AUXIVO

# EduExo Pro
# Handbook and Tutorial

# EduExo Pro

# The Advanced Robotic Exoskeleton Kit

## Handbook and Tutorial

Second Edition

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English

Auxivo AG

www.auxivo.com

**EduExo Pro - The Advanced Robotic Exoskeleton Kit. Handbook and Tutorial.**



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# Forewords

In over 13 years of teaching courses on physical human-robot interaction and exoskeleton technology, I have witnessed firsthand how project-based learning fosters critical thinking, creativity, and collaboration among students from diverse backgrounds, including engineering, health sciences and technology, and medicine. Connecting theoretical concepts to hands-on work with hardware challenges students not only to grasp fundamental principles but also to acquire practical skills and develop the confidence and mindset needed to develop real-world solutions.

As the field rapidly evolves, there is a growing interest in integrating exoskeleton technology into secondary and higher education. The EduExo robotics kit, tailored for science, technology, engineering, and mathematics (STEM) education, represents a significant leap forward in exoskeleton and wearable robotics educational tools. By seamlessly blending comprehensive theory with practical application in an engaging and accessible format, this kit not only demystifies complex engineering concepts but also empowers students to apply these principles in real-world scenarios, thus enriching their learning experience and preparing them for future challenges.

By offering a tangible, interactive platform for learning and teaching, EduExo enables educators, students, and enthusiasts to explore and engage with exoskeleton technology, irrespective of their prior experience or available resources. As you delve into this handbook and the accompanying hardware kit, you will discover a rich source of knowledge, inspiration and a practical tool that facilitates the integration of exoskeleton technology into education.

**Prof. Roger Gassert**

Roger is Full Professor of Rehabilitation Engineering at ETH Zurich and Vice Chair of the ETH Competence Centre for Rehabilitation Engineering and Science. His research focuses on the development and clinical validation of portable and wearable rehabilitation technologies such as exoskeletons. He is also a Co-Founder and Scientific Advisor at Auxivo.

Robotic exoskeletons are a unique solution that merges robotic technology with the human body. Through my work, I've discovered the incredible value that exoskeleton technology offers to neuro-rehabilitation patients and to workers performing frequent repetitive movements in occupational and industrial settings.

In this endeavor, I learned that while my knowledge of robotics provided a solid foundation, the most crucial element was a deep understanding of the interaction between the human body and the exoskeleton - a concept best grasped by donning an exoskeleton and experiencing it first-hand.

I believe the EduExo Pro is a unique and vital educational tool that provides the opportunity for anyone interested in the fields of engineering and exoskeletons to gain essential theoretical and practical knowledge. My favorite feature is that it empowers all interested individuals to develop the necessary skills independently by providing a handbook that not only guides them through the theory but also encourages them to immediately apply what they've learned in practical tutorials.

Last but not least, as an exoskeleton enthusiast, I am very excited that the EduExo Pro will generate more experts and advance the field of exoskeletons.

**Dr. Lijin Aryananda-Blatter**

Lijin holds a Ph.D. in Robotics from MIT, was formerly the technical project lead at Hocoma, a medical exoskeleton pioneer, and later the Head of the Robotics Platform at the Wyss Zurich Institute. She later served as Auxivo CTO, leading the development of several industrial exoskeletons.

# Preface

Dear Reader,

Welcome to the fascinating world of wearable exoskeletons, where technology merges with the human body to expand our capabilities. This handbook will introduce you to robotic exoskeleton technology and guide you through the journey of building the EduExo Pro, an arm exoskeleton you assemble and program yourself.

The EduExo Pro kit is a comprehensive educational tool that covers various aspects of exoskeleton technology, including human anatomy, mechanics, design, electronics, software, control systems, virtual realities and video games, and scientific experiments. Each chapter begins with an introduction to the theoretical background of a topic. Most chapters then continue with a practical tutorial where you can apply what you've learned to build the EduExo Pro exoskeleton.

This kit was developed for professors and teachers, high school and university students, engineers, and researchers interested in fields such as wearable exoskeletons, robotics, electronics, haptics, force-feedback systems, and virtual reality interfaces. Using this kit does not require prior experience in robotics, though some basic knowledge of programming and electronics will be helpful. Depending on your prior knowledge, some sections of this handbook may discuss concepts you already know, while others might not provide all the details on a topic that you are interested in. However, by actively engaging with the material and making use of online resources when necessary, you will be well-equipped to understand and master every aspect of this kit.

Upon completing this kit, you will have a solid understanding of wearable exoskeleton applications, design, sensor integration, microcontroller programming, control system development, and user interaction. You'll also have learned how to create a video game, how to use the exoskeleton as a haptic interface for a virtual world, and how to conduct a scientific experiment.

We hope this is just the beginning of your journey into the world of exoskeletons. With your new knowledge, you can further modify the EduExo Pro, add sensors, program new control systems, or develop new games. For additional support and resources, please visit our website at www.auxivo.com.

We wish you a great experience with the EduExo Pro and are excited to help you start your adventure in wearable robotics!

Zürich, June 2024 The Auxivo Team

# Contents

Chapter 1

# Introduction


Summary

This chapter will introduce you to the field of robotic exoskeletons. A brief look at exoskeleton history, examples of their applications, and an explanation of their basic functionality will help you understand the technology. At the end of this chapter, you will be introduced to the EduExo Pro hardware. The first two chapters do not include a hands-on tutorial section, but all the others do. So there's plenty to look forward to!


## 1.1 Robots and Robotic Exoskeletons

Robots have a huge impact on our everyday lives, often without us noticing. They have been used in industry for mass production for decades. Today, they can be found in applications ranging from lawn mowing to warehouse logistics and autonomous cars. The technology is still developing and includes wheeled robots, underwater robots, flying drones, and even quadrupedal and bipedal walking robots that can operate in many different scenarios.

Typical industrial robots are stationary articulated robot arms (Figure 1.1) that are very good at executing pre-programmed, repetitive movements very fast and accurately for 24 hours, seven days a week. They are used, for example, in assembly lines, where they execute tasks like moving loads around, welding, or spray painting parts of new cars. Each robot is programmed and equipped to do a single, strictly defined task. As these systems can be very strong and fast, they are often too dangerous to work together with humans and are, therefore, separated from human workers.

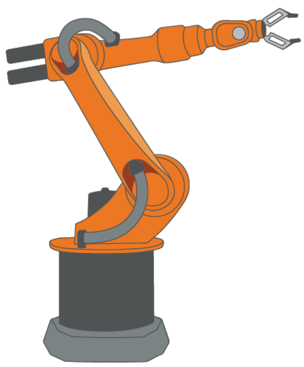


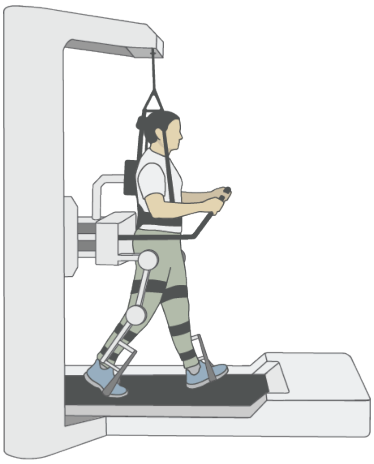
Figure 1.1: A stationary articulated robot arm.

Figure 1.2: A vacuum cleaner robot.

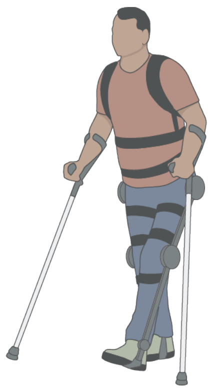
On the other hand, service robots are designed to interact with humans. A typical example is vacuum cleaner robots (Figure 1.2). These mobile robots have integrated vacuum cleaners that move through apartments to clean them. They are usually shaped like small, flat disks, allowing them to navigate even in cluttered apartments and clean underneath furniture. By performing the task for us, preferably when we are not at home, they relieve us of the tedious chore of vacuuming.

Robotic exoskeletons are wearable robots that resemble the shape of the human body, making them look like an outer (greek: exo) shell or skeleton. These types of robots are comparatively new. If this is your first introduction to robotic exoskeletons, your ideas about them might be heavily influenced by science fiction movies such as Iron Man, Aliens, or Edge of Tomorrow. While the depiction of the technology in those movies may be exaggerated, leading to unrealistic expectations, the core concept is accurate. The exoskeletons enable the heroes to accomplish difficult tasks that they would otherwise be unable to do, such as defeating the alien queen. This main motivation translates to today's real-world robotic exoskeletons. Unlike other robots that assemble cars or clean our apartments, exoskeletons are not designed to take over tasks for us. Instead, they support us humans in performing physical tasks, making them easier or even possible.

The need for physical support can arise in many situations. A task might be too difficult for the average person, such as carrying heavy parts in a shipyard, or someone might be unable to perform an activity due to a physical impairment. In either case, a robotic exoskeleton provides the necessary physical assistance. Typical applications include industrial jobs that require lifting and carrying heavy objects, rehabilitation of stroke survivors, and gait restoration for people with spinal cord injuries. Although these systems are not yet as widespread as other types of robots, the field of robotic exoskeletons is growing rapidly, with more companies and research institutions developing new systems (for more on exoskeleton history, see the next section).



(a)



(b)

Figure 1.3: Examples of exoskeleton applications in medicine: (a) a rehabilitation exoskeleton used for gait training of stroke and spinal cord injury patients; and (b) a lower extremity exoskeleton for functional gait restoration of paraplegic users.

In the medical field, robotic exoskeletons have shown significant potential for the rehabilitation of movement impairments. Various medical conditions can lead to such impairments. For example, spinal cord injuries can cause paraplegia, resulting in paralysis (inability to move) of the lower extremities. Another example is stroke survivors who suffer from hemiplegia, a form of paralysis affecting only one side of the body due to brain damage. In all cases of paralysis, the use of the impaired limb is limited or even impossible. This is where robotic exoskeletons can be beneficial, as they can be attached to the paralyzed limb and provide the necessary support to move it (Figure 1.3).

In case of a stroke or an incomplete spinal cord injury (spinal cord partially severed), patients often lose some, but not all, ability to move on their own. In some cases, the residual movement can improve over time if the patient follows an intensive rehabilitation and training program.

If the impairments are too severe and the patients cannot use their arms or legs without support, they require assistance to complete their rehabilitation program. One possibility to provide patients with the necessary assistance is robotic exoskeletons for rehabilitation. Such systems are usually placed in hospitals and are used to train multiple patients per day. In the example (Figure 1.3a), patients follow treadmill-based gait training as part of a gait rehabilitation program. Patients are connected to the device, and their leg movements are supported by the exoskeleton. The support can often be adjusted to the impairment level of each individual patient. Such rehabilitation exoskeletons have several potential advantages. They relieve the therapy staff of the exhausting task of manually supporting the patient by holding the patient's arms or legs and moving them, as would be done in conventional therapy. By using an exoskeleton, therapy sessions can be longer and more intensive, as robots do not get tired. The exoskeleton's integrated sensor systems can measure the amount of support the patient needs and automatically record the recovery process over time. The exoskeleton can also be combined with video games to keep the patient motivated during week- and month-long therapy programs (more on this subject in chapter 9).
If healing is not possible, e.g., a complete spinal cord injury resulting in permanent paraplegia, smaller exoskeletons can be used to enable walking again by substituting the lost function of the legs (Figure 1.3b). They can also help to prevent or reduce the negative effects of prolonged sitting, such as osteoporosis (weakening of the bones) or decubitus (damage of the skin and soft tissues due to prolonged exposure to pressure). These support systems provide the strength and stabilization to move the legs of paralyzed users. Some devices even allow stair climbing and other 'advanced' movements, enabling the user to regain locomotion capabilities that exceed those provided by a wheelchair, the currently common way to restore locomotion in paralyzed patients.

