White Paper
How Exoskeletons Provide Support

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Introduction

Welcome to the Auxivo White Paper on exoskeleton support. This paper discusses the most important mechanical and biomechanical principles of how wearable exoskeletons work and how they support their users.

Wearable exoskeletons are devices that are worn by human users to provide physical support. They are being used today in medical applications, e.g., to assist users with mobility impairments, and in occupational settings, where they support workers by reducing the workload to prevent exhaustion and injuries caused by overload.

Our goal with this white paper is to provide the reader with the information necessary to understand human-exoskeleton interaction and how exoskeletons can reduce physical strain on the human body. It addresses common concepts of exoskeleton support on a conceptual level to provide a good overview and only adds technical or scientific details where necessary for comprehension.

As a potential exoskeleton user, we aim to provide you with the information needed to understand the possibilities and limitations of exoskeletons and make an informed, fact-based decision if exoskeletons are the right choice for you.

We hope you enjoy the read! Please reach out to us in case you have further questions.

The Auxivo Team

White paper structure

Section 1
introduces the most important engineering mechanics and biomechanics principles required for understanding how exoskeletons provide support.

Section 2
Discusses the mechanisms and concepts of how wearable exoskeletons support their users.

Section 3
Addresses some of the most common misconceptions about exoskeleton support, building on the information and concepts introduced in sections 2 and 3.

Section 1
Important (Bio)mechanical Principles

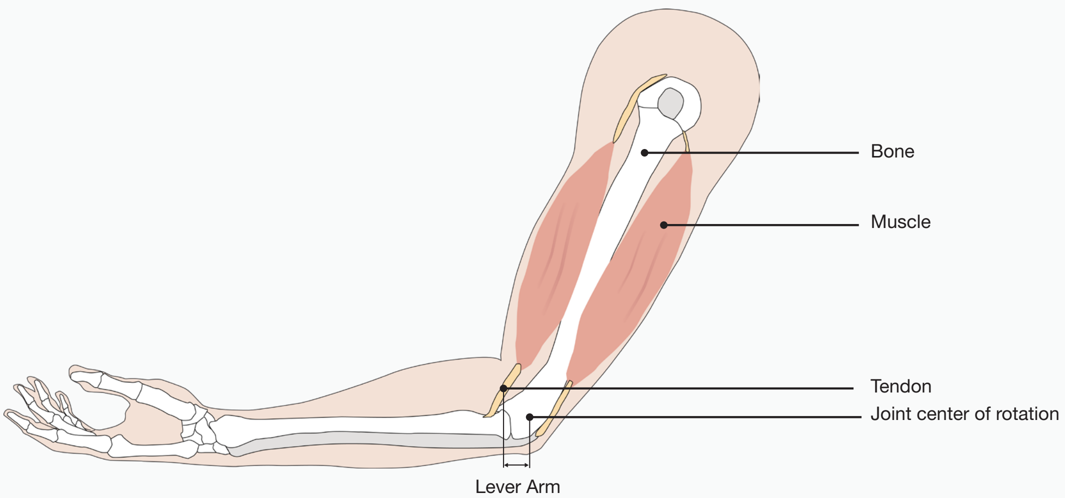
Before discussing how exoskeletons provide support, we must introduce some important mechanical and biomechanical principles. This will help us understand how physical work causes strain on the human body and how a mechanical system can help reduce this strain. Once we have understood these basics, understanding exoskeleton support mechanisms will be easy since they rely on these principles.

The Human Musculoskeletal System
First, let us quickly summarize on a very high level how the human body can move, hold, and lift objects by looking at the human musculoskeletal system.

The bones of our (endo)skeleton are connected by joints that allow movement. Muscles connect the different bones across one or multiple joints through tendons. When the muscles contract, they create a pulling force on the bones. There is some distance between the muscle attachment and the joint center of rotation, which we call the lever arm. Because of this lever arm, the muscle force results in a rotational force (also called torque) at the joint level, which causes the bones to move in a rotational movement around the joint.

If an external load (or the weight of the human body itself) imposes a torque on a human joint, the corresponding muscles need to contract to generate a counter-torque around this joint. This allows the human to hold or move an external load through muscle force. Human muscles can only generate a pulling force. They cannot push against a bone. To generate movement in two directions, you have (at least) two muscles per joint, which can counteract each other's force. We call a set of counteracting muscles agonist and antagonist.

If you activate both the agonist and antagonist muscles of a joint at the same time, the joint becomes very stiff. This way, you can prevent it from moving and create stability. This is called co-contraction. Co-contraction can also be used to stabilize a series of joints, such as the spine. For example, in everyday life, the back and abdominal muscles collaborate to generate and hold an upright posture.



