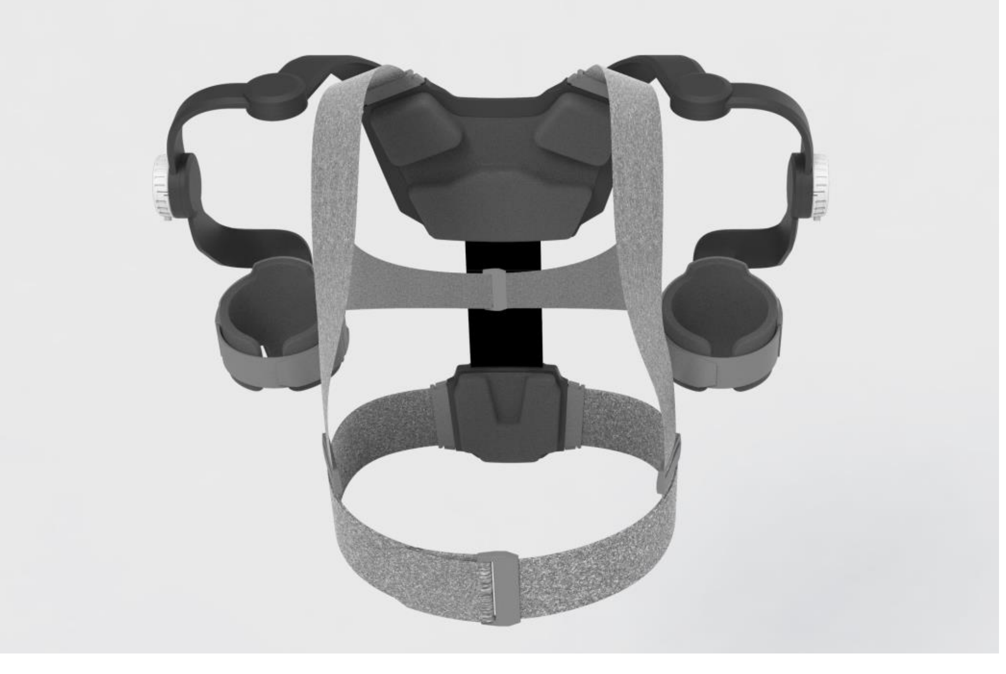


*Fig. 5-7* Construction of straps

*Moving parts*

The moving mechanism itself is formed by three segments interconnected by movable joints. The rear segment is fixed to the upper back part with back joint. The shape of this link follows the back of the user and ends above the shoulder joint. The second arm link emerges from the second joint, surrounds the arm and ends in the third joint which carries the support mechanism. On the outside of the third joint there is a shape-related rotary button, which allows the spring to be prestressed and thus the support force can be easily regulated. From this joint the arm link continues downwards, wraps around the arm to its rear part, in which there are rails for linear movement of the arm cuff.

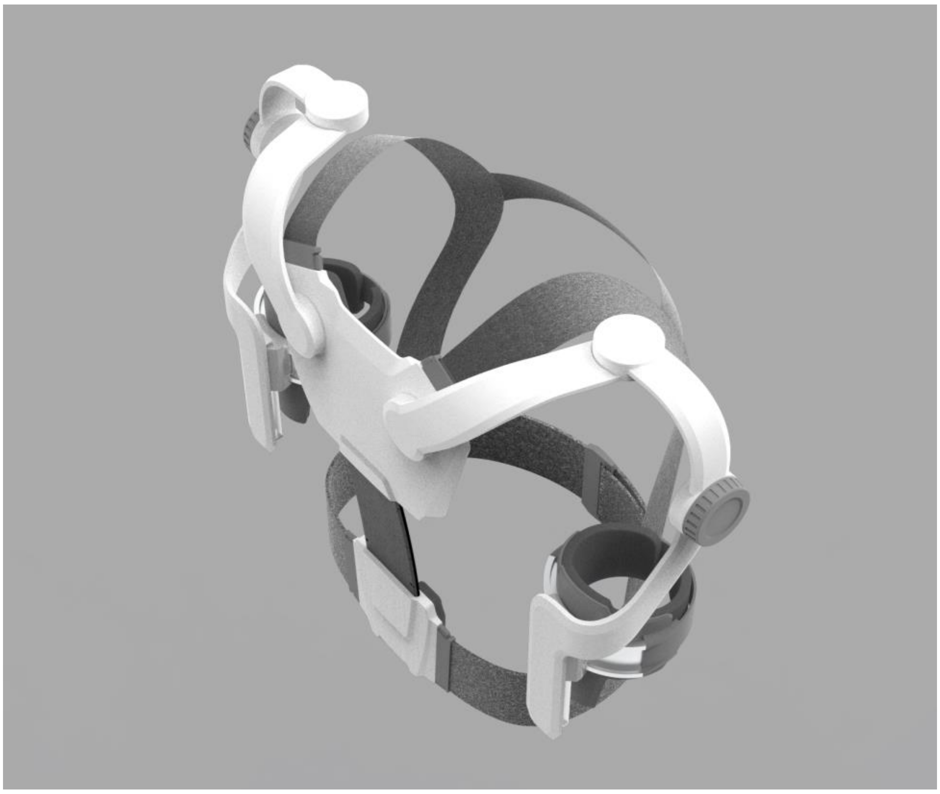


*Fig. 5-8* View of moving parts

The shaped of the joints corresponds to their function, so the round shape is preserved here. The connecting section is flat in shape, a variation of the trapezoid in cross section. From the overall point of view, it creates the impression of chamfering the edges, so it follows the common features of all parts and the overall shape. This shaping also contributes to better strength characteristics.

***Fig. 5-9*** Connection between joints

The arm cuff is shaped to provide maximum comfort for the arm. Its shape is based on a half cylinder, but in the central part there is expanded seating area, which offers greater and more comfortable support when raising the hand. However, these are relatively narrow parts, that do not limit the possible small deflection of the hand from the cuff.

***Fig. 5-10*** Arm cuff

At the back of the cuff is a curved linear guide that compensates the movement of the arm while raising or flexion. The end profile smoothly follows the rail, and it also serves as a bed for attaching the arm strap. The cuff, back and lumbar part contain ergonomically shaped foam linings, which can be individually adapted to the needs of the user.