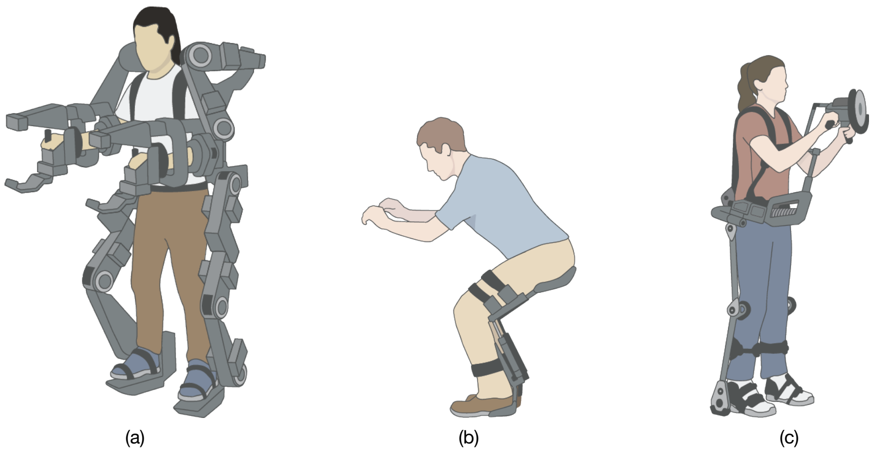



Figure 1.4: Examples of industrial and occupational exoskeletons: (a) for strength augmentation; (b) for mobile body weight support; (c) for power tool support;

In industrial and occupational settings, exoskeletons support workers performing physically demanding tasks. They are especially useful for heavy physical labor, helping to prevent injuries typically caused by high workloads on the body, such as those affecting the back, shoulders, or knees. In these settings, powerful robotic exoskeletons can increase a user's strength and endurance, enabling the prolonged lifting of heavy objects (Figure 1.4a). Additionally, smaller, passive exoskeletons provide relief from the user's own body weight (Figure 1.4b) or the weight of an external payload (Figure 1.4c), effectively reducing the risk of injuries.

The examples above illustrate that exoskeleton designs vary significantly depending on the intended task and the required amount of support. We can distinguish, for example, between stationary systems and mobile systems. Stationary systems, such as the gait trainer in Figure 1.3a, are often permanently installed in a room, and users come to the system to use it. Mobile systems, on the other hand, enable the user to move around. While mobility is required for many applications, it also necessitates that all components, such as power supplies and actuators, are integrated into the system.

Most exoskeletons are also not 'full-body systems'; that is, they do not cover the entire body and support all limbs. More commonly, they cover only the parts of the body where support is needed, such as the legs of a paraplegic user or the back of a warehouse worker.

## 1.2 The History of Exoskeletons

The development of modern exoskeletons began already in the second half of the 20$^{th}$ century. Around 1965, General Electric (USA) began developing the Hardiman, a large full-body exoskeleton designed to augment the user's strength to enable the lifting of heavy objects. The first exoskeletons for gait assistance were developed at the end of the 1960s at the Mihajlo Pupin Institute (Serbia), and in the early 1970s at the University of Wisconsin-Madison (USA). Due to the technical limitations of the time and the lack of experience and knowledge, it took several decades for the technology to mature and for the first exoskeletons to be ready for commercialization and operational use.

With the beginning of the 21$^{st}$ century, the first exoskeleton products made their way into the market and became accessible to an increasing number of users. One of the first applications was gait rehabilitation in stroke and spinal cord patients. An example is the gait rehabilitation exoskeleton Lokomat® (Hocoma AG, Switzerland), released in 2001 and has since been used in hospitals and rehabilitation centers worldwide. In 2013, Hocoma announced the shipment of the 500$^{th}$ device.

Development continued in the first decade of the 21$^{st}$ century at an increasing number of research labs and companies. Towards the end of the decade, several prototypes of military exoskeletons that aim to augment their user's strength and endurance were presented. Examples are the Raytheon XOS exoskeleton, which is a full-body exoskeleton, and Lockheed Martin's 'Human Universal Load Carrier' (HULC), which supports its users to carry a heavy backpack.

Since around 2010, several gait assistance and restoration exoskeletons have been presented and gradually introduced to the market. Most of them are designed to provide the necessary support for paraplegic users to leave the wheelchair and walk upright. Examples are the ReWalk™ (ReWalk Robotics, Israel) and the Indego® (Parker Hannifin, USA).

More and more of these exoskeletons receive certification (e.g., CE in Europe or FDA in the US) for clinical use and also for use outside of medical facilities, which is an important step for enabling home therapy. In September 2016, ReWalk Robotics announced the 100$^{th}$ exoskeleton delivered for use at home.

Besides medical applications, several manufacturers started developing exoskeletons for industrial use and introduced the first systems to the market around 2015. One of the first examples was the Chairless Chair from the Swiss company Noonee. It is a leg exoskeleton that allows

users to sit anywhere, relieving the legs of prolonged standing. Another pioneering example was the Laevo back support exoskeleton from Dutch company Laevo BV. It is a mechanical system providing back support for its users during repetitive lifting or prolonged forward-leaning work.
Especially in the industrial exoskeleton field, passive systems (without motors) quickly became popular, as powered actuators are not always necessary to relieve the user of a payload or their own body weight. The trend also moved toward more specialized devices that support specific activities. This focus on simpler, specialized devices makes the resulting exoskeletons potentially lighter, smaller, and cheaper than more complex devices, all aspects that can significantly increase their market acceptance.

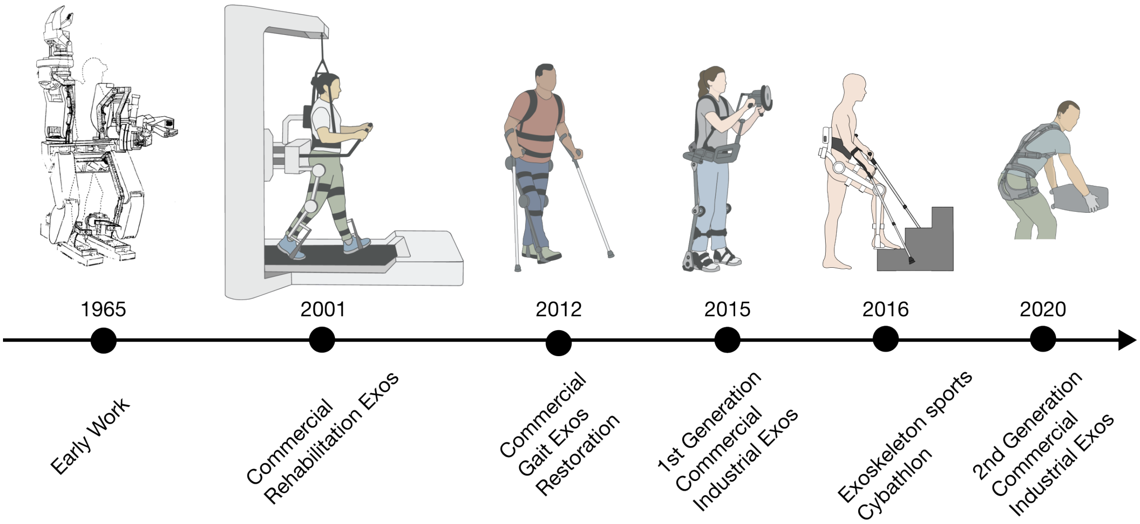



Figure 1.5: Timeline of exoskeleton developments (not in scale).

In the mid-2010s, the concept of textile exosuits emerged to further reduce the constraints caused by the size, weight, and rigid structure of traditional exoskeletons. These soft exoskeletons are primarily made of textiles and often resemble clothing more than conventional exoskeletons. They provide support through soft and lightweight actuators such as special pneumatic actuators, textile springs, or motors connected to cables that are then integrated with the textile suits. Pioneering work was conducted by the Wyss Institute at Harvard University, which developed exosuits to support walking, and later at the Sensory-Motor Systems Lab at ETH Zurich, which developed exosuits for people with mobility impairments.
This approach was incrementally used for the design of exoskeleton products. In the medical field, for example, the company ReWalk Robotics announced in 2017 that it licensed the Harvard exosuit technology and received approval for use by stroke patients in rehabilitation centers in 2019. The developments at ETH Zurich led to the incorporation of MyoSwiss, an ETH spin-off that launched the MyoSuit in 2020. This leg exosuit was designed to help people with mobility impairments in home, recreational, and rehabilitation settings. Around 2020, the first industrial textile exoskeletons entered the market. Early examples include the Flex Lift from the US company Kinetic Edge, the SoftExo from the German manufacturer Hunic, and the LiftSuit from the Swiss company Auxivo (yours truly).
In the industrial field, these new technologies and many other incremental improvements have led to a significant increase in performance. This "second generation" of commercially available

industrial exoskeletons provides better support, is easier to use, and, in many cases, is more affordable than the early devices. Since around 2020, these advancements have significantly driven their wider adoption across various sectors, such as manufacturing and logistics.
Today, encountering an exoskeleton in industrial settings is considerably more likely than it was just a few years ago. However, overall use remains limited. Further improvements and increased awareness of the capabilities of industrial exoskeletons are necessary to drive their mass adoption. As these devices become more advanced and affordable, and their benefits more widely recognized, they can drastically change how physical labor is performed, making safer and more efficient work environments accessible on a global scale.
In addition to all the development efforts, an increasing number of manufacturers began promoting their systems to a wider audience to demonstrate their capabilities and increase awareness of the technology. In 2012, Claire Lomas, who has paraplegia, used a ReWalk exoskeleton to participate in the London Marathon, crossing the finish line after 17 days. In 2016, she participated in a half-marathon and finished after five days.
In 2014, a paralyzed exoskeleton user performed a symbolic kick-off at the FIFA World Cup in Brazil. He was assisted by a 'mind-controlled' exoskeleton, which measured brain activity to control the exoskeleton's movements. This exoskeleton was developed as part of the Walk Again project.