Lever Arms – Why the Same Load can Cause Different Strains on our Body

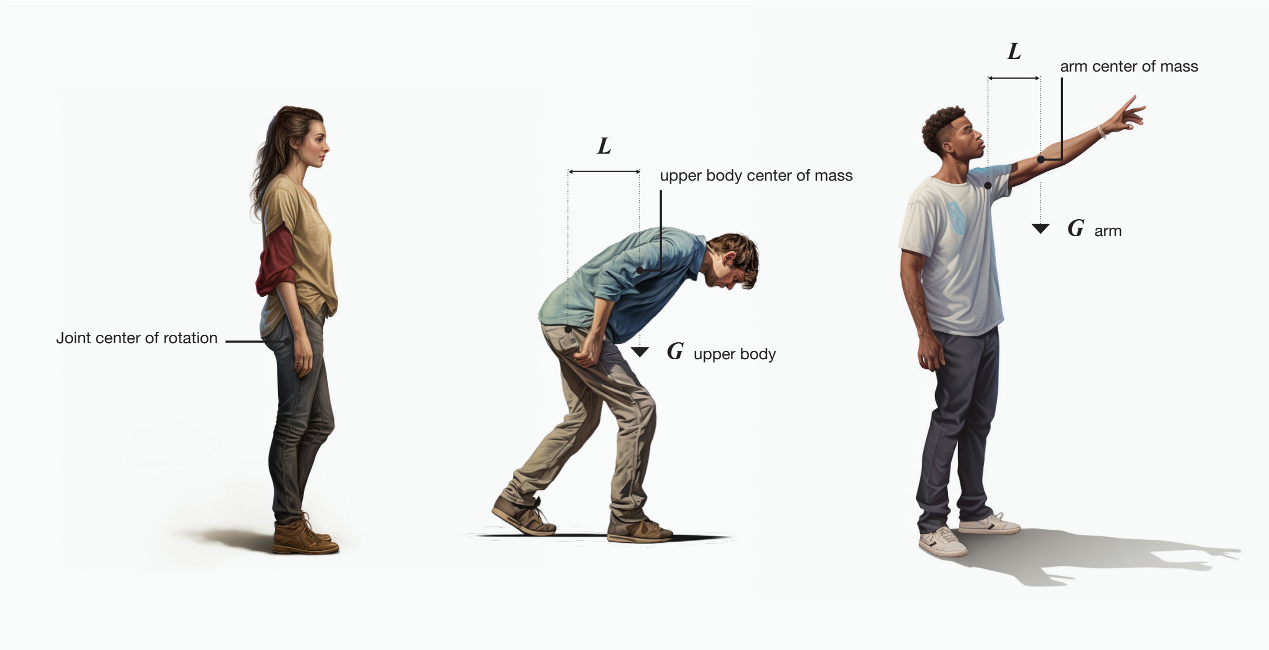
How much force the human muscles need to generate when handling an external load depends on several factors. One aspect is the absolute mass of the external load. There is, of course, a difference if you hold 5 kg or 20 kg. But there is a little more to this that is important to understand.

How you hold and handle the mass can significantly impact the strain it causes on your body more than the mass of the load itself. Let's imagine (or try) to hold a bag of 10 kg. If you carry the bag on the side of your body, you can hold it without much effort for a long time. But the moment you lift it in front of your body, you instantly feel the load in your shoulder increasing and quickly struggle to hold it in this position.

The reason for this effect is that often, not the force is the critical aspect that exerts the primary strain on your body, but rather the torque that this force creates on your joints. This torque is the force multiplied by the horizontal distance between the force and the joint center of rotation (lever arm): $T = F*L$, where T is torque, F is force, and L is the lever arm.

As a result, increasing the lever arm horizontally by holding a load in front of you or leaning your body forward can quickly increase the joint torque significantly, which can then cause overload in the affected joints.

The effect of the lever arm (i.e., the horizontal distance between the human joint and the external force) is illustrated.
◂Left: The person carries a bag on the side of the body. The bag is more or less aligned horizontally with the shoulder joint. As a result, the bag's weight only induces a small torque in the shoulder joint that needs to be counteracted by the shoulder muscles. ▸Right: the person holds a bag in front of the body. This results in a considerable horizontal distance (lever arm) between the bag's center of mass and the shoulder joint's rotational axis, resulting in a higher torque that the shoulder muscles need to compensate.



The influence of body mass and posture in the gravitational field on the joint load.
◂ Left: With the body in an upright position and the arms hanging vertically on the side, the load on the shoulder, back, and hip is relatively small. ▴ Middle: With the upper body in a more forward-leaning position, the load on the back and hips increases. ▸ Right: With the arm reaching forward, the arm center of mass has a horizontal distance to the shoulder joint, resulting in a significant lever arm and shoulder torque.