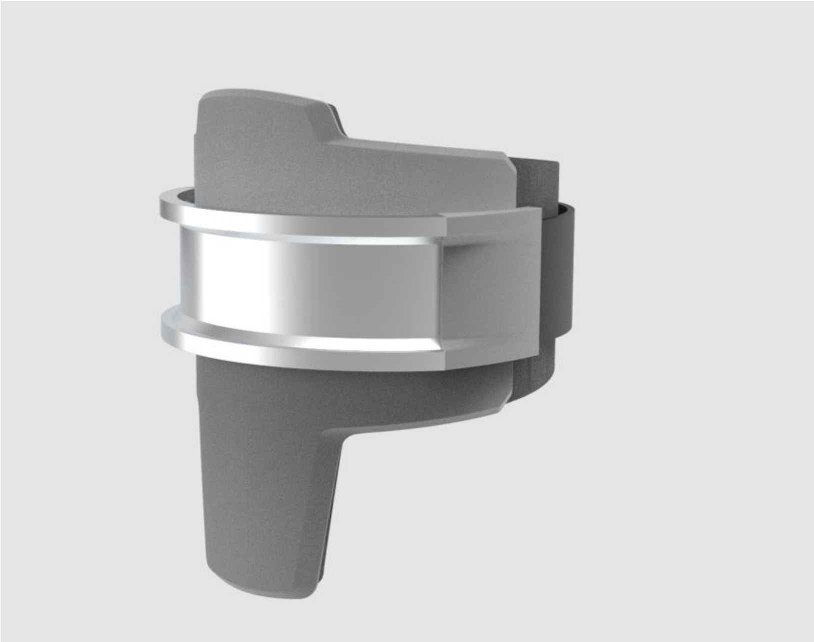


***Fig. 5-11*** Arm cuff – curved linear guide

# 6 DESIGN, TECHNOLOGY AND ERGONOMIC SOLUTION

During design process, the task was not only to create a visually attractive solution but also to understand the product, meet the requirements of the user and bring solution also in terms of construction, technology, and ergonomics. The results are described in the following chapter.

## 6.1 Dimensions and adaptability

Due to the great diversity in the dimensions of the human body, the universal size of the exoskeleton is not proposed. The final product is designed in the way to preserve universal parts including lumbar and back unit, and the straps. Other moving parts and flexible back unit can be assembled according to individual dimensions of the user.

The most important parameters to ensure the wearing comfort and proper function of the device are the shoulder width, torso length, arm length and arm circumference. To cover the largest possible dimensional range, 3 to 4 size variants are intended to be produced. The set includes different sizes of moving units having the same size of connecting joints, so it makes the product adaptable for specific user.

The length of the flexible back unit is also adapted to the length of the torso of the individual users. Due to the compact and minimal shaping of these parts, a radical increase in the cost of mould making is not expected. The disadvantage of this solution can be considered the mirror symmetry of the back and arm moving unit, where it is necessary to create two forms for each side. The resulting design corresponds to the 50th percentile of the average figure of a man.

Foam linings of the cuffs, lumbar and back unit, their thickness, stiffness or shape can be chosen individually according to the user's needs for proper seating on the body. It increases the adaptation to the shape parameters of the user and their comfort.

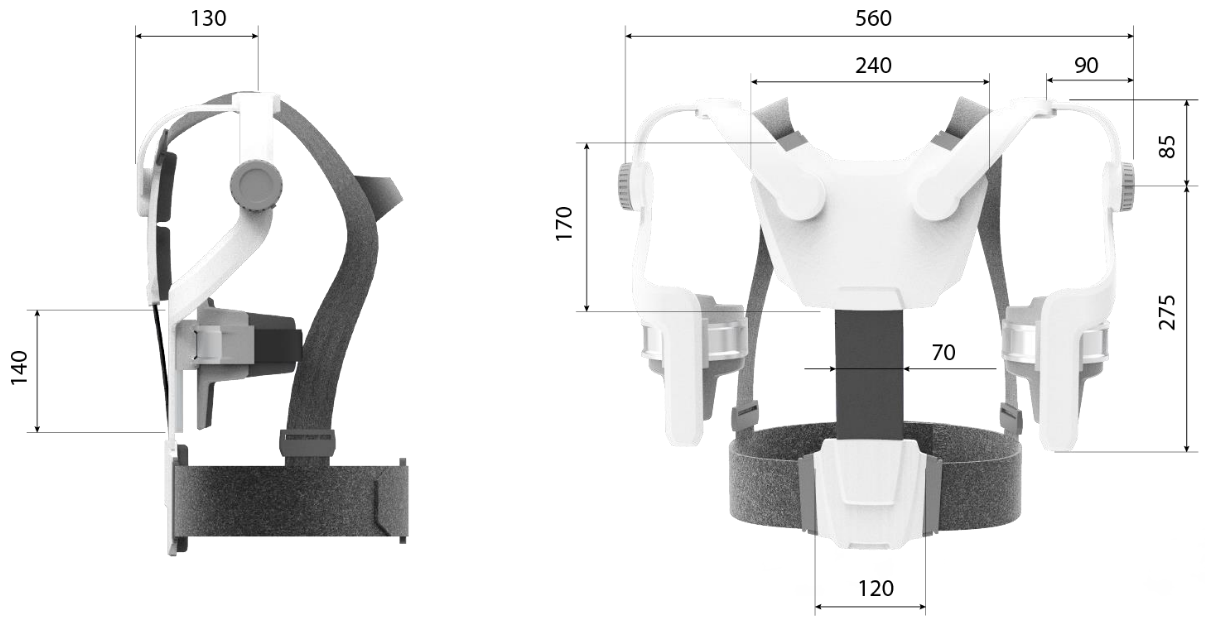



***Fig. 6-1*** Ergonomics – joint kinematics

## 6.2 Technical components

Since the resulting variant uses a passive mechanism, many production costs and subsequent design solutions are reduced. The support mechanism is simpler variant to powerful and complex mechanisms requiring a power source. It is also reflected in the resulting weight, which is estimated at 3 kg.