Figure 1.6: Impression from the first Cybathlon,2016. (Source: ETH Zurich CYBATHLON)

In October 2016, ETH Zurich in Switzerland hosted the first Cybathlon, a competition in which, among other disciplines, exoskeleton-assisted paraplegic users, called pilots, raced each other on an obstacle course. To win, the teams needed both a skilled pilot and state-of-the-art technology. The exoskeleton users had to solve tasks such as sitting down on a couch and standing up again, walking up and down slopes, walking over stones like you would cross a shallow mountain river, and conquering stairs.
At this first edition, none of the participating pilots could overcome all obstacles, and it took even the fastest teams more than 8 minutes to finish the 50 m long obstacle course while solving most

of the obstacles. In comparison, an unimpaired adult can complete all tasks in less than a minute without being in a rush.
The 2nd Cybathlon took place in 2020, with teams completing the course remotely and comparing results via a live stream (because of a global pandemic if you are reading this in the distant future). The event highlighted the progress made by gait exoskeleton technology during these four years. All four finalists of the exoskeleton race could finish the course and overcome all obstacles. The fastest athlete finished in only 3 min 49 s, and even the last finished in 6 min and 54s. If you are interested, you can find recordings of all competitions online (search for CYBATHLON 2020 exoskeleton race). A 3rd Cybathlon event is planned for October 2024.
Since 2021, the Fraunhofer IPA Institute in Germany has been organizing an event called the Exoworkathlon for industrial exoskeletons. This event features a parkour course where industrial exoskeletons are used during simulated work activities by users with significant experience in these jobs. The goal is to benchmark the exoskeletons, at the same time, demonstrate their capabilities to the broader public. Therefore, it is often organized as a public event, most recently held in October 2023 at the A&A trade fair in Düsseldorf, Germany.
Advancing this kind of standardized product benchmarking is crucial for the advancement of exoskeletons. It allows potential customers to compare different devices and find the one best suited to their requirements.
This look back in time shows us that exoskeletons have been around for quite some time. In fact, if you dig deep, you will find even earlier examples of exoskeletons from the early 20$^{th}$ century and before. However, this early work did not lead to the continued use of exoskeletons. Therefore, the modern-day history of exoskeletons in the 21$^{st}$ century marks the period when the technology began evolving into products that are increasingly used today.
It will be inspiring to see where the technology goes next and what opportunities it will present.

## 1.3 User-Exoskeleton Interaction

The general task of all exoskeletons is to provide the right amount of support at the right time. To ensure that, the interaction between the exoskeleton and the user has to be bidirectional. It can include the exchange of a variety of input and feedback modalities, such as forces, movements, and biosignals (Figure 1.7).
Robotic exoskeletons provide support by transferring the power of their actuators to the user. In addition, their rigid structure can provide stabilization and protection and can transfer loads away from critical parts of the body. A typical robotic exoskeleton consists of the same components as any 'normal' articulated robot. A rigid frame, joints, and actuators enable movements. Sensors, electronics, computers, and software are used to control the device.
Because robotic exoskeletons do not act independently but rather in coordination and synchronized with the user, several additional components are necessary. Mechanical interfaces connect exoskeleton and user to transfer support. Adjustment mechanisms can adapt the length of the exoskeleton segments to fit different users. When it comes to controlling the exoskeleton, several approaches are possible. Sometimes, exoskeletons are directly controlled by the user through buttons or steering body movements. Alternatively, additional sensors can be integrated to improve the exoskeleton's autonomy, for example, by measuring biosignals such as muscle activity, brain activity or heart rate from the user, allowing the exoskeleton to better anticipate the

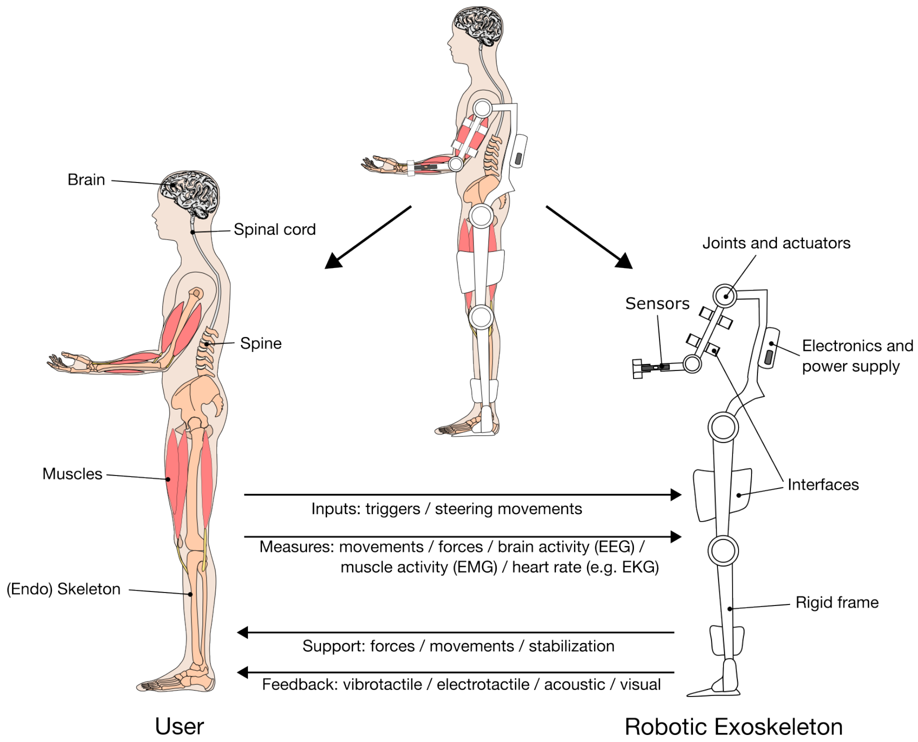



Figure 1.7: Illustration of user-exoskeleton interaction.

user's intentions and needs and react accordingly. In the other direction, feedback systems such as sounds (acoustic feedback), blinking lights (visual feedback) or vibrations similar to a mobile phone (tactile feedback) can be used to inform the user about upcoming exoskeleton actions to improve usability.

## 1.4 Limitations and Constraints

After reading these first sections, you might think that robotic exoskeletons are the solution to many problems and will augment the physical capabilities of everyone who uses them. However, a closer look at the field and the technology reveals that today's robotic exoskeletons still have several limitations and, in many cases, are simply not good enough. Despite providing support, certain constraints and disadvantages can occur at the physical connection between the exoskeleton and the human user.

### 1.4.1 Mass

The first potential problem is the exoskeleton's mass (Figure 1.8). This mass may have to be carried by the user. Or, the mass can considerably modify the person's center of mass, inducing altered and unnatural poses.

Additionally, the exoskeleton's mass has to be moved and accelerated by the user when moving around. Especially distal masses – at the end of the arms and legs – are exposed to high accelerations when the human is performing fast movements, thus significantly increasing the load on the human. As a result, the exoskeleton user may fatigue faster or may have reduced

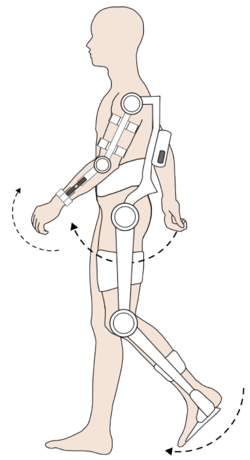



Figure 1.8: The user has to carry and move the exoskeleton's mass.

strength. Of course, it is not always the case that the user has to carry, move and balance the exoskeleton's entire mass. Many exoskeletons, especially stationary ones that are connected to an external structure and the ground, can compensate and support at least a part of their own mass. Nevertheless, it is very likely that a high exoskeleton mass will negatively affect the user.

### 1.4.2 Kinematic Mismatch and Misalignment

Another potential problem is the exoskeleton's rigid structure (Figure 1.9). This structure may cause problems if the exoskeleton does not perfectly resemble the users' anatomy, e.g., spanning a human joint without incorporating a corresponding joint itself. For example, human hip joints have three degrees of freedom (DOF): flexion/extension, abduction/adduction and internal/external rotation. However, many hip exoskeletons typically only move along the flexion/extension axis. This restricts the human's movements, similar to a ski boot that constrains your ankle movements (Figure 1.9a).

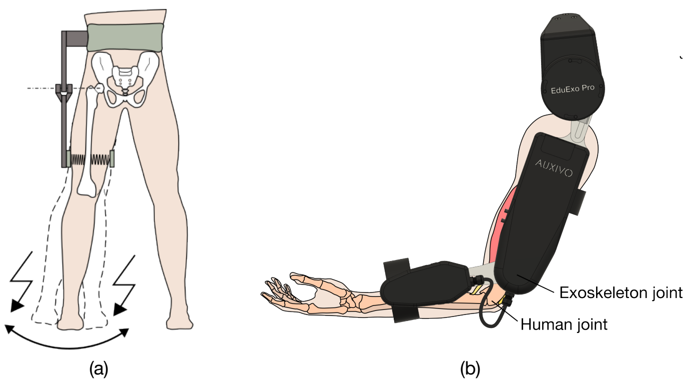



Figure 1.9: The exoskeleton's rigid structure can constrain the user's movements: (a) a one degree-of-freedom exoskeleton hip joint connected to a three degree-of-freedom human hip joint; and (b) misalignment between the user's and the exoskeleton's joints can cause constraints.

Another source of constraints related to the exoskeleton's rigid structure may come from misalignment between the axes of the exoskeleton joint and the corresponding human joint (Figure

1.9b). Misalignment causes constraints due to the offset between the centers of rotation of two bodies that are mechanically connected. It originates mainly from inaccurate alignment during the setup, or slippage of the exoskeleton along the limb during operation.

### 1.4.3 Interfaces and Size

The interfaces that connect exoskeleton and human may negatively affect the user (Figure 1.10a). Most exoskeleton interfaces are designed as braces or textile cuffs that are wrapped around the human limbs and torso. A tight fit is often required to enable the transfer of the loads and avoid slipping and shifting of the interface on the skin. These interfaces may not fit perfectly and therefore cause discomfort or even pain and injury when performing movements. If the fit is too tight, it limits the increase of muscle diameter during contraction, creating high compression on the soft tissue that causes soreness or skin irritation. The interfaces may also cover large parts of the skin, like an additional thick layer of clothing, and can cause excessive heat for the user. The interfaces can also span multiple joints, for example, a torso interface over multiple vertebrae, limiting the user's mobility.

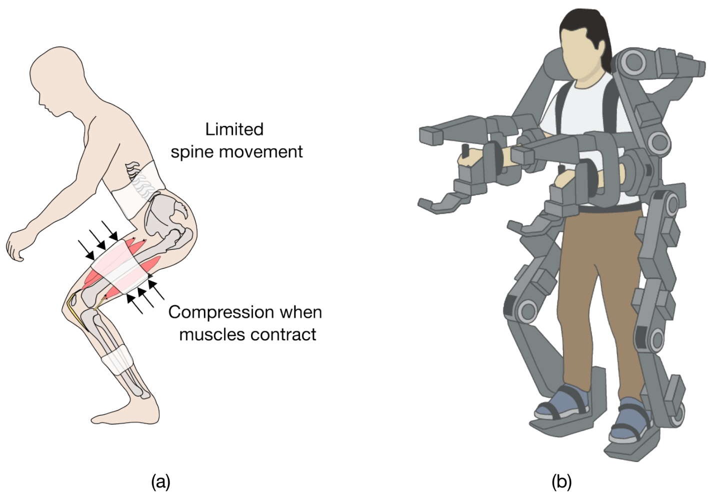



Figure 1.10: Other potential sources of constraints: (a) the exoskeleton interfaces can cause discomfort or limit movements; and (b) the size of the exoskeleton may cause collisions with the environment.

Another potential cause for constraints is the size of the devices themselves (Figure 1.10b). The rigid structure, large actuators, mobile power supply and the control computers all add volume to the human-exoskeleton system. This added volume can increase the risk of a collision with the environment or between parts of the exoskeleton, e.g., the left and the right legs. It may also restrain interaction with the environment, such as preventing the user from sitting down on a chair because it is not wide enough for the exoskeleton.