Gravity and Mass of the Human Body

Directly related to the previous section, it is worth highlighting the dominant role that gravity and the human body's mass play when we talk about workload or strain. While other aspects are at play, like dynamic force caused by accelerations and movements, gravity is our main enemy regarding physical workload. It permanently pulls everything downwards, including any load we handle and all our body parts. Our muscles must work continuously to counteract this downward gravitational force.

It is important to consider that the lever arm principle described above also applies to the mass and center of mass of our body segments. Thus, the strain caused on our individual joints and muscles strongly depends on our body posture. When we stand straight, the load on our muscles is relatively small. However, once we lean our upper body forward or lift our arms, we increase the joint loads significantly, and the muscles in the back or shoulder need to work hard, as illustrated above.

Very often, the strain caused by one's own body mass is the main contributor to the overall workload. To understand this, we can look at our forward-leaning example above. Around 60% of the human body weight is typically located in the head, arms, and torso. So, the back and hip muscles of an 80 kg person who is simply leaning forward already need to stabilize around 50 kg of load. This means that the strain on the body caused by its own weight is often higher than the additional strain caused by lifting a 10 kg or 15 kg object. Therefore, using an exoskeleton to compensate for the body weight can significantly reduce load.

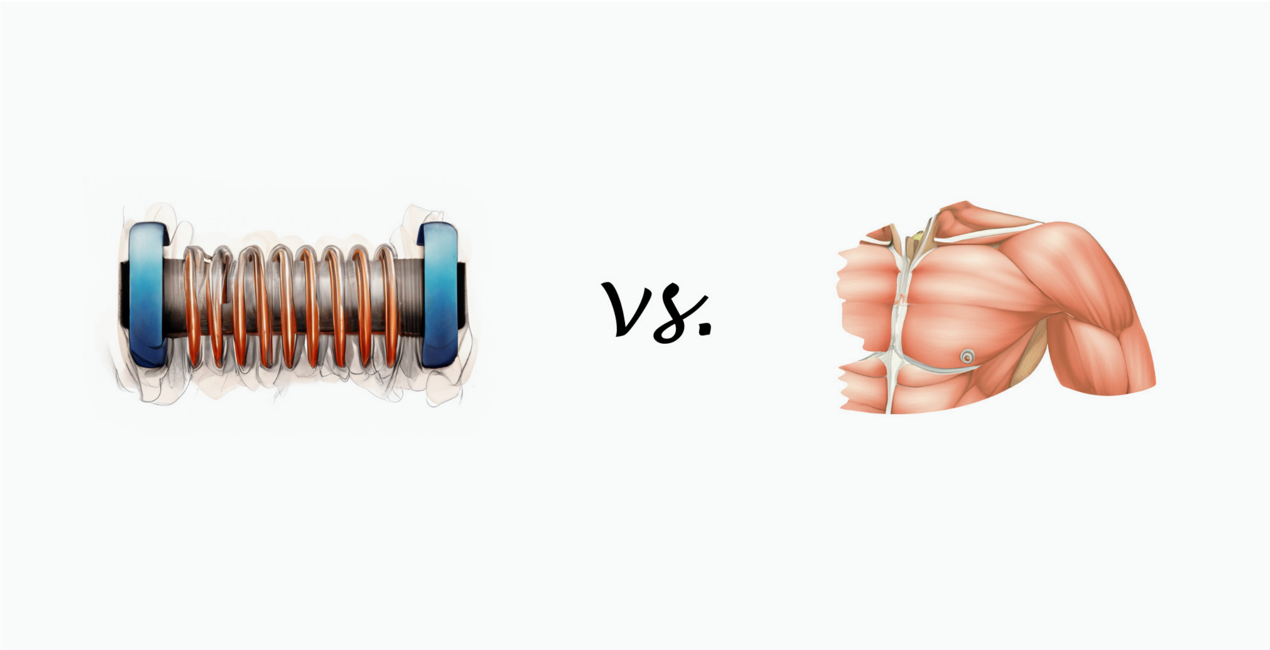
Important Differences Between Engineering Mechanics and Biomechanics

The human body is not a machine. And while this might sound rather obvious, it is essential to understand what this means on a mechanical and biomechanical level. While many principles in engineering mechanics (dealing with forces and movements in machines) and biomechanics (dealing with forces and movements in the human body) are similar, there are differences. When discussing exoskeletons, an important difference is how human muscles and mechanical springs create force.

A muscle under tension is very different from a mechanical spring under tension from an energetic perspective. Stretching a mechanical spring requires energy. This energy is released when the spring is relieved. While it is stretched, the mechanical spring permanently creates a force with no additional energy required. This force can be used to support a load against gravity.