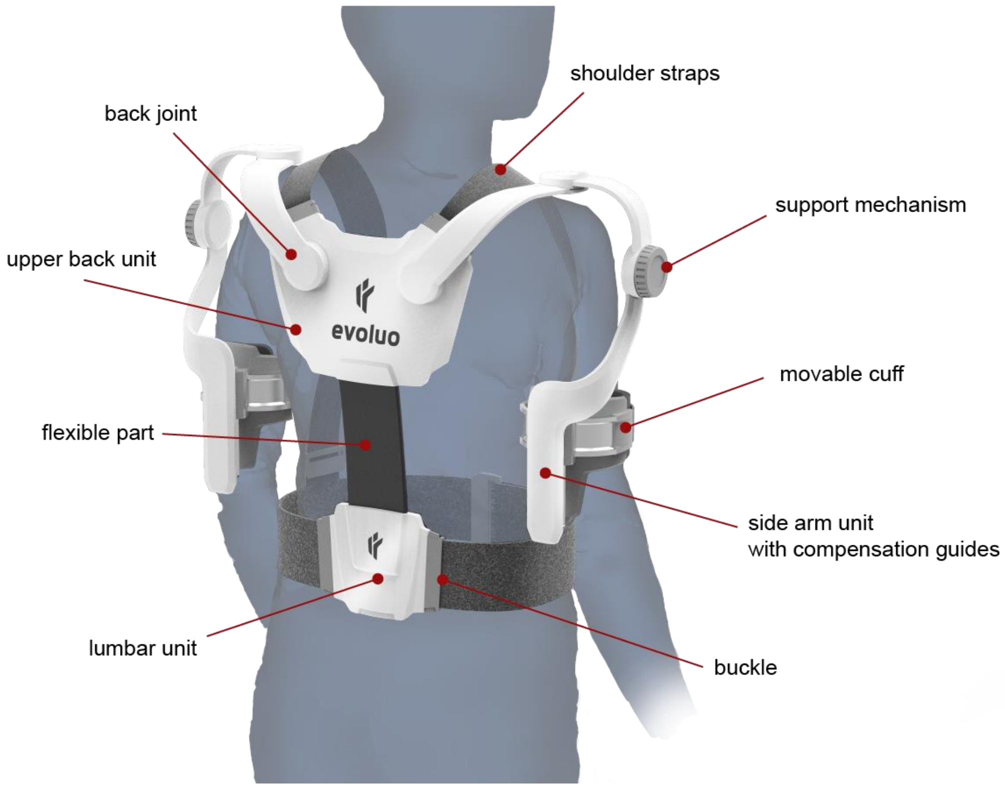



***Fig. 6-2*** Basic components of exoskeleton

### 6.2.1 Joints

Radial ball bearing with a small ratio of outer diameter to inner diameter is used in the joints to ensure the smooth running of the exoskeleton. The bearing is pressed into the shaped elements on the individual moving units, thus creating a firm connection between these two parts. The advantage of this type is that it transmits high radial loads, at the same time axial, which is totally sufficient for the required function.

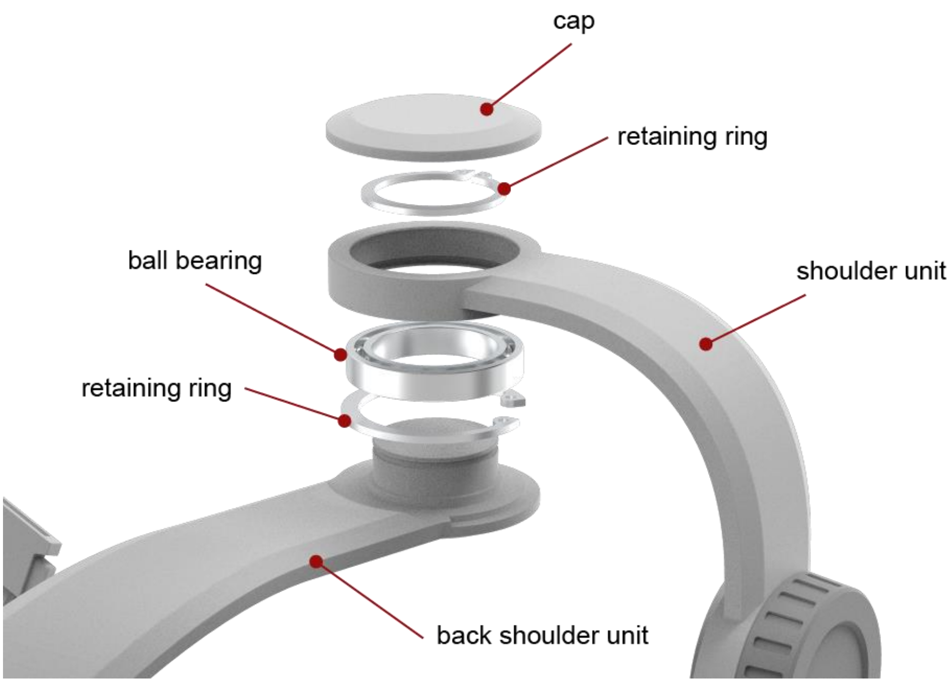



***Fig. 6-3*** Shoulder joint

### 6.2.2 Support mechanism

The support mechanism works on the basis of a torsion spring, which is placed in the shoulder joint. The main advantage is the small installation size and the possibility of setting the prestress by twisting the spring while maintaining its constant dimensions. This prestress can be set using the rotary button placed outside the joint. By pressing the small knob on the side of the button and then turning it, the user can set any amount of assisted force during the operation.