### 1.4.4 Sum of Benefits and Constraints

With these limitations in mind, the performance of an exoskeleton can be considered as the sum of the benefits it provides minus the constraints it imposes on the user (Figure 1.11). If the benefits are dominant, it will reduce the effort to conduct a specific task. If, on the other hand, the constraints outweigh the benefits, using the exoskeleton will make the task more difficult.

The challenge for developers is to design a system that provides the right amount of support while imposing as few constraints as possible on the user. The dilemma is that it is often impossible to optimize every aspect of the exoskeleton simultaneously because some of them trade-off others. For example, an exoskeleton with a stronger motor usually has an increased mass. Or, the larger interface required to transfer higher forces could impose additional interface constraints. The exoskeleton will offer a benefit only if we achieve a good balance. Therefore, the development can be a bit of a balancing act between increasing benefits and reducing constraints.

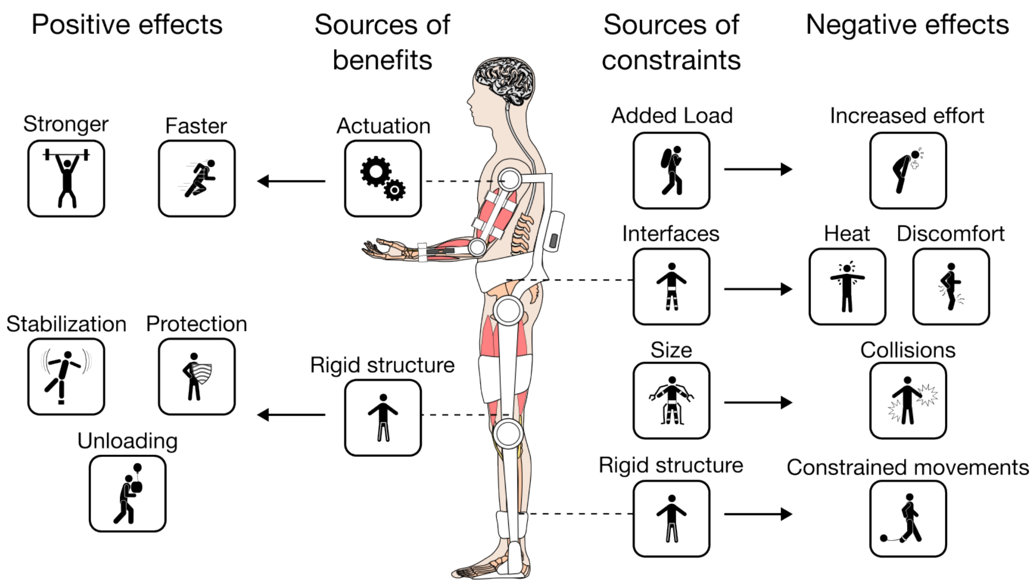



Figure 1.11: The overall performance of a robotic exoskeleton can be considered as the sum of its benefits minus the constraints it causes.

## 1.4.5 Task and User

To make things even more complicated, it is important to understand that benefits and constraints are not absolute, but rather depend on several factors. One factor is the activity that is performed while wearing an exoskeleton. Running involves higher accelerations and forces than walking. Climbing stairs requires a larger range of motion in the joints than level walking, potentially causing larger constraints due to kinematic mismatch, joint misalignment or interfaces. Another factor is the user. A strong, well-trained worker will react differently than an elderly person to the same exoskeleton weight. An impaired user might perceive a rigid structure as more supportive than a healthy user, who might perceive it as constraining. As a consequence, robotic exoskeletons are usually highly specialized devices that are only suitable for a narrowly defined user group and application, and can be completely useless for other applications.

## 1.5 The EduExo Pro Exoskeleton

Now that you have some basic understanding of the field of robotic exoskeletons, let's start building our own exoskeleton by using the hardware provided together with this handbook. The EduExo Pro exoskeleton (Figure 1.12) covers many aspects also found in 'professional' exoskeletons to teach you relevant knowledge.


Figure 1.12: A fully assembled EduExo Pro.

The EduExo Pro spans the human shoulder and elbow joints. It is connected to the user's torso, upper arm, and forearm through mechanical interfaces. A spring in the shoulder supports the user in lifting the arm. A single motor at the elbow joint assists with elbow flexion and extension. An angle sensor integrated into the motor measures the elbow angle. A force sensor in the forearm segment measures the interaction forces between the exoskeleton and the user. The EduExo Pro contains an Arduino microcontroller, which stores the control system. The microcontroller can be connected to a PC to visualize sensor signals or to use the EduExo Pro to play a video game.

The EduExo Pro is, as an educational system, subject to some limitations. To make sure that your expectations match our intentions, here are some quick facts about the EduExo Pro kit:

**EduExo Pro Quick Facts**

**What it is:**

- An educational robotics kit that will help you learn about wearable exoskeleton technology.
- A do-it-yourself kit that requires active participation and willingness to learn new things.

**What it is not:**

- It is not a medical device that is intended to be used for any kind of medical application.
- It is not an exoskeleton that will make you super strong. The actuation is only intended to illustrate basic exoskeleton principles.
- It is not a robot that works out of the box. You have to make it work, that is a feature!

**For whom it is:**

- For teachers and professors who want to set up exoskeleton courses or labs.
- For researchers looking for a versatile exoskeleton research platform.
- For high school and university students who want to learn about robotic exoskeletons.
- For makers and hobbyists who are looking for a fun project in a fascinating field.

The following chapters will introduce the components and their functionality step-by-step. With the help of the tutorial section in each chapter, you will assemble and program the exoskeleton, add functionality, and test new concepts.
The EduExo Pro is designed for users who are new to robotic exoskeletons. Basic programming and electronics skills are beneficial, but you can learn everything you need while using the kit. We encourage you to solve the tutorials on your own, but they also include sample solutions to help you if you get stuck.

Chapter 2

# Exoskeleton Development


Summary

If you are a student thinking about making exoskeleton development your next career step, this section is intended to give you an idea of what kind of work exoskeleton developers do all day, how exoskeleton development is executed, and what skills are required.


## 2.1 The Team: Who Develops Exoskeletons?

As robotic exoskeletons are highly interdisciplinary, you usually need team members and experts from different fields to achieve optimal results. Consequently, different paths and educations can lead to a career in the field of robotic exoskeletons.

Very roughly, you can divide the team into members with a technical background and team members with knowledge about the human inside. On the 'human side', you have, for example, medical doctors, therapists, movement scientists, neuroscientists, ergonomic specialists, and related disciplines. Their knowledge is critical to understanding the use case, considering the human user's requirements, evaluating the (ideally positive) effects the exoskeleton has on its user, and helping derive technical requirements. The 'technical people' (engineers with all sorts of backgrounds: textile, mechanical, electronics, software, and control system engineers, mechanics, orthopedic technicians, etc.) derive the technical requirements, design and build the device, and conduct all the technical tests.

As usual, when working in an interdisciplinary field, a basic understanding of most or even all the fields involved will significantly benefit the team's collaboration. An engineer with some basic knowledge about anatomy and a therapist who is a little familiar with the steps necessary to develop the technology will work much better together and avoid misunderstandings than people without this 'extracurricular' knowledge.

As with every other technical development, involving the end user (patients, therapists, or industry workers) from the beginning and throughout the development process will help ensure that the real-world requirements are met.

## 2.2 The Development Process

A development process is a number of steps necessary to complete from your first idea to your final product. Typical steps include:

1. Analyze the users and use case: Are they people with paraplegia, well-trained workers, or older people with reduced muscle strength?
2. Derive requirements and specifications such as level of support, maximum weight, maximum costs, etc.

3. Develop concepts for your exoskeletons: This typically includes a lot of brainstorming on a whiteboard and sketching preliminary designs by hand.
4. Develop the design: Once you have chosen an overall concept, it is time to detail the design. This is typically done using so-called CAD software (Computer Aided Design) for the mechanical and electronic components.
5. With a first design ready, it is an important step to build and test prototypes. Prototypes are particularly important for exoskeletons, as the subjective feel and testing with human users are crucial to understanding what concepts work well.
6. Finalize the design. Typically, prototype designs are not optimized and ready for mass manufacturing. So, once you have successfully tested your prototypes and are confident that you have a good concept and design, it is time to start optimizing the design for the final product. This can include, e.g., additional mass reduction using lightweight design methods (remove all material that is not necessary for stability) or optimizing the design to make it easier and faster to assemble (consider that you might need to assemble 1000 and not just one prototype).
7. Manufacture and assemble the product. Conduct quality control.
8. Once on the market, make sure you keep collecting feedback from your customers to inform future product generations.


Figure 2.1: Some of the steps of the EduExo Pro development.

How the process is then planned and executed can vary from product to product, from team to team, and from company to company. Is it done step by step, are several steps done simultaneously, and are specific steps repeated at a later stage?
The more 'traditional' approach is to define the product specifications as precisely as possible, and only once you have considered everything you start developing step by step. Changing the specifications again is not really accepted in this approach, as a lot of work would need to be repeated. In this approach, you will need to spend more time early on, talk to the customer and user, and make sure not to have not overseen essential requirements (which could lead to a bad product).
In the so-called 'agile' approach, it is more accepted that not everything is defined before development starts, but you adapt your specifications along the process. In this approach, you typically spend less time defining your specifications early on but rather start developing under

Chapter 3

# Anatomy and Mechanics


Summary

This chapter introduces the fundamentals of anatomy, mechanics, and the interaction between the user's body and the exoskeleton. In the second part, we will introduce the design of the EduExo Pro, followed by a step-by-step tutorial to guide you through the mechanical assembly of the exoskeleton.


## 3.1 Human Anatomy and Strength

Our musculoskeletal system enables us to move: run, jump, grasp objects, and so on. It consists of bones, joints, muscles, tendons, and a few other tissues. Bones give structure to our bodies. The connection between bones is called a joint. The geometry of our joints and how they are arranged and connected define what movements we can execute. Movements are generated by muscles that produce forces. When muscles contract, they pull (but they cannot push!). Muscles are connected to bones through tendons. Muscles and tendons span our joints; when muscles contract, they pull on the bones they are attached to, bringing the bones together. We will now look closer at one of the joints that concern us for our exoskeleton – the human elbow joint. We can identify certain characteristics that define its functionality (Figure 3.1).

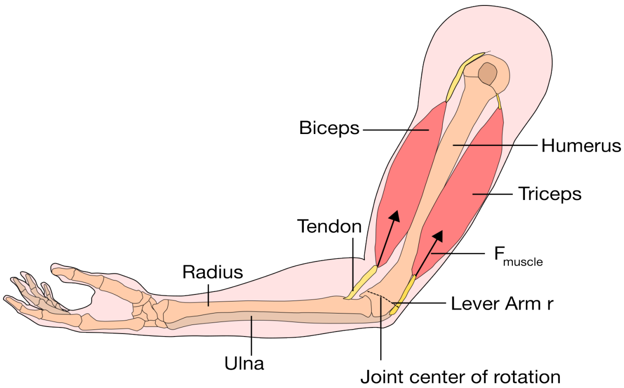



Figure 3.1: The human elbow joint and some of the major muscles responsible for elbow movement.