On the other hand, human muscles generate force through contraction using proteins that convert chemical energy into mechanical energy. The proteins in the muscle can slide into each other, making the muscle fibers shorter, resulting in a pulling force. While active, the muscle permanently requires energy provided by cellular metabolic processes. This can lead to a depletion of energy reserves, neuromuscular fatigue, and other metabolic and neuromuscular effects that need energy and limit the muscle's ability to contract.

In summary, a mechanical spring, once extended, can create a permanent force without additional energy. In contrast, a human muscle requires a constant energy supply to stay contracted, leading to fatigue and exhaustion.



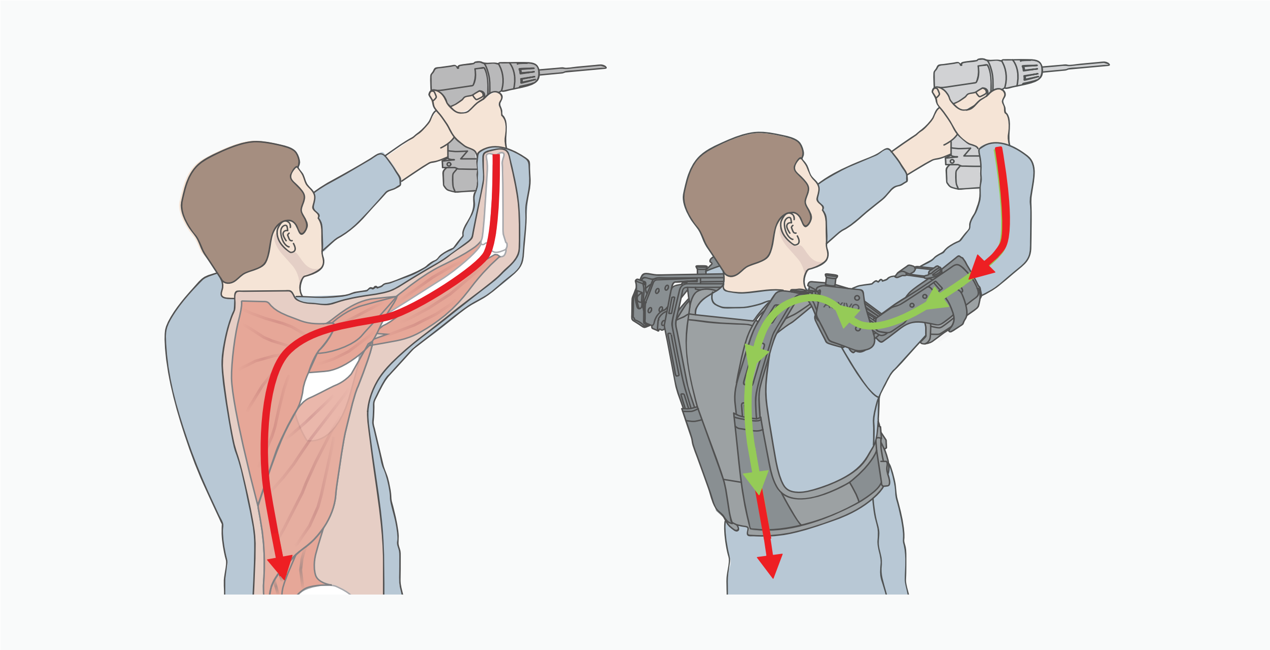
It is essential to understand that mechanical springs and human muscles generate force differently. A pre-tensioned mechanical spring does not require energy to generate a constant force and can support a load indefinitely. In contrast, the human muscles will need a constant energy supply and will fatigue quickly.

Section 2
How Exoskeletons Support Their Users

Now that we have covered the most important (bio) mechanical basics, let's explore how exoskeletons can support their users. Most exoskeletons combine multiple of the following principles, but we'll discuss each one separately to make it easier to understand.

The Bypass Principle
This is a comparatively simple but effective approach. Many exoskeletons mechanically bypass the load around one or more human joints. So, for the body parts covered by the exoskeleton, it transfers the load (or part of it) from your body to the exoskeleton, and the load is then routed through the exoskeleton and bypasses your musculoskeletal system. At the lower attachment point of the exoskeleton, the load is transferred back to the body, where it is transferred to the ground, similar to the load path without the exoskeleton.

For example, when you are holding a mass of 5 kg in your hand, this load is channeled through your wrist, elbow, and shoulder, down your spine, through the hip into your legs, knees, ankles, and eventually into the ground. Along the way, it puts strain on all these body parts. When using a shoulder exoskeleton, like the Auxivo DeltaSuit, a significant part of the load is directly transferred from your upper arm to your torso, bypassing the comparatively vulnerable shoulder joint.