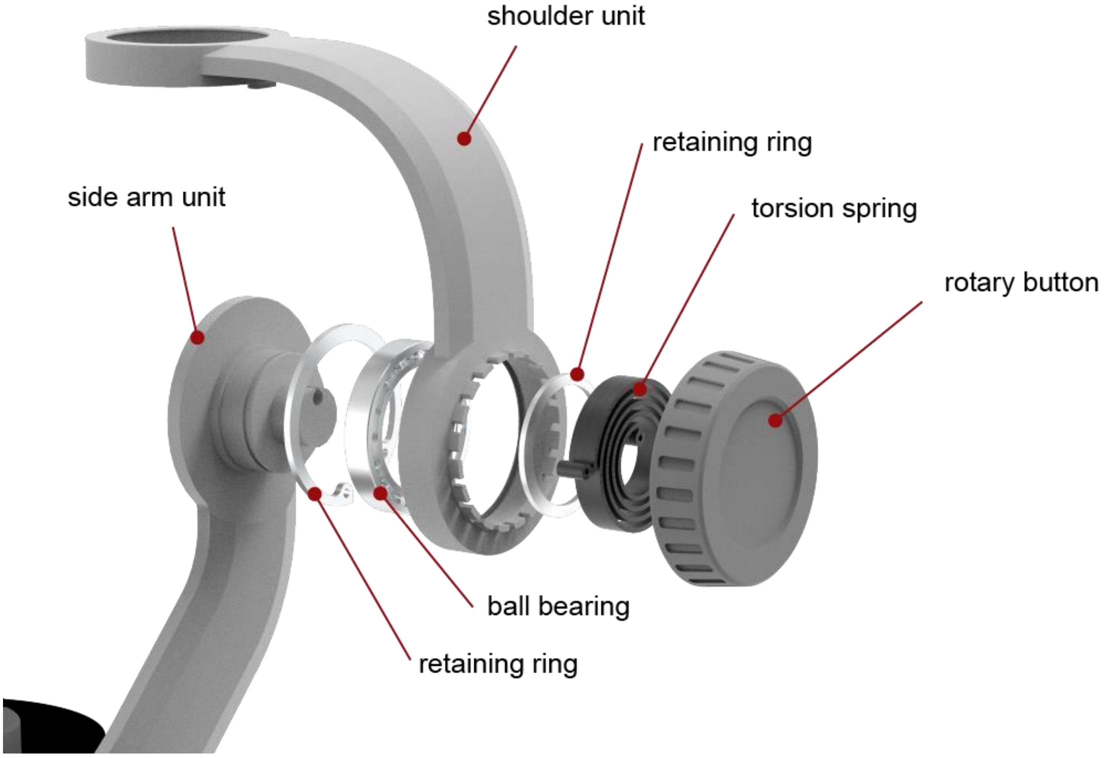



***Fig. 6-4*** Support mechanism

### 6.2.3 Cuff movement compensation

Since the exoskeleton surrounds the user's body on the outside, it is difficult to preserve parallel movements and copy peripheral length expansion. Dimensional changes of the device occur when the arm is moved upwards or sideways. As a result of these movements, the cuffs on the arms become unintentionally moved, resulting in feeling of discomfort. This movement is compensated both by a linear prismatic guide on the arm unit, which is very compact and carries a large load, and by a curved linear guide on the cuff, which allows movement in a circle. These moving elements are connected by a common carriage and form a mutual compensating unit. The metal guide rail is inspired by the existing curved guides produced by *drylin*®. In this part, the carriage is equipped with flexible teflon bushings.

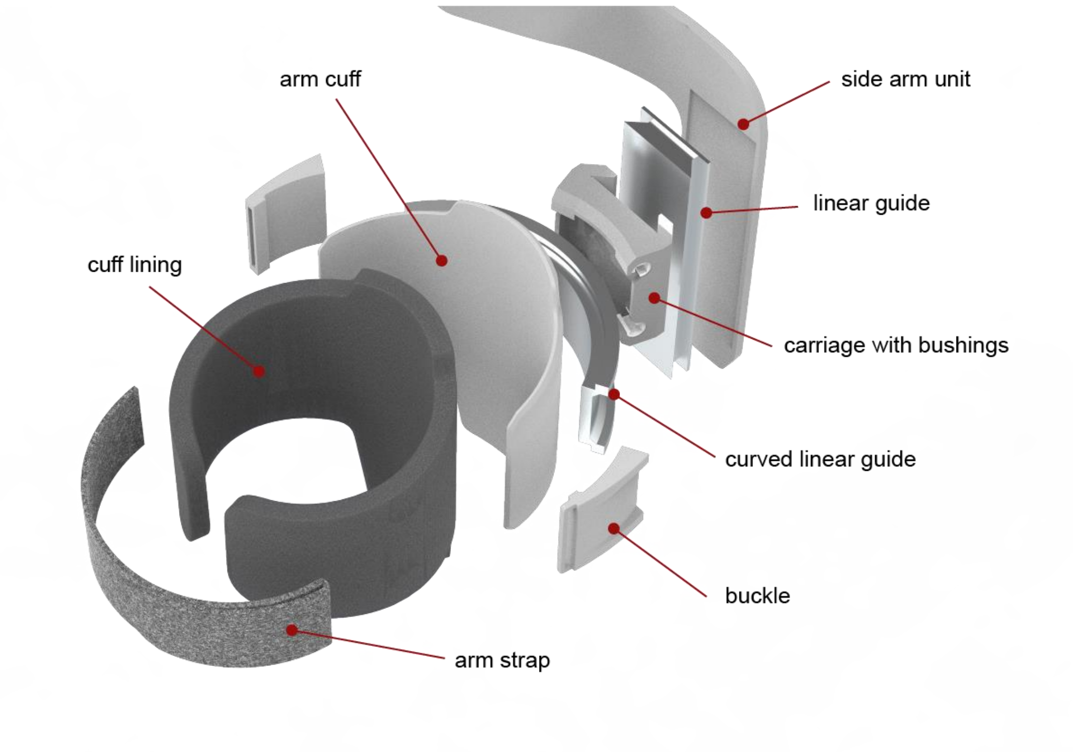



***Fig. 6-5*** Components of compensation unit

### 6.2.4 Flexible back unit

A flexible back unit profile is used to connect the upper back and lumbar part. It is composed on the basis of a silent block (bushing) from the segment of solid steel and rubber parts. It ensures sufficient rigidity and flexibility, which is important in terms of load transfer towards the lumbar part. The part can be produced by vulcanization in the furnace. The ends of the part are metal; thus it can be easily shortened according to dimensions of the user.

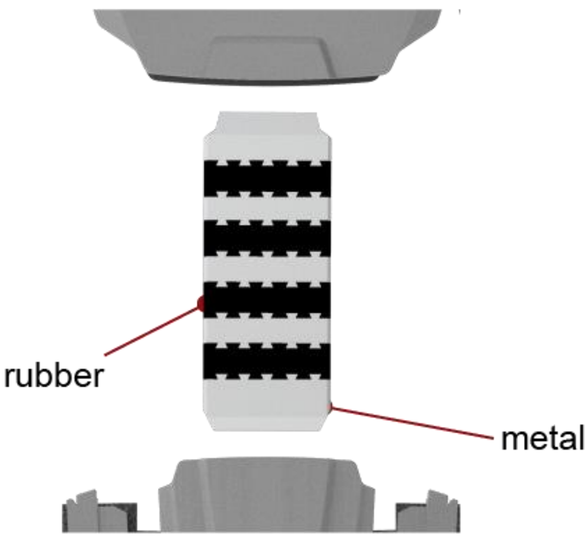



***Fig. 6-6*** Flexible back unit

## 6.3 Materials and production

A wearable exoskeleton is a device that requires as little weight as possible and a certain strength due to the performed activity. All static and moving parts are made of carbon composite, that provides shape variability and exceptional strength due to its lightness.

The moulds for the production of each unit consist of two parts, which are then processed and laminated separately. The two halves of the unit are then connected, and anchors for attaching the straps and flexible back body are inserted between them. The core is made from expanded polystyrene.

Another possibility of manufacturing these parts is offered by casting from a light magnesium alloy or titanium. By using these materials, unlike laminate, the product would become more sustainable for the possibility of recycling and reusing metal parts.