The elbow joint is a hinge joint. This means that we have one possible movement (often referred to as degree of freedom or DoF), which is the flexion and extension of the elbow. When talking about human joint movements, the direction of the movement is usually specified. 'Elbow flexion' means moving your elbow so that your hand goes towards your shoulder (presenting your impressive biceps); 'elbow extension' is the reverse movement when you straighten your elbow joint. Accordingly, the muscles that generate elbow flexion are called (elbow) flexor muscles, and the muscles that extend the joint are called (elbow) extensor muscles. Examples of muscles that

generate movement at the elbow joint are the biceps (flexor) and the triceps (extensor).
When muscles contract, they create a pulling force $F_{\text{muscle}}$. Because of a lever arm $r$ between muscle force and joint center of rotation, the force results in a torque $T_{\text{muscle}}$ at the joint level that induces a joint rotation (Equation 3.1). If we want to move back, the muscle relaxes and a muscle on the other side of the joint (antagonist) contracts to pull the joint back.

$$T_{\text{muscle}} = F_{\text{muscle}} \cdot r \tag{3.1}$$

When we look at our elbow joint, we realize that the movement is limited. Usually, full extension of the elbow (0° flexion) forms a straight arm, and we can flex the elbow until the forearm touches our upper arm at about 150° flexion. This range of angles is called the range of motion (RoM) of the elbow. The RoM is different for every joint. Also, there can be variations for the same joint between different people. Knowing the RoM of joints when designing an exoskeleton, for example, is important so that the exoskeleton does not move beyond these natural RoMs, which could lead to injuries.

## 3.2 Exoskeleton Kinematics and Force

Similar to how humans have joints and bones, robotic exoskeletons have joints and segments. The exoskeleton's joint arrangement, and the length of the segments connecting the joints are described by its kinematic configuration. This kinematic configuration and the shape of the exoskeleton should appropriately resemble the human anatomy to best fit and support its users (Figure 3.2). For example, an exoskeleton intended to support a specific human movement should be able to execute that movement itself. As a counter-example, an exoskeleton that spans a human joint without having a corresponding joint will very likely constrain the user's movement.

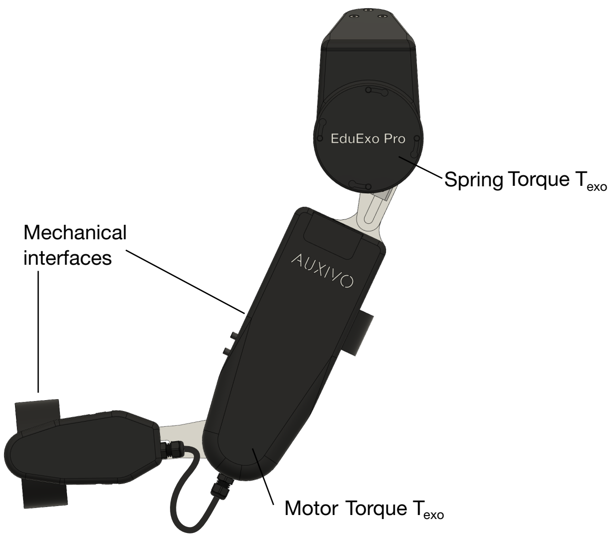



Figure 3.2: The exoskeleton mechanics: the motor and the spring at the joints create torques $T_{\text{exo}}$ that are transferred through the mechanical interfaces to the human inside.

If you look at different exoskeleton designs, you will find both passive joints and actuated joints. Passive (non-actuated) joints allow free joint movements while still transferring certain forces and loads across the joint. Therefore, they can be very useful in applications where the exoskeleton

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Chapter 4

# Mechanical Design


Summary

In this chapter, you will learn about the mechanical design of exoskeletons. Mechanical design is one key engineering skill required to develop exoskeletons. The introduction will explain the main tasks typically involved in developing an exoskeleton design. In the tutorial, you will learn how to design your own personalized cuffs using a computer-aided design (CAD) program. If you have access to a 3D printer, you can apply this knowledge to redesign and print the cuffs and covers of your EduExo Pro. If you prefer to continue assembling the EduExo Pro, you can skip this chapter and proceed to chapter 5. You can always return to this chapter later. Of course, you can also read through it to learn about mechanical design, even if you don't intend to modify your EduExo Pro right away.


## 4.1 Overview Exoskeleton Design

When you develop a new product, the design will undergo several iterations. This is a normal part of product development. When testing shows that your initial design does not work as intended, you will return to the drawing board, improve it, and test again. This way, you will refine the design step-by-step from an early concept to a final product. Typically, the process of developing the mechanical design for an exoskeleton goes as follows:

- Define specifications and requirements based on a use case analysis.
- Develop first concepts and designs. Do all the necessary calculations and create sketches of how the exoskeleton could look. Typically, this involves drawing increasingly detailed designs of your exoskeleton by hand on a piece of paper.
- Once you have a design that you think will work, you can start building a model using a CAD software tool.
- While you build this computer model, you can also conduct numerical stress-strain analysis to ensure your exoskeleton is sufficiently robust. Adjust the design if necessary to make sure it can withstand the loads.
- Once your design is finalized, prepare all files and documents that you need for manufacturing.
- Send the documents to manufacturing, answer any questions from the workshop, and wait for your parts.
- Once you receive all parts, conduct quality control and assemble them to get your exoskeleton. During assembly, you might discover shortcomings in your design as not everything fits

perfectly and cannot be assembled as planned. This might require some 'creativity' during the assembly, or you might need to redesign certain parts and manufacture them again.

- Once assembled, test the resulting prototype to see if everything works as wanted.
- Identify all things that might not work, improve them, build a new prototype, and test again. Repeat this loop as often as necessary.
- Once everything works well, you can finalize the design, start producing it, and deliver it to the user.

The following sections will introduce you in more detail to the tasks typical for an engineer developing an exoskeleton.

## 4.2 Introduction to Mechanical Design

### 4.2.1 Requirements and Specifications

When designing an exoskeleton (or any machine, for that matter), it is crucial to understand the intended use case, and the end-users need to develop the right solution.
Once this is done, you summarize the requirements by defining the so-called 'specifications' of your exoskeleton. This includes, for instance, what kind of support is required, what movements should be possible, who the end-users are, etc. These specifications are documented to provide the engineering team with something to work with.
There is more than one way to prepare the specifications. The list can be finalized early on or adapted and finalized later, following a more agile product development process. No matter which approach you choose, at some point, you need to specify what your exoskeleton should be able to do.
Here are some requirements and the corresponding specifications for the EduExo Pro to give you a few examples. Typically, in the first step, one starts by outlining the requirements as follows:

1. The arm should fit most users, male and female, at high school and university age. These are our target users for an educational exoskeleton. If the EduExo Pro is the wrong size for these users, it will be uncomfortable for them to wear.
2. The support provided by the motor at the elbow joint should be sufficient to move the forearm when it is relaxed. With this level of support, the EduExo Pro should be strong enough to provide an exciting learning experience to our users. If it were too weak to move the arm, users could be disappointed.

Of course, these 'requirements' are still a little vague. So, typically, before you start developing, you would need to translate them into something more specific and put some numbers on them. In our EduExo examples, this could look like this:

1. Size of the exoskeleton to fit high school and college students:

   Before you start worrying, you will not need to go out there and measure the arms of hundreds of students to collect this information. Someone else already did this and wrote it down, and now we can look up these values in literature. You can typically find this type of

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Chapter 5

# Electronics


Summary

This chapter will introduce the theory behind the EduExo Pro's electronic components and discuss their functionality. In the tutorial, you will connect all the electrical components.


## 5.1 Description of the Main Components

The main electronic components of the EduExo Pro (Figure 5.1) are the motor with an integrated angle sensor, the force sensor, an amplifier for the force sensor, the microcontroller, the EMG sensor, the batteries and the PCB that connects the components. The microcontroller is connected to a computer for programming.

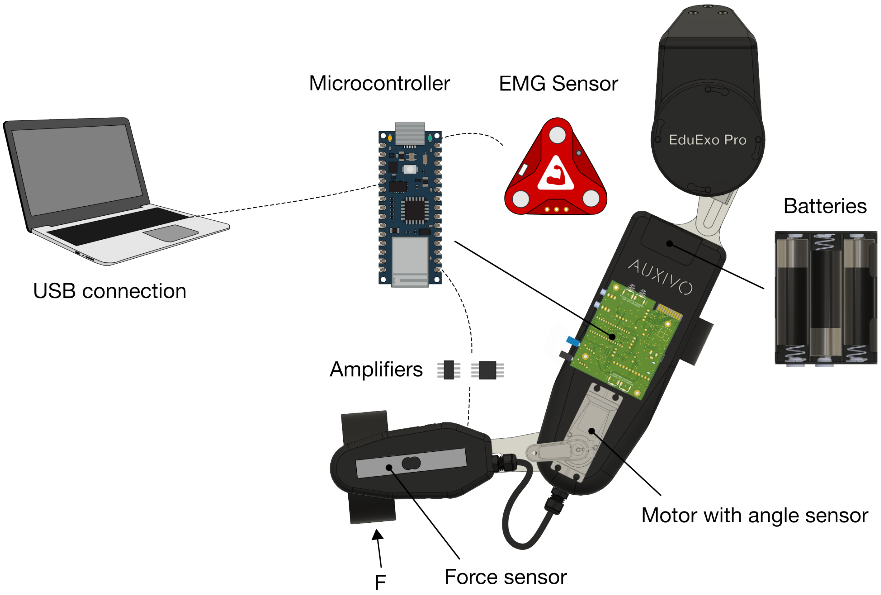


Figure 5.1: The main electronics components of the EduExo Pro.

**Warning**

Please be careful when handling the electronic components. You can damage the components simply by touching them, especially the pins of the chips, because of electrostatic discharge (ESD). We advise you to read up on ESD before handling the electronic components. There are some basic rules that you should look up and follow (e.g. do not walk over that nice rug before handling electronics, and discharge yourself by touching grounded metal components like a heater).

To start operating the exoskeleton, we first have to connect the components. Then, we can start programming the Arduino. This is usually done on an external computer, which is connected to the Arduino. The program is compiled on the computer and then uploaded to the Arduino.

### 5.1.1 Microcontroller: The Arduino Nano 33 IoT

The Arduino is the main microcontroller of the EduExo Pro. Microcontrollers are essentially miniature computers. Usually, they have additional components and interfaces to connect directly to other devices (e.g., analog-to-digital converters, and a variety of communication interfaces and buses). The microcontroller used for the control of our exoskeleton is the Arduino Nano 33 IoT (Figure 5.2).

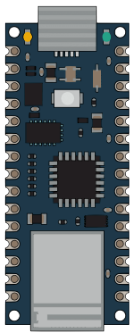

Figure 5.2: The Arduino Nano 33 IoT microcontroller that is used to control the EduExo Pro.

The IoT at the end of the designation stands for 'Internet of Things'. This means it has additional options for connecting it to other devices, such as WiFi and Bluetooth. We will not use these interfaces in our tutorial but instead connect the Arduino to our PC using a USB cable. However, if you want to implement wireless communication with other devices later, this Arduino offers the possibility to do so.