The Bypass Principle implemented in the Auxivo DeltaSuit
The red arrow indicates the load path through the body without the exoskeleton and the green one with the exoskeleton. By transferring the load to the exoskeleton, the strain on the muscles, tendons, and joints along the bypassed section can be reduced.

Illustration of the load redistribution concept.
◂Left: the load is carried in the hands and affects the body from there. ▸Right: The CarrySuit spreads the load attachment across the entire upper body, reducing local peaks.

The Load Redistributing Principle

When an external load affects your body locally or asymmetrically, e.g., when you carry something heavy with one hand, it will typically cause most of the strain on only a small part of your body. This happens because the load will be routed along the most direct path through your body to the ground. This also means that you have a high risk of local overload in specific joints, while the rest of your body may be barely affected by the load.

This is something that exoskeletons can change by redistributing the load and spreading it more evenly over larger parts of the body and away from body parts at risk of a local overload. One exoskeleton example using load distribution is the Auxivo CarrySuit, which consists of a frame around the upper body. When a load is attached to it, the frame will automatically distribute the load more evenly across the user's body, connecting it to the hip and shoulder on both sides.

Applying this principle, of course, means that the exoskeleton can increase the load on other parts of the body, such as the hip, which, out of context, might sound counterproductive. However, it also means the load is more evenly distributed across your body, avoiding local peak loads that often increase the risk of injuries.

Muscle Support with Artificial Muscles

The idea of artificial muscle support is simple: passive or active tensioning systems on the outside of the body create a supporting force similar to the force created by the human muscles. Exoskeletons using this concept have “artificial muscles” that are connected to the body, typically using textile interfaces, and are arranged to create a pulling force in parallel with the human muscle underneath, thereby supporting this muscle. These artificial muscles can be powered by an actuator connected to a cable or realized through springs or elastic bands that stretch during movement and create a mechanical pulling force.

This concept is often utilized by textile exoskeletons (also referred to as Exosuits) because it can be used without a rigid frame. In this case, the artificial muscles rely on the human (endo)skeleton for stability.

The main aim of artificial muscles is to reduce the strain on the user’s muscles and tendons. If the user’s muscles work less hard, they fatigue less quickly. When muscles are tired, it becomes harder to coordinate them. Repetitive strain and fatigue are risk factors for developing musculoskeletal disorders. So, the main idea is to assist human muscles with artificial muscles and reduce muscle fatigue, exhaustion, the risk of injuring the muscles or tendons, and the overall workload.