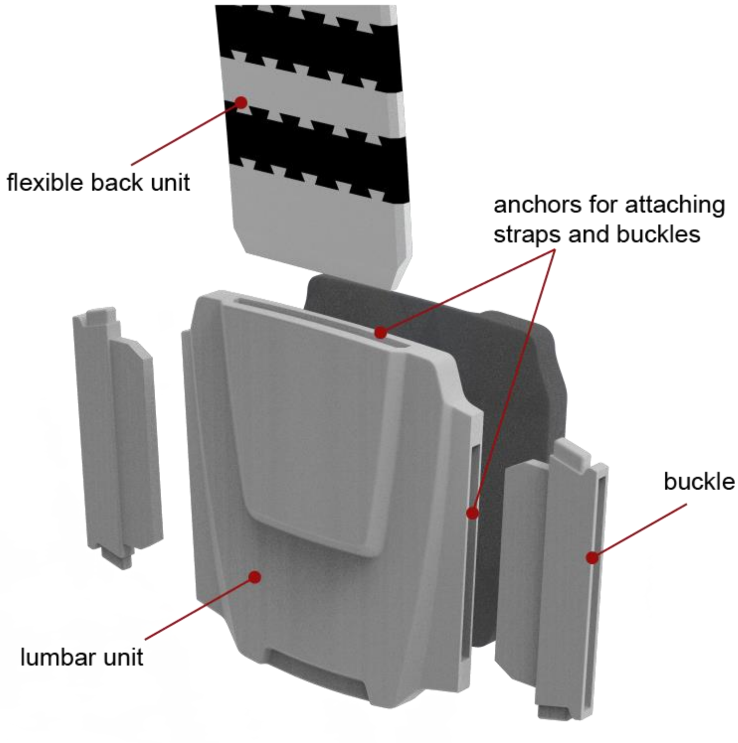



***Fig. 6-7*** Static part assembling

### 6.3.1 Straps and foam lining

The individual straps of the harness are made of washable textile fabric, which are attached to the device itself with the help of buckles. The fabric is laminated in the buckle in a form-fit epoxy resin to maintain a firm connection and prevent tearing. All the straps use a Velcro to individually set the length and avoid their hanging ends. At critical contact points such as hips or neck, the soft foam cushions can be added. Linings are made of hypoallergenic and breathable perforated foam material, that allows user to feel comfortably during wearing.

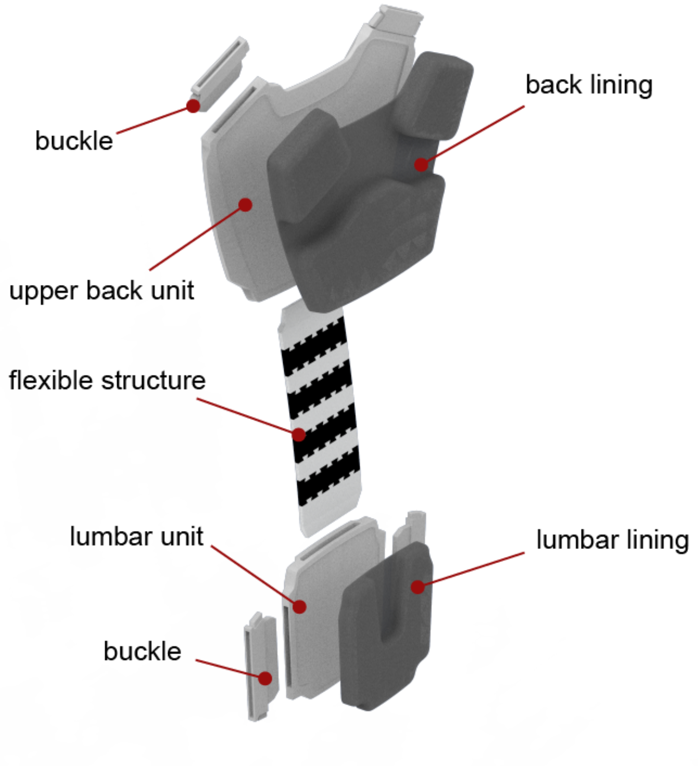



***Fig. 6-8*** Assembling of straps and linings

## 6.4 Ergonomics

The ergonomic solution includes an analysis of the basic operations made when using the device and the definition of range of the working area. The scan of a woman's figure (173 cm) is chosen to demonstrate specific situations.

### 6.4.1 Joint kinematics

The movement of the shoulder joint is described by 9 degrees of freedom. This complex movement is the sum of the movements of the shoulder, scapula, muscle and tendons. Since nowadays it is very difficult to design a device that would accommodate all these movements, this complex movement of a shoulder joint is simplified to 3 degrees of freedom, which are quite sufficient for the purposes of the exoskeleton. The basic requirement for ensuring shoulder flexibility is that the axes of the exoskeleton joint intersect at the centre of the actual shoulder joint.

*Fig. 6-9* Ergonomics – joint kinematics

The cuff compensation system adds an additional 2 degrees of freedom to this type of exoskeleton, thus provides additional internal or external rotation of the arm and compensates cuff movement when the arm is flexed.

*Fig. 6-10* Ergonomics – additional DoFs

### 6.4.2 Working area of the device

The extent of the active working area of the exoskeleton is given by the actual construction of the exoskeleton. The final design allows movement in the vertical direction in the range of 130 degrees and in the horizontal direction 170 degrees.