The software and control system will run on the Arduino. Therefore, the Arduino needs to be connected to all sensors to read their sensor signals and to the motor to control the motor movements. To simplify the connection of all these components, we designed a printed circuit board (PCB) on which a socket is mounted for the Arduino. Using such a socket makes for a solder-free connection, which allows you to exchange the Arduino if it gets damaged by simply unplugging it, without having to desolder all 30 pins.

The entire Arduino microcontroller family has a vast user base. If you run into any trouble or have questions that are not answered in this handbook, you can find a lot of help and tutorials online. You can start, for example, on their official website (www.arduino.cc).

You also have the option to purchase an Arduino Nano and replace the Nano 33 IoT with a normal Nano. This can be useful, for instance, if you want to connect an additional sensor that requires a 5V output, which the normal Arduino can provide. It also offers different memory types. You can simply exchange the two.

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Chapter 6

# Software


### Summary

In this chapter, we will start programming the EduExo Pro and implement the first functionalities. We will write programs to read the elbow joint position, EMG, force, and IMU signals. We will calibrate the sensors, an important step that must be done before implementing the control systems. Additionally, we will write a first program to control the motor and take a look at how to assign functionalities to the push buttons. Each new programming code is introduced in detail, line by line, to make it easy to follow and understand.


Before you start, we recommend you fix the EduExo Pro to either a chair's backrest or, if available, a mannequin (Figure 6.1). This setup makes programming and testing much more convenient. **Remember, always test your code to make sure the exoskeleton moves in a safe way and does what you want, and only then put it on! Stay safe!**

(a) (b)

Figure 6.1: Recommended programming set-up.

In this chapter, we will write programs to use each of the EduExo Pro components one by one: the servo motor, the push buttons, the EMG sensor, the force sensor, and the IMU. If one of the codes does not work as described in the handbook, there could be multiple reasons. Either the code could be implemented incorrectly, or the electronic assembly might be faulty; for example, you might have made a mistake while soldering the components together, or a component might have been damaged.

In such a case, first double-check if you have copied the code correctly to rule out a software bug, and then inspect your electrical components. Are any wires loose? Did you put heat shrink tubing over all soldering connections to avoid creating a short circuit? If nothing obvious is visible, use a multimeter to check that your soldering is good, as a connection may look fine but not conduct properly.

## 6.1 Installing the Arduino IDE

Before you can start programming the microcontroller, you have to install the Arduino Integrated Development Environment (IDE).
You can download The IDE for several operating systems on the Arduino website. Search for: 'Arduino IDE' on the internet and download the Arduino IDE 2 software. Note that the examples in this handbook refer to the IDE 2.3.2 version.
Once you have installed and opened the IDE (Figure 6.2a), you will find everything you need to write code and upload it to the Arduino microcontroller. This includes an editor with syntax highlighting to improve code readability, a compiler to translate the source code into machine-readable files, all the tools you need to connect the Arduino, and a Serial Monitor and Plotter that come in handy to read and visualize data.

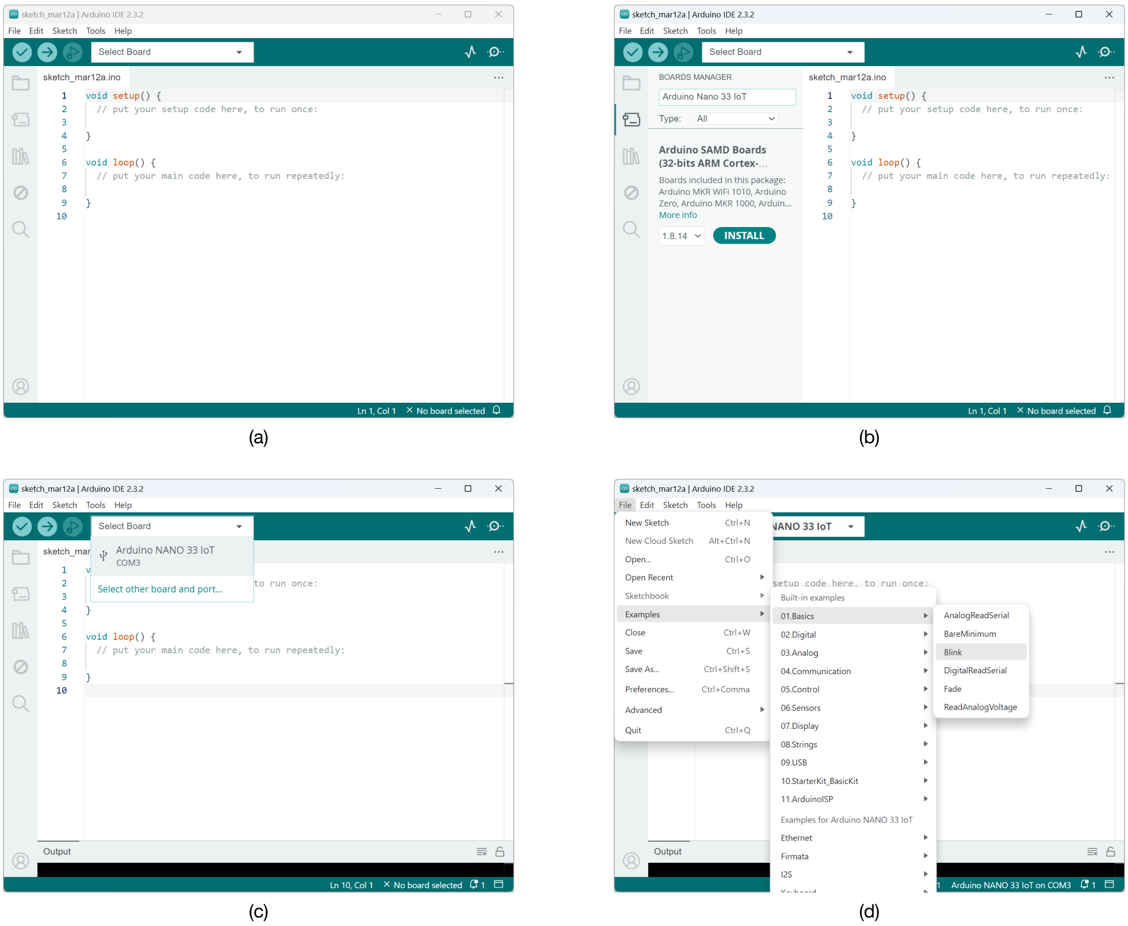


Figure 6.2: The Arduino IDE (Windows version) and the first steps to get started with programming on the Arduino.

Let's get started. Turn on your EduExo Pro and connect the Arduino to your laptop with the USB cable. A little yellow light should light up when you plug it in. Open the Arduino IDE. In the left-hand menu, click on the second icon to access the Boards Manager (Figure 6.2b). Search for 'Arduino Nano 33 IoT' and proceed to install the Arduino SAMD Boards on your computer. Once this is done, you can close the Board Manager. Click on the drop-down on the top of the page

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Chapter 7

# Basic Control Systems


Summary

In this chapter, we will develop and implement different control systems that define the exoskeleton's behavior. To do so, we will specify a set of rules on how the robot should act and react when worn by the human, translate those rules into equations, and implement these on our Arduino microcontroller.


## 7.1 Control Systems

### 7.1.1 Introduction

Control systems are generally programs containing a set of rules and algorithms that define the behavior of technical systems. They can be found in many technical systems and are used to control all kinds of variables. For example, they control the fast and precise movements of the robot that assembled your car. They come along in the form of the autopilot that flies you to the Caribbean. And, they are what keeps your self-driving car on track in the streets, driving at a constant speed. In our case, the control system is responsible for the support that is provided to the user by the exoskeleton.

For a control system to work, sensors and actuators are needed. Sensors provide information about the state of the system (for example, the position and movement velocity of the robotic exoskeleton). Actuators can react to the measured states. How these actuators react depends on predefined rules implemented as the control algorithm. Typically, control systems are represented by a control diagram (Figure 7.1).

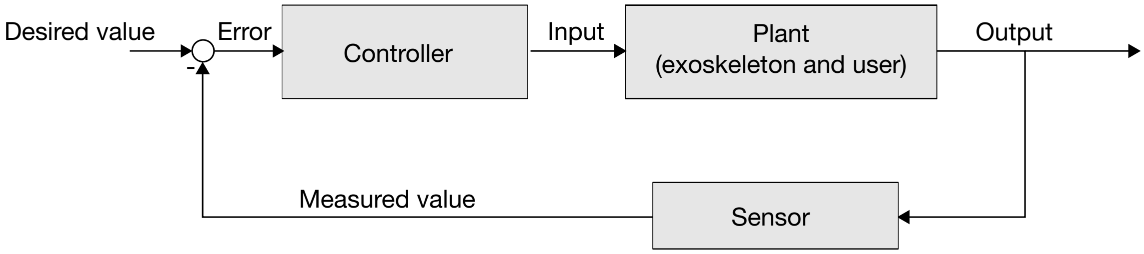


Figure 7.1: Control diagram of a generic control loop.

On the left, the desired value of a variable or system state, such as position, force, or velocity, is shown. This desired value gets compared to the values measured by a sensor (bottom of the diagram, feedback loop), and the difference is calculated. This difference is then sent to the controller that adjusts, for example, the motor current, opens and closes a valve, or executes an action to 'push' the system (called 'plant') towards the desired value. After this input is applied to the plant, the sensors measure again if the desired value is achieved, and the controller reacts accordingly. This is repeated over and over again to put and keep the system at the desired value. The desired value can change over time, and the job of the controller is to make sure the system follows these changes.

Often, you can distinguish between high-level and low-level control systems. A high-level controller (sometimes called a control strategy) is a set of rules that define, for example, in which situation the exoskeleton provides assistive force or executes a guiding movement. It does not include the specifics of which motor needs to be actuated to make this movement. It rather just decides if a movement has to be made and then communicates this to the low-level control. The high-level control can include user intention detection to ensure that the exoskeleton support meets the user's current needs. The low-level control system is responsible for the individual joints and actuators providing that desired support.

It is not uncommon in robotic exoskeletons for the user or a second person to remain at least partially in control of the high-level control system. For example, by controlling the exoskeleton manually by pressing control buttons. However, there are several approaches where exoskeletons autonomously detect the user's movement intentions and need for support. This can be done, for example, by measuring the user-exoskeleton interaction forces or the user's muscle activity. The two following examples will help illustrate how a robotic exoskeleton's control system defines its behavior.

### 7.1.2 Example: Control of a Gait Restoration Exoskeleton

To control an exoskeleton for gait restoration in users with paraplegia, manual control inputs combined with a position controller can be used. As the user's legs are paralyzed, the exoskeleton has to provide all the power required to move them.