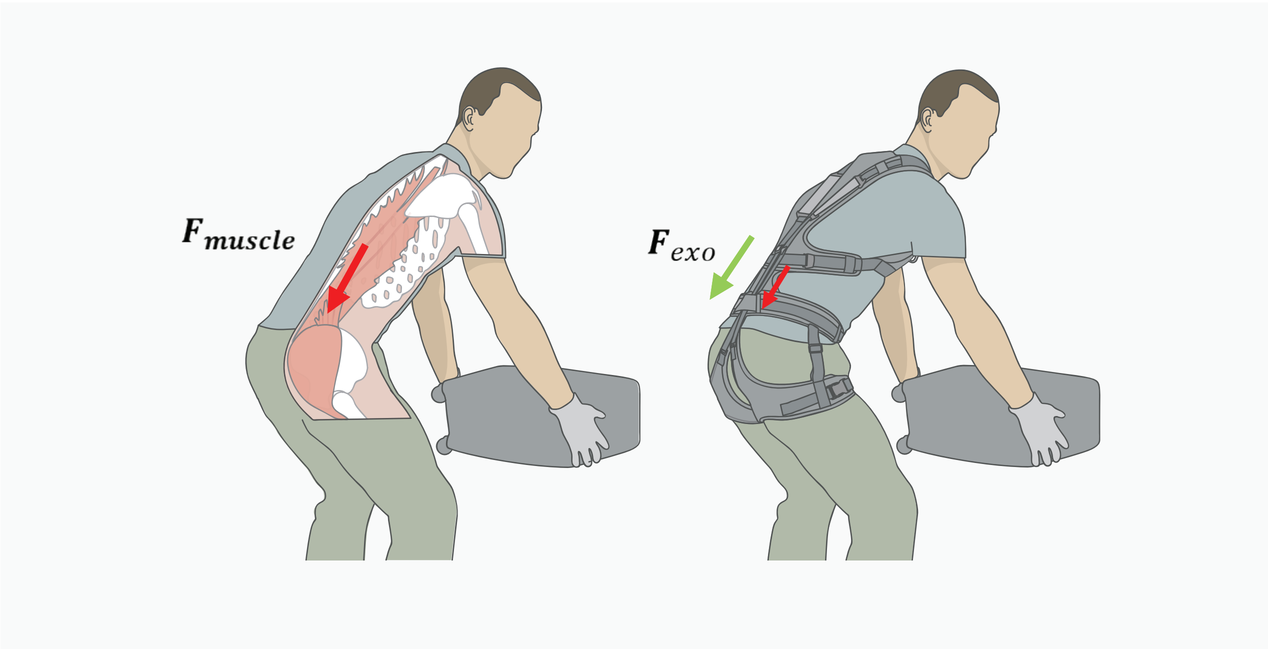


Illustration of how the Auxivo LiftSuit’s artificial muscles support the user’s back muscles.
When the user leans forward, the back muscles must contract and create a force to hold the body in the forward-leaning position.
With the exoskeleton on the outside, the “artificial muscles” create a force directly supporting the back muscles underneath, thereby reducing the muscle strain.

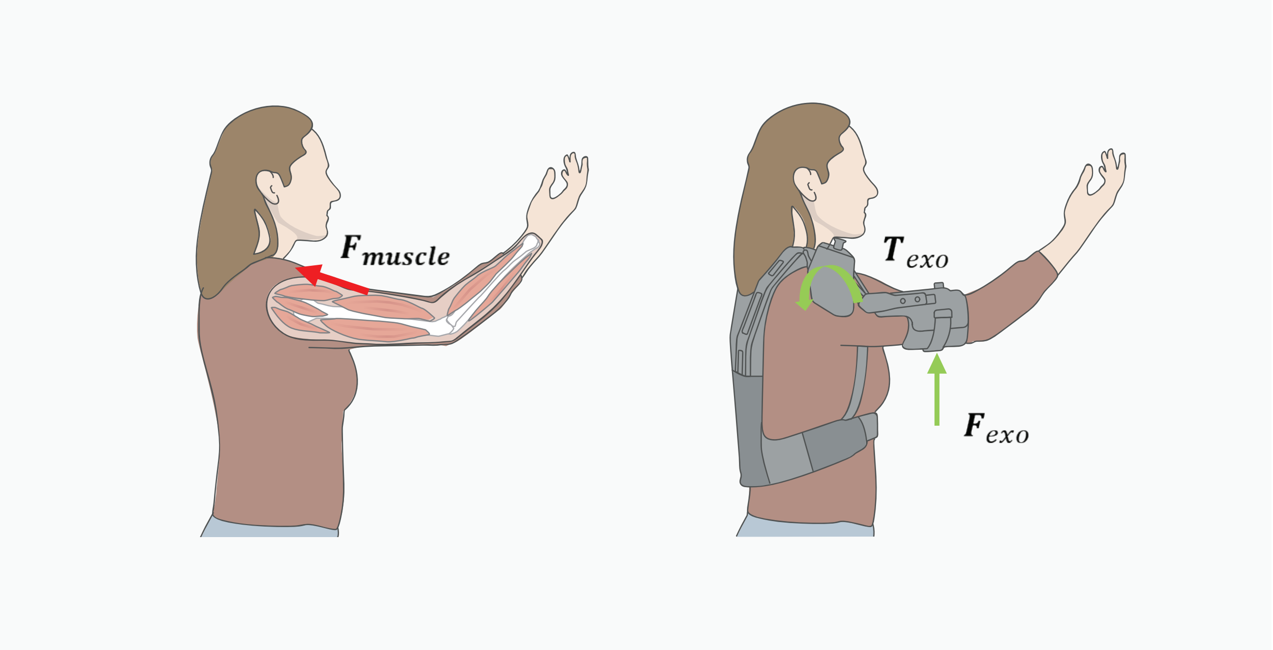


Illustration of exoskeleton support on a joint level.
◂Left: When the user lifts her arm, the corresponding muscles in the shoulder contract and create a pulling force, which then creates a torque in the shoulder joint that lifts the arm. ▸Right: With the joint supported by the exoskeleton, the exoskeleton provides a torque at the joint that creates an upward force at the upper-arm interface to support lifting the arm.

Joint Support with a Torque

Another possibility of how exoskeletons can support their users is by applying an assistive torque around a specific joint.

Exoskeletons can generate joint torque in different ways. Active exoskeletons typically rely on powered actuators, and passive exoskeletons typically rely on springs that are arranged in such a way that they create torque at the joint level. In either case, the human muscles can relax to a certain degree since at least part of the required joint torque, e.g., to lift the arm, is provided by the exoskeleton.

Another benefit of this method is that it can reduce joint compression and potentially prevent joint damage such as osteoarthritis. The reason is that joint support also leads to a reduction in muscle force similar to artificial muscles. However, unlike an artificial muscle, it does not just substitute one pulling force with another. It creates a torque around the exoskeleton joint and then transfers this torque through the rigid frame as a force perpendicular to the body. This mechanical difference can result in an overall reduced compression force on the joint.