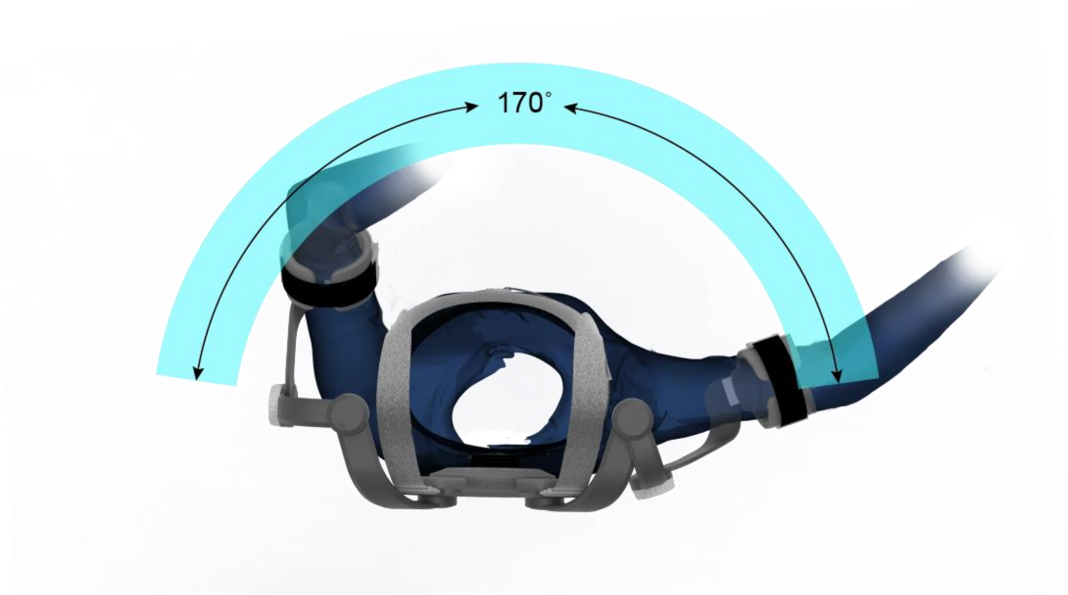



***Fig. 6-11*** Ergonomics – spreading the arms

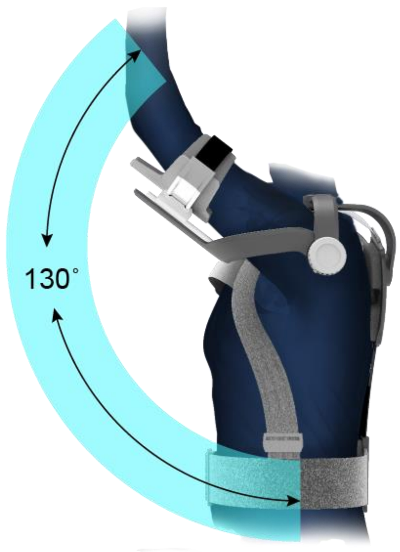



***Fig. 6-12*** Ergonomics – lifting the arm

### 6.4.3 Assisted force settings.

During the work, the user can easily adjust the spring preload and thus the amount of assisted force by turning the rotary button. On the side of the button is located a small knob, which allows the button to rotate.

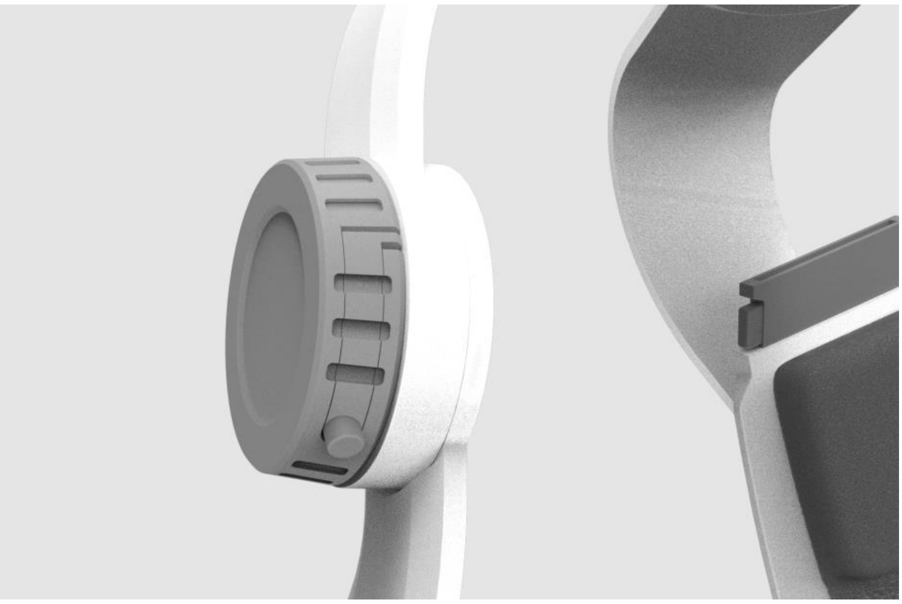


***Fig. 6-13*** Rotary button for adjusting force

# 7 COLOUR AND GRAPHIC SOLUTION

Colour is integral to the overall perception of the product. Colours have a great impact on our subconsciousness and affect our behaviour when buying a product. This knowledge is widely exploited in marketing and brand building, as the first impression is based on the colour of the product and makes it a recognizable and memorable in the market. It is also important to choose the colour scale of the product regarding the customer's reaction and suitability for the product.

## 7.1 Colour solution

The colour solution is based on the work environment in which the device will be used. One is the production hall, which can be both exterior and interior, can be clean or it can be an environment exposed to dust and external weather conditions. The application of colours is based on a composition and construction of the device. Dominant colour covers main visible parts of the product. The removable and washable textile parts are differentiated by a darker colour, due to the contact with the wearer's body and thus the prevention of discoloration caused of perspiration or environmental impact. Furthermore, the functional parts such as the strap attachment and the rotary button are finely differentiated.


***Fig. 7-1*** Colour variant - white

Two neutral colour combinations were chosen, namely white and anthracite. The idea was to create a product that would become part of a human body that does not draw any attention to itself and, at the same time is not unnoticed. As this is not a dangerous device that would require a distinctive colour, colours that look neutral and elegant are chosen.

Even though the perception of colours is very individual and depends on the utilization and personal preferences, the purpose of the product and the message it conveys should reflect in its colouring - that evokes purity, hygiene, strength and elegance.


***Fig. 7-2*** Colour variant - black

Although the main structure offers only two basic colours, there is the possibility of colour variability of the detachable straps and harness. This enables to individually adjust the colour of the product to work environment, user’s preferences or corporate identity.


***Fig. 7-3*** Colour variability of the straps

## 7.1 Graphic solution

The graphic solution includes the creation of a pictogram, logotype and its appropriate placement on the device. The idea in creating the logo was to design the logo in such a way that could be used within the corporate identity covering a wide range of health and work aids. It would not only reflect the development and design of devices to support the upper limb, but the whole range of devices such as exoskeletons for various body parts and compensatory aids for workers in the workplace, or medical aids for home exercises to help cope better with strain and regenerate after work.

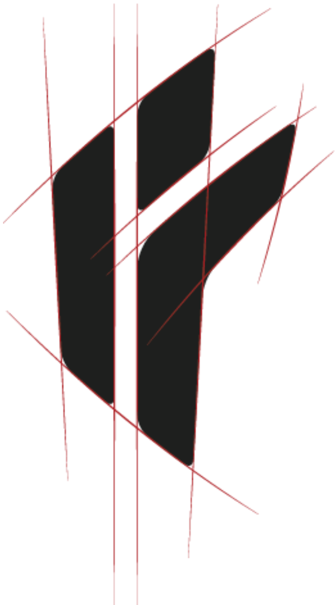


***Fig. 7-4*** Construction of pictogram

The proposed pictogram is a combination of several characterizing features of the product. There is a visible figure with raised hands symbolizing work with hands overhead, and a kind of backpack symbolizing a load or assisted device. The figure with a raised hand is also a symbol of some energy and joy of movement.

***Fig. 7-5*** Final logo

Logotype "evoluo" from lat. evoluo = evolution, tells about some other stage of human evolution, when for sedentary and demanding work the upright attitude of man began to bend. Therefore, with the help of aids and an exoskeleton, the posture can be straightened again, and the device becomes the part of the body when the technology and the human being are connected. The font of the logotype is "Dyno" and its cut "bold italic", which makes the logo more dynamic. Logo is located at the back and lumbar unit on the final product.