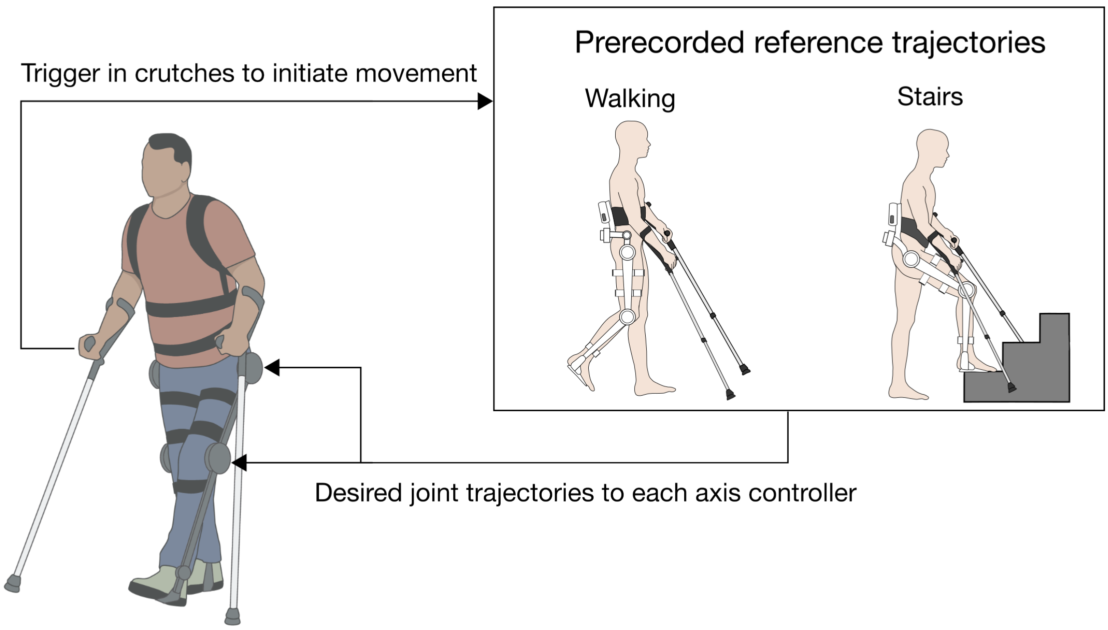


Figure 7.2: Control of a gait restoration exoskeleton.

In this case, the high-level control is implemented as manual control by the user. Buttons lo-

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Chapter 8

# Advanced Control Systems

## 8.1 Introduction to EMG Control

Summary

In this chapter, we discuss more in-depth how to design control systems that ensure users receive the right support at the right time. In the first part, the theoretical background of muscle activity-based control is introduced. In the tutorial, you will connect the EMG sensor to your arm and write a program to control the exoskeleton's movement according to the measured muscle activity.

### 8.1.1 Control of Robotic Exoskeletons

As discussed in the Control Systems chapter, the aim of an exoskeleton's control system is to ensure that the wearable exoskeleton robot provides the right amount of support with the right timing. In other words, the exoskeleton's movements and forces should always match the user's momentary needs. You have already learned that different situations and users can profit from different exoskeleton control systems. A position controller imposes a movement on the user, which can be appropriate, for example, to move a paralyzed limb. Or, an admittance controller can be used to provide a supportive force or avoid constraining the user's movements (zero-force control).

However, these low-level control systems only provide very basic control. They fall short in many ways when it comes to really anticipating the user's needs. To do so, more advanced control approaches are necessary. Luckily, the field of robotic control and exoskeleton control is very large and there are many control approaches already available. And, with the current surge of robotic exoskeletons, new control designs are continuously being developed.

The basic idea of developing an exoskeleton control system is simple: the more understanding and information we have about the user's momentary needs and plans on what to do next, the better we can support and assist with the exoskeleton. However, developing a good exoskeleton controller is often a challenging art.

So, let's dive into the field and look at what kind of different approaches are possible. As a first step in our effort to develop a great exoskeleton control system, it might be a good idea to think about how we can measure, estimate or even anticipate the user's movement intentions and support needs. If we knew what support the user currently needs or even what the user might need in one or two seconds, it would greatly improve our possibilities of controlling the exoskeleton in ways that optimize the support.

If you remember the gait restoration exoskeleton from the control chapter (Figure 7.2), the simplest way of knowing what the user wants is to give the user direct control of the exoskeleton, e.g., by pressing a button to initiate a movement. These buttons can be placed on the crutch handles. While, in many ways, this can be sufficient or even the best way to control an exoskeleton (having

full control of a big robot attached to your leg is certainly reassuring), it also requires that the user concentrates on the exoskeleton to a certain degree. This means part of their mental resources are used for concentrating on the control. Therefore, a so-called cognitive load is imposed on them. The result is that their capacity to focus,e.g., on the environment, is reduced.
Another example of exoskeleton control was the load-carrying exoskeleton (Figure 7.3). Here, an additional sensor system is used to gather more information about the environment and intended tasks. Pressure sensors placed in gloves measure when the user is holding a payload. If a force is measured in the palms of the user, the exoskeleton provides support. If no force is measured, the exoskeleton goes into a zero-force mode to minimize the constraint on the user's movements.
In addition to the examples above, the users themselves are a great source of information that helps us understand how they want to move or exert a force. The question is what kind of information is available and how we can access and measure it to use in our exoskeleton's control system. The following examples will give you an idea of different possibilities.

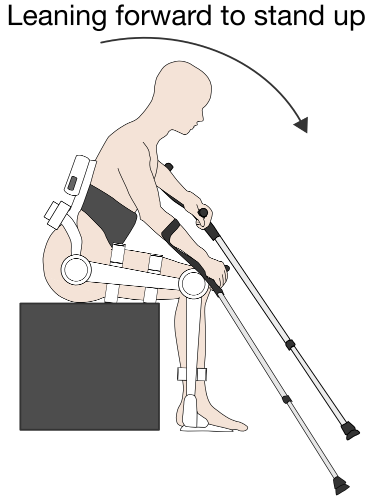


Figure 8.1: Example of a movement that we can use to control an exoskeleton. If a person wants to stand up from a seated position, they usually first lean their upper body forward to move the body's center of mass above the feet. If we attach a movement sensor to the torso, we can detect this movement and initiate sit-to-stand transfer motion with the leg exoskeleton.

The exoskeleton user's body movements can be a great indicator of what they want to do next. And we are not necessarily talking about the movements of the limbs inside the exoskeleton. Most activities involve multiple body parts and limbs, and information extracted from one body part can control an exoskeleton that supports another body part. For example, a person who is sitting and wants to stand up will typically first lean the upper body forward to move the body's center of mass above the feet (Figure 8.1). Only then do the legs push to stand up (try it yourself). Suppose we placed a movement sensor on the upper body of, e.g., an exoskeleton user with paraplegia. In that case, we could detect this trunk movement and then initiate a sit-to-stand movement with the leg exoskeleton. Our control system should just ensure that it can distinguish between leaning forward to stand up and leaning forward to tie shoelaces.
Another example of using body movements to control exoskeleton support is complementary limb movements. This is based on the fact that, for many activities, the legs and arms on one side of the body mirror the movements of the other side. When you jump, the left and right legs execute almost the exact same movements. Or, when you walk, your left and right arms swing with (almost) the same pattern but with a time delay. Thus, if a user has only one limb impaired

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Chapter 9

# Virtual Realities and Video Games

Summary

In this chapter, you will learn how computer games and exoskeletons can be used together, either in rehabilitation or just for fun. In the tutorial, we will create a computer game, connect the exoskeleton to your computer, and use it as an interface to the virtual world.

Now that we know how to use, program, and control our exoskeleton, we can connect it to a PC, create a computer game, and play the game with the exoskeleton. What may sound like fooling around (and it certainly is fun) is also not uncommon in rehabilitation exoskeletons, where virtual realities (VR) and games are well-established methods used in combination with exoskeletons. The purpose of the games is to keep patients motivated and engaged during their rehabilitation. The exoskeleton's adjustable support and different difficulty settings in the games can be used to adapt the training difficulty to the patient's abilities, facilitating recovery. Of course, exoskeletons can also be used in general to interact with virtual objects in a simulated environment or control video games for entertainment.

## 9.1 Background: VR/Games and Exoskeletons

We previously discussed how exoskeletons can be valuable tools for the rehabilitation of incomplete paraplegia or hemiplegia after a spinal cord injury or a stroke. They provide adjustable support to enable training at a difficulty level that optimizes the patient's recovery. Typical applications are leg exoskeletons that support gait training or arm exoskeletons that support the training of arm and hand movements such as reaching and grasping. Most of these devices are stationary and placed in hospitals, where multiple patients can use them every day.

Rehabilitation programs often stretch over weeks and months and involve many very repetitive training sessions. This can quickly become boring, tedious, and, if progress is slow, demotivating. However, for optimal recovery, a high training intensity with active participation of the patient is crucial.

This is where games and VR can be valuable assets (Figure 9.1). Instead of walking in an exoskeleton on a treadmill and staring at a wall, you can control an avatar in a game with your movements and run in the forest, collecting points for every 100 steps completed. Or, you steer an airplane by moving your partially impaired arm in the exoskeleton to keep the plane from crashing into obstacles. The exoskeleton becomes your controller for the game, making the training more exciting.

The application is, of course, serious (they are actually called 'serious games' and the field is called 'serious gaming' if you want to read more about it), but the main motivation is similar to games for entertainment: to be fun and to keep you engaged. As in any other game, the difficulty level must match the user's skill level for it to be fun and motivating. Otherwise, it might be too simple or too overwhelming. In the context of serious games, the skill level is usually connected

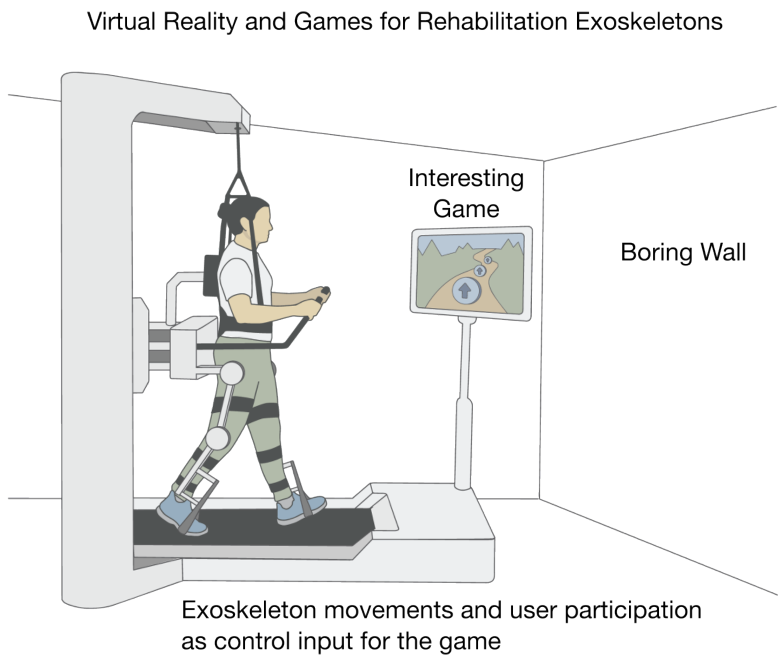


Figure 9.1: Concept of the use of VR and computer games in combination with exoskeletons for gait rehabilitation.

to the user's impairment level. This difficulty adjustment can be done in the game settings (as in any other game), or, and this is special about exoskeleton-based games, by adjusting the level of support provided by the exoskeleton.

The games can also be designed to directly contribute to relearning activities of daily living (ADLs). They often simulate tasks in a virtual environment (e.g., reaching and grasping virtual objects) that will help patients restore abilities they need in daily life.

In addition, the exoskeleton can become an assessment device to monitor and quantify the patient's performance and progress (like a fitness tracker, but with more information). The exoskeleton can record data during therapy, allowing the patient, therapist, and doctor to compare, for example, today's session to yesterday's session or the session two weeks ago.