It is important to note that natural joint compression is nothing bad. It actually helps to stabilize the joint under load. However, if high forces are imposed on a joint frequently, this can lead to overuse injuries and pain caused by damage to the ligaments and cartilage of the joint.

Gravity Compensation: Offsetting the Gravitational Loads

Since gravity is one of the main causes of a high physical workload, offsetting the effects of gravitational forces using an exoskeleton is a prominent approach.

The idea of gravity compensation is illustrated below using the OmniSuit exoskeleton, which provides both back and shoulder support. The gravity compensation provided by the back support module of the OmniSuit exoskeleton starts working when the user leans forward, and gravity begins to pull the upper body downwards. Without exoskeleton support, the back and hip muscles must compensate for this gravitational pull by contracting and pulling the upper body upward. When wearing the OmniSuit, elastic springs on the back are automatically stretched when the upper body bends forward, absorbing part of this load and thus relieving the human muscles.

Another example is the shoulder support module of the OmniSuit exoskeleton. While worn, it will automatically support the shoulder progressively when the arm is lifted. The shoulder joint's spring arrangement is engineered to provide maximal support when the arm reaches a horizontal position, so when it is maximally "exposed" to gravity.

One important detail here is that both support modules of the exoskeleton only provide gravity compensation when gravity imposes a load on the relevant joints because of a lever arm. Thus, in our examples, the back support module does not pull when the wearer stands straight, and the shoulder support module does not push upwards when the arms hang vertically to the body's side. Only when the user leans forward or lifts their arms then the exoskeletons will start supporting them.

Typically, an exoskeleton will not completely compensate for gravity. It will simply offset a certain percentage (typically 20%- 50%) of the gravitational load on the body and, therefore, will make every repetition or every second you work easier. This partial compensation also means that the human muscles do not need to tension the springs of a passive exoskeleton – gravity does.

Gravity compensation, in combination with the fact that human muscles require constant energy when holding a force, explained in Section I, are the primary principles of exoskeleton support during static tasks, such as prolonged forward leaning or overhead work.