***Fig. 7-6*** Application of logo

# 8 DISCUSSION

Psychological, economic and social functions show how the product is perceived in the market, what is its market potential and competitiveness. The product must be evaluated from different perspectives, through its specific applications or a focus on a certain target group.

## 8.1 Psychological function

Psychological function is mainly about emotional reactions and the relationship that people have with products. Since this is a product in which there is a direct human interaction with the device, it is necessary to design the product that will be not rejected by the user. The perception of the product in terms of aesthetics and design contributes to the positive relationship of man with the device and the joy of its use. Knowing the needs of target users allows us to work with stimuli that could otherwise disappear when designing a good product and create a negative experience with the product used.

The user's initial contact with the device is visual. It is both its colour and shape. The colour of the product reflects the environment in which the product is used and distinguishes it from the competition. Significant colour variations can affect the perception of the product as something dangerous, which in the case of exoskeleton is not intended to achieve. It is similar with the perception of shape. The way in which humans need to interact with objects often dictates their form. Because the exoskeleton is associated with humans, sharp and angular shape is not appropriate that could be aggressive.

Colour and shape solutions, its functions, form and structure contribute to greater intuitiveness of the use of the device and the creation of a positive relationship with the product. Intuitive use allows you to get to know the product better and easier, learn quickly how to handle the product, how to set it up and thus eliminate the need to help the person with dressing or setting up the device. Adjustment of dimensional parameters based on individual requirements of the employee, contributes to the feeling of owning a personalized and original product.

## 8.2 Economic function

The price of the exoskeleton is an important factor in its competitiveness compared to other products available on the market. The proposed product belongs to the higher price category. With its appearance, ease of use and easy maintenance, it creates a valuable product among the existing competitors on the market. The use of a passive simple mechanism eliminates additional costs and expenses for energy supplies and their replacement at the end of their lifetime period. The most expensive element is the production of several size variants of the supporting structure, which is reflected in the final price. The price of the final product is estimated at CZK 50,000. It is a more expensive product, but with its features and health benefits it appears to be sustainable, and the initial investment will be reflected in a reduction in the number of incapacities for work of employees and the associated expenses.

### 8.2.1 Costs of sick leave

Musculoskeletal disorders are the cause of many diseases in the workplace. These are mainly back and muscle pain and other associated problems. On the one hand, this affects both the individual's work and personal life, and at the same time the company. The company is obliged to pay the salary in case of sick leave of the employee, whereby the company loses the workforce and at the same time money. Higher expenses of the company can be reflected on the salary of employees. By using aids, such as exoskeletons, it can help reduce the risk of work-related injuries, and thus retain the economic state of the company.

### 8.2.2 SWOT

The SWOT analysis is used to describe the strengths and weaknesses of the company and their products, and reveals the impact of the external environment, which can positively or negatively affect the further development of the company and its position in the market.

| | HELPFUL | HARMFUL |
|---|---|---|
| INTERNAL ORIGIN | **STRENGHTS**<br>- wide range of offered products<br>- market covering<br>- developing new technologies<br>- opportunity to expand abroad | **WEAKNESSES**<br>- dependence of distribution companies<br>- price<br>- rigid structure of design<br>- insufficient size variability |
| EXTERNAL ORIGIN | **OPPORTUNITIES**<br>- new markets<br>- original on the domestic market<br>- cooperation with other companies<br>- e-shop | **THREATS**<br>- high foreign competition<br>- developing of soft exosuit<br>- fear of new technologies |

***Fig. 8-1*** SWOT analysis

## 8.3 Social functions

The product is intended mainly for production sites of both, smaller and large companies or for the production lines of automotive industry. This specific type is used mainly as a support for work with hands over head, where the upper limbs, back and neck are overloaded. These products are experiencing a boom today, but they are not yet fully accepted by company employees.

### 8.3.1 Human - technology interaction

Exoskeletons act as something extra, which restricts the user's movement or binds during handling and assembly on the production line. Getting acquainted with and getting used to new technologies takes some time, and thus there may be resistance to their use at the beginning. The final product, with its visual appearance and adaptability, contributes to a more positive perception of aids. At the same time, individual settings, wearing comfort and large range of motion and lightness should comply with the working environment. The aim is to become a part of the employee's working life, as a kind of helper in preventing health problems, which might reflect in their personal lives.

### 8.3.2 Ecology

Emphasis is also placed on the sustainability and ecology of the product. Due to the technology used and the choice of material, a long product life is expected. The use of recyclable and reusable materials does not make the product a major burden to the environment. The service life of the main structure is estimated at 7-10 years with intensive use. The textile parts are washable and reusable, which reduces the cost of buying new components.

# 9 CONCLUSION

The diploma thesis deals with the design of a working exoskeleton used mainly for overhead work. The use of this type of equipment is expected mainly in the automotive industry, where the work environment places an extensive physical demand on employees. However, working exoskeletons are products that are just establishing themselves in the work environment, therefore there is an opportunity for the development of these devices.

In the first part of the diploma thesis, a detailed research of existing products on the market and design approaches is shown. The technical part focuses and analyses construction elements of both, active and passive exoskeletons. The analysis of kinematics and ergonomic requirements are an integral part of understanding the motion function of the human body and the results are then reflected in the final design as that defines the relationship between the human body and the product.

For better understanding of the user´s needs, some helpful and explicit observations were made directly at the VolksWagen factory in Bratislava. First-hand meetings with users helped to point out the problems associated with the use of the device, identified the drawbacks and the further potential for the improvement. Based on these findings, the objectives and the future goals were set.

The presented solution of the final work involves the study of various support mechanisms, and the assembly of the joint, in order to ensure a sufficient range of motion. Furthermore, in variant studies, different approaches to reach the goals are presented.

The final variant uses a passive spring mechanism which appears to be the most convenient to current needs and demands and offers a very simple solution. It utilizes a three joint mechanism to satisfy the range of motion of the human arm. The laminate skeleton offers a firm, light solution with a long service life. Removable exoskeleton straps and linings solve the issue of hygiene and maintenance of the entire device they are easily replaceable in case of wearing out. With its long service life without loss of mechanical properties, it meets the ecological needs.

Exoskeletons are spreading into everyday life, and their use on regular basis at work as well as at home will be playing a key role in the future. This study peers into some problems of the existing exoskeletons on the market, however, for further development the ongoing use of new technologies, especially 3D printing and individual customization, will be crucial.