## 9.2 Preparation for VR and Games

We will use the Unity 3D game engine to create our game. You can download it from their website. It is free for non-commercial use or small businesses, but requires registration. Execute the installer, launch Unity, and create an account with a personal license.

You will only have to pay later on if you want to sell your awesome exoskeleton games on a big scale. If you are completely new to Unity, we suggest you first take a look at one of the beginner tutorials to familiarize yourself with it. We will explain many details below step-by-step, but it will certainly be easier if you go through their tutorials. You can quickly learn how to create some simple and fun games and already get inspiration for what you can do later once you know how to integrate the exoskeleton to control your games.

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Chapter 10

# Scientific Experiments

Summary

In this chapter, we will evaluate whether our exoskeleton really supports us and makes certain tasks easier. For this, we will conduct two experiments using the EduExo Pro. In the first experiment, we will test if we have increased endurance in our shoulder when using the exoskeleton to support lifting our arm. In the second experiment, we will look at the exoskeleton's effect on our muscle activity using the EMG sensor.

## 10.1 Introduction to Scientific Experiments

Conducting a scientific experiment means you test something systematically to ensure the results are valid and not just random chance.

This means, for example, that when conducting experiments to evaluate if an exoskeleton reduces the workload of its users, you test several people, not just one or two. If you test with only two people and both show a slight reduction in workload, you cannot be sure if this can be replicated for 100 people. On the other hand, if you see a reduction in workload for each participant when testing ten people, the chances that this is similar for the average person are much higher. To draw conclusions from your measurement in a scientific experiment, you analyze the data using statistical methods to ensure your results are not simply good or bad luck.

Lastly, you should conduct experiments under somewhat controlled conditions to ensure that you measure the effects of the exoskeleton and not of something else. For example, temperature influences your heart rate. The hotter the temperature, the higher the heart rate. If you collect heart rate data without your exoskeleton on a very hot day and with your exoskeleton on a very cold day, you might find that the heart rate without the exoskeleton is higher. This will make you very happy because you think the exoskeleton reduces the workload. In reality, your data might tell you more about the weather than about your exoskeleton.

### 10.1.1 Lab Testing vs. Field Testing

Exoskeletons are typically designed for use in a specific location or environment, such as a rehabilitation clinic or construction site. Testing them directly at the location where the exoskeleton will be used later with participants who conduct real work is called field testing. Field testing is important because it evaluates the exoskeleton performance under realistic conditions.

However, it is challenging to create controlled conditions, such as a constant temperature daily in the field. Therefore, we also need to do lab testing, usually conducted inside a laboratory under more controlled conditions. Lab tests are an ideal tool to investigate isolated benefits and effects of the exoskeleton. They typically require less preparation and time and can be performed more frequently during development. Nevertheless, when you plan a lab experiment, it is essential to

consider the real-world field application and design the experiment to represent it. Otherwise, your lab results will tell little about how well your exoskeleton will perform in the field.
In the end, you need both, and systematic experiments are essential to exoskeleton development. When you change some aspect of your design, you want to know if it improves the exoskeleton. You can do this by collecting data from old and new prototypes and comparing the two. This way, you can continue your development process in an informed manner.

### 10.1.2 Two-Sample vs. Repeated Measures Experiments

When you want to compare two things, for example, working overhead with and without an exoskeleton, there are two ways to design your experiment. You can, for example, do a two-sample experiment. In this case, you divide all your participants into two groups. The first group conducts the experimental task with the exoskeleton, and the second group conducts the task without an exoskeleton. Afterward, you compare their performance to analyze if the exoskeleton was helpful.
Alternatively, you can conduct a repeated measure experiment. In this case, every participant will perform the task twice. Once without the exoskeleton, once with the exoskeleton. You then compare the performances of each individual participant for both conditions.
Which approach you choose depends on many factors and influences what statistical methods you can use to analyze your data. You will have to consider, for example, how many participants you can find, how much time you have, or how much recovery each person needs after the experiment.

## 10.2 Tutorial Experiments

### 10.2.1 Experiment One: Increased Endurance

The EduExo Pro supports your shoulder muscles and should make it easier to hold objects on or above shoulder level. For this test, we will hold a load, e.g., a full water bottle, on or above shoulder height and measure how long you can hold it. Hold it as long as you feel comfortable, and put it down once you feel that your shoulder is exhausted.

> **Hint**
>
> Make sure that the spring in the shoulder joint is tensioned so that you feel support when holding your arm at shoulder level. If this is not the case, open the lid, remove the circlip, and rearrange the spring.

You then measure the time you can hold the weight comfortably in this position. You do this measurement twice, once without the exoskeleton and once with the EduExo Pro. Thus, this is a repeated measures experiment. It is important to take a long break between the two measurements to let your arm muscles rest and recover from fatigue. To increase the quality of your experiment, you should repeat it with a couple of people. Ask a couple of friends or family members and run this experiment with each of them. Write down the two results for each participant. If you have multiple participants, you should change the order in which the experiment is conducted. If you started without the exoskeleton for the first measurement and put it on for the second, you ask the next person to do it the other way around. When you have ten participants,

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Chapter 11

# Beyond the Handbook

We hope you enjoyed reading this handbook and that you gained new knowledge and skills while building the EduExo Pro. Although you have finished the handbook, your journey doesn't have to end here. Consider the EduExo Pro as a launch pad for your own ideas and experiments. By now, you know every aspect of the exoskeleton and have the knowledge and skills to modify and expand it. To get started, consider exploring these initial ideas:

- Develop new games: the game we developed was very basic. Wouldn't you prefer to steer a spaceship through an asteroid belt using the exoskeleton while being chased by aliens?
- Explore new applications: how about an exoskeleton curl counter for your dumbbell training? Maybe exoskeleton-based training can help you achieve your New Year's resolution.
- Adjust the exoskeleton hardware: why not redesign the housing and engrave your university's name?
- Implement new control systems: as mentioned, the field of exoskeleton control systems is quite large. Maybe you can implement an approach that creates a better support behavior.
- Change the game feedback: is the feedback good enough to allow you to play the game with your eyes closed? If not, can you achieve that by adjusting the feedback?
- Improve the communication between Unity and Arduino: you can implement a proper protocol with plausibility checks. Right now, we do not really 'ask' for data, we simply send it and hope it will be received.
- Implement filters to improve the force and position signal: signals can be quite noisy, which affects the control system. Can you implement a software filter or even build a hardware filter to improve that?

But we are sure that you have many great ideas of your own. If you explore new possibilities with the EduExo Pro kit and implement and test something new, we would be delighted to hear about your projects! Please write us at: eduexo@auxivo.com.

Additionally, if you're curious to learn more about our industrial and occupational exoskeletons, be sure to visit our website at www.auxivo.com. There, you'll find further information and resources about our exoskeletons.

For now, we thank you for your interest and wish you great success!

The Auxivo Team

# About Auxivo

Founded in 2019 as a spin-off from ETH Zurich, we specialize in the development and manufacturing of occupational exoskeletons designed to improve worker safety and well-being. Our goal is to provide practical, wearable solutions that reduce physical workloads and minimize injury risks.

Today, our exoskeletons are used globally across various sectors, including logistics, construction, manufacturing, healthcare, and agriculture. For professionals in these industries, we offer effective solutions that support physically demanding tasks, reducing muscle load and strain during activities such as lifting, carrying, and working in difficult positions.

With a strong academic foundation, the Auxivo team brings decades of expertise in exoskeleton research and education. We use this extensive experience to create high-performance occupational exoskeletons and are committed to sharing our knowledge with the next generation of developers and users through our educational exoskeletons.

For more details on our company and exoskeletons, please visit www.auxivo.com

# Occupational exoskeletons

As of 2024, we offer four occupational exoskeletons. Each features passive support mechanisms, ensuring they are reliable, lightweight, easy to maintain, and ready for use anytime and anywhere.


## LiftSuit

The LiftSuit supports the user's back and hip muscles during lifting and forward-leaning tasks. It is typically used in logistics, construction, agriculture, and healthcare.


## DeltaSuit

The DeltaSuit supports the neck, shoulders, and arms of its users during prolonged work at or above shoulder height. It is typically used in manufacturing, maintenance, or construction.


## OmniSuit

The OmniSuit provides neck, shoulder, back, and hip support during a wide variety of multitask activities. It is typically used in logistics, construction, manufacturing, and agriculture.


## CarrySuit

The CarrySuit relieves the muscles in the torso and arms when carrying and holding heavy loads by transferring the payload to the user's hips. It is typically used in construction or relocation.

If you want to learn more about the mechanical and biomechanical principles of our occupational exoskeletons, you can read our white paper by scanning the QR code provided.

# Auxivo as Partner for Exoskeleton Education

Coming from an academic background, we have extensive experience in education and research, with many of our team members having taught exoskeleton technology, robotics, movement sciences, and other subjects at universities. Through this teaching experience, we have found that project-based, hands-on learning is essential for a deep understanding of exoskeletons. Building and wearing them connects theoretical concepts to practical experience, helping grasp fundamental principles, acquire practical skills, and develop the confidence needed to create real-world solutions.

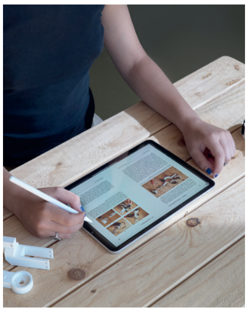
As the exoskeleton industry is still young and rapidly evolving, access to up-to-date learning resources and hardware for project-based learning is very limited. We aim to close this gap by providing schools, universities, students, and enthusiasts with access to exoskeleton knowledge and hardware.
Our educational EduExo kits are designed to make learning about exoskeleton technology more accessible and efficient.

## EduExo Pro

The EduExo Pro kit includes all the components needed to build an arm exoskeleton that spans the shoulder and elbow joints.
It was developed primarily for universities, offering both hardware and a comprehensive handbook to facilitate teaching about exoskeletons, human-robot interaction, and related topics.

## EduExo Lite

The EduExo Lite kit includes all the components needed to build an elbow exoskeleton. It is ideal for students, hobbyists, and educators. The kit can be used for individual learning at home or as a teaching tool in schools, providing a foundation in hardware design, electronics, programming, control theory, and game design.



## EduExo Maker

The EduExo Maker edition is a fully digital open-source exoskeleton that can be downloaded for free. It contains a PDF handbook, STL files to 3D print a simple elbow exoskeleton, and a list of the required components to order.

# The Advanced
# Robotic Exoskeleton Kit

**What it is**

- An educational robotics kit that will help you learn about wearable exoskeleton technology.
- A do-it-yourself kit that requires active participation and willingness to learn new things.

**What it is not**

- It is not a medical device that is intended to be used for any kind of medical application.
- It is not an exoskeleton that will make you super strong. The actuation is only intended to illustrate basic exoskeleton principles.
- It is not a robot that works out of the box. You have to make it work, that is a feature!

**For whom it is**

- For teachers and professors who want to set up exoskeleton courses or labs.
- For researchers looking for a versatile exoskeleton research platform.
- For high school and university students who want to learn about robotic exoskeletons.
- For makers and hobbyists who are looking for a fun project in a fascinating field.

**Educating Future**
**Exoskeleton Pioneers**