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# 11 LIST OF FIGURES, GRAPHS AND TABLES

# 12 LIST OF ABBREVIATIONS

| | |
|---|---|
| AC | alternating current |
| DC | direct current |
| SMA | shape memory alloy |
| DEA | dielectric elastomer actuator |
| EMG | electromyography |
| EEG | electroencephalography |
| D-H | Denavit-Hartenberg |
| DoF/DoFs | degree of freedom / degrees of freedom |
| UK | United Kingdom |
| EU | European Union |
| OVOC | voice of the customer |
| VW | VolksWagen |
| kg | kilogram |

# 13 LIST OF ATTACHMENTS

Reduced Summary poster

Reduced Technical poster

Reduced Ergonomic poster

Reduced Presentation poster

Photography of the model

Designer Poster A1

Technical Poster A1

Ergonomic Poster A1

Presentation Poster A1

Physical Model 1:1

# 14 ATTACHMENTS


DESIGN OF WORKING EXOSKELETON
ERGONOMIC POSTER
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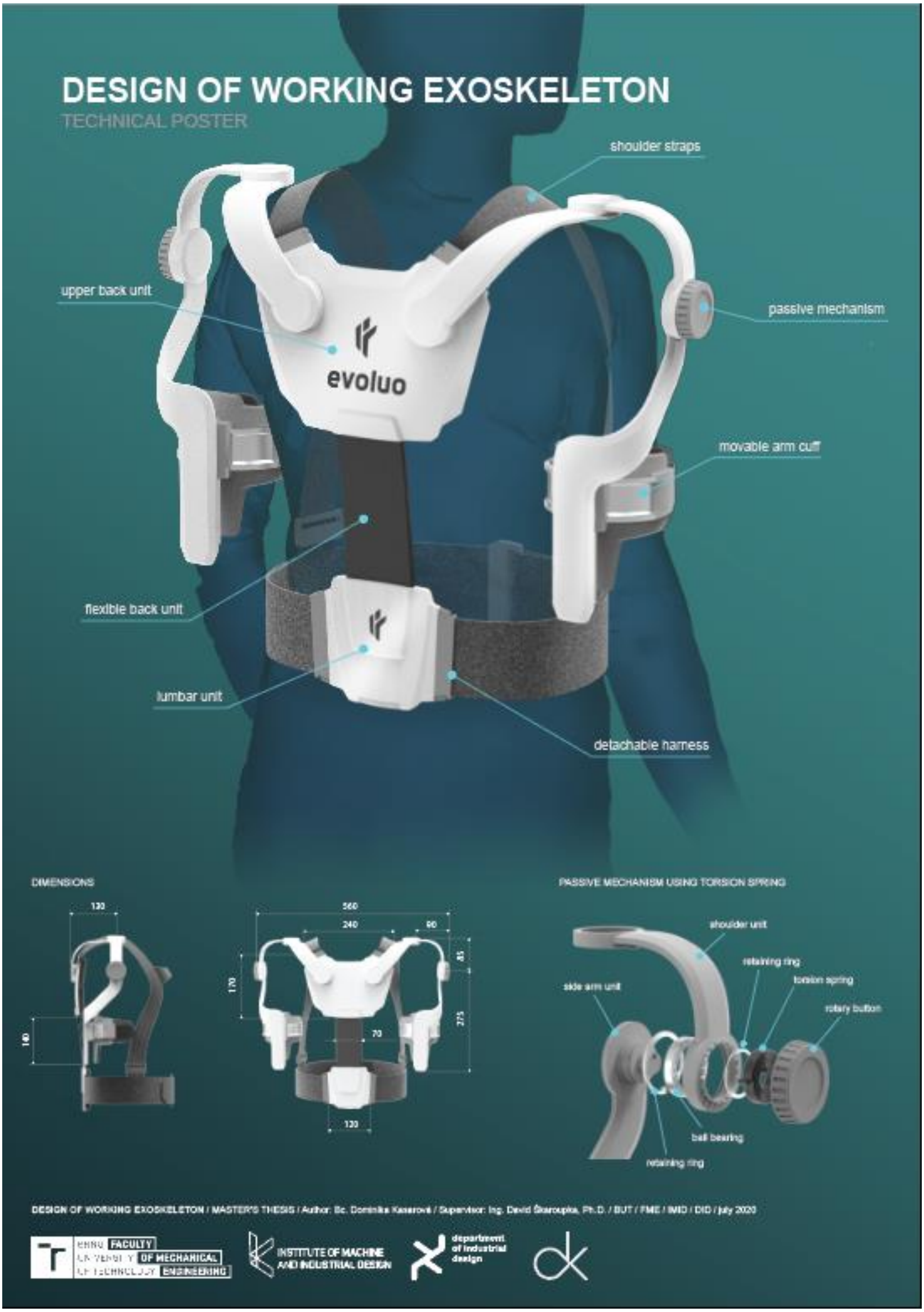
DESIGN OF WORKING EXOSKELETON / MASTER'S THESIS / Author: Bc. Dominika Kaserová / Supervisor: Ing. David Škaroupka, Ph.D. / BUT / FME / IMID / DID / july 2020
BRNO UNIVERSITY OF TECHNOLOGY
FACULTY OF MECHANICAL ENGINEERING
INSTITUTE OF MACHINE AND INDUSTRIAL DESIGN
department of industrial design


DESIGN OF WORKING EXOSKELETON
TECHNICAL POSTER
shoulder straps
upper back unit
passive mechanism
evoluo
movable arm cuff
flexible back unit
lumbar unit
detachable harness
DIMENSIONS
130
560
240
90
85
170
275
140
70
120
PASSIVE MECHANISM USING TORSION SPRING
shoulder unit
retaining ring
torsion spring
side arm unit
rotary button
ball bearing
retaining ring
DESIGN OF WORKING EXOSKELETON / MASTER'S THESIS / Author: Bc. Dominika Kasarová / Supervisor: Ing. David Škaroupka, Ph.D. / BUT / FME / IMID / DID / july 2020
FACULTY OF MECHANICAL ENGINEERING
INSTITUTE OF MACHINE AND INDUSTRIAL DESIGN
department of industrial design


DESIGN OF WORKING EXOSKELETON
SUMMARY POSTER
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The most common cause of occupational diseases are musculoskeletal problems. The use of aids such as exoskeletons minimizes the risk of work-related injuries, which results in a prolongation of the active life of the individual. The design of the working exoskeleton is intended mainly for workers in the automotive industry, where employees on the production line are exposed to long work with their hands over head. This type can also be used in other industries
COLOUR VARIANTS
130°
DIMENSIONS
ERGONOMICS
340
90
70
275
130
170°
DESIGN OF WORKING EXOSKELETON / MASTER'S THESIS / Author: Bc. Dominika Kasarová / Supervisor: Ing. David Škaroupka, Ph.D. / BUT / FME / IMID / DID / july 2020
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