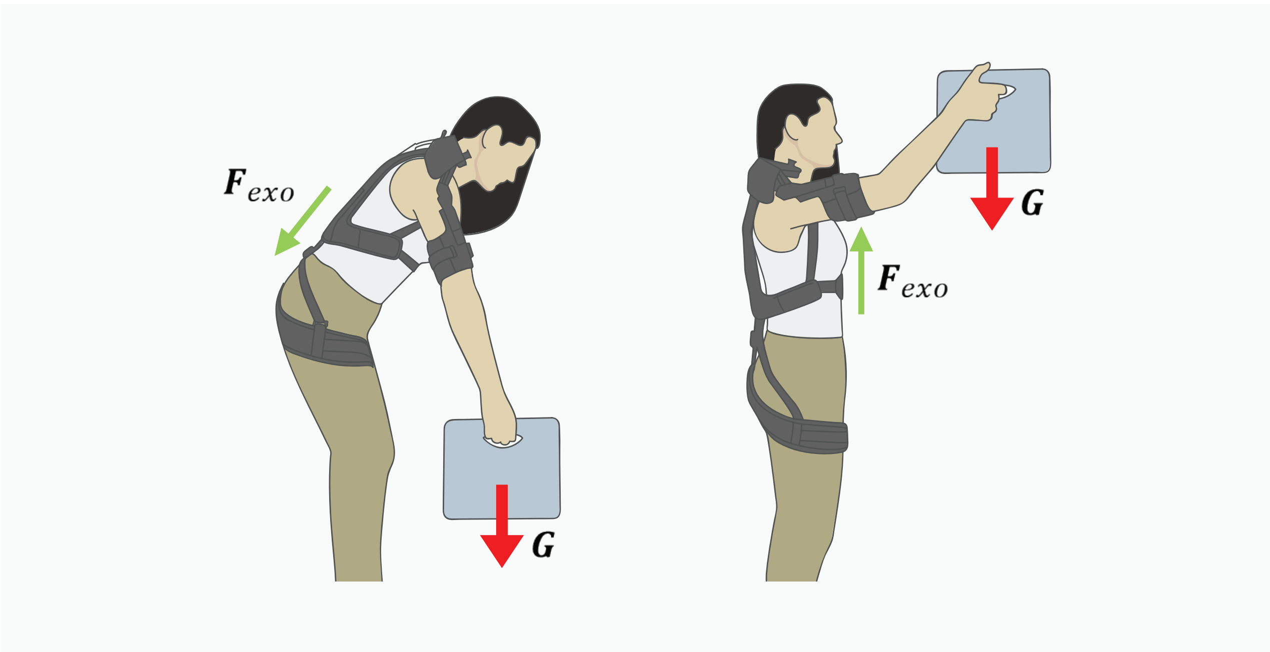


Illustration of the gravity compensation concept with the Auxivo OmniSuit.
◂Left: When the user starts leaning forward or holds a load in front of the body, gravity will start pulling the upper body downward. When wearing the OmniSuit, leaning forward automatically also starts stretching the springs in the back of the exoskeleton. The resulting force of the spring pulls the user back and offsets part of the forward-pulling gravitational force. ▸Right: The OmniSuit shoulder support is illustrated. When the user starts lifting an arm, they will feel gravity pulling it downwards. When wearing the OmniSuit, the exoskeleton will progressively support the shoulder the higher the arm is lifted, offsetting the gravitational downward force by pushing the arm upwards.

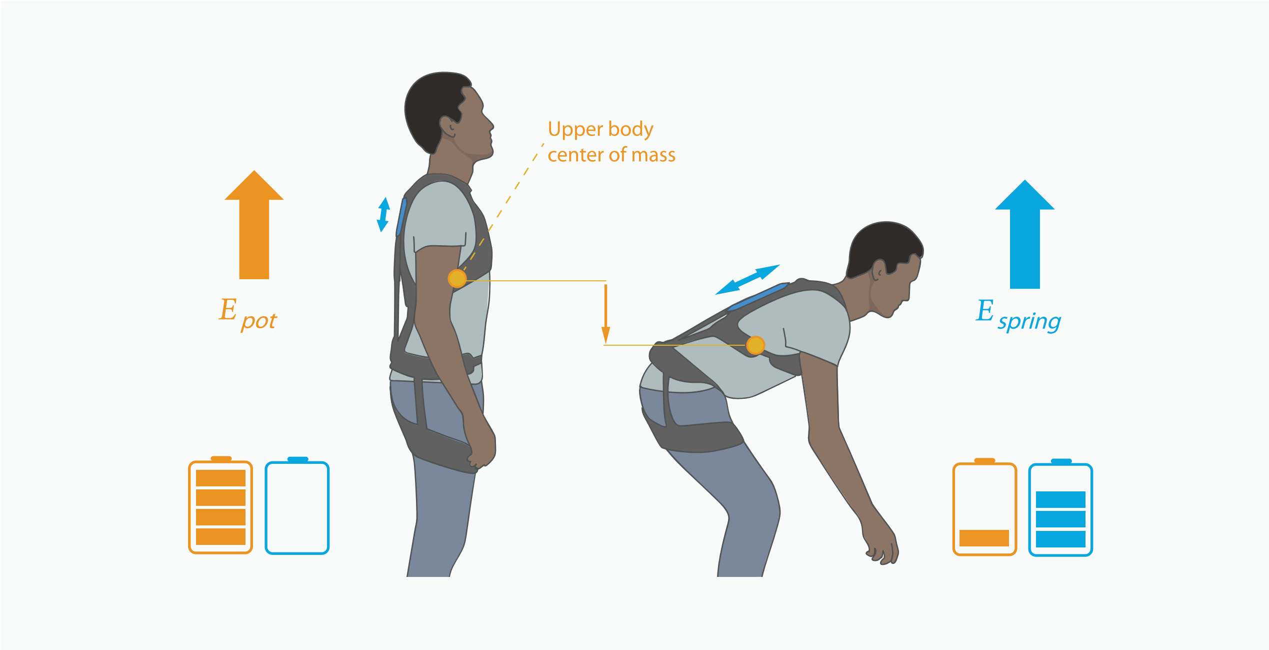


Illustration of the energy storage and recuperation concept.
When the human is standing in an upright position, the mass of the upper body stores potential energy, while no energy is stored in the springs of the LiftSuit back support exoskeleton. When the user leans forward, lowering the center of mass of the upper body, the potential energy is released and transferred to the springs of the exoskeleton, where it is stored. When the user moves back to an upright position, the energy is converted back to potential energy, supporting the movement in this way.

Energy Recuperation: Doing the Work Only Once
A very important concept of passive, spring-based exoskeletons is energy recuperation. A frequently asked question is where the energy needed to tension the springs of a passive exoskeleton comes from. The answer is: the energy is already there, stored in your body when standing upright. Or put differently: you built up the potential energy of your body in the morning when you got out of bed. To explain this, we quickly need to introduce some physics: Every object with a mass in a gravitational field has stored so-called potential energy. The amount of energy stored in this object is $E_{pot} = m \cdot g \cdot h$, so the mass m of the object multiplied by its height h multiplied by Earth's gravitational acceleration g. This potential energy changes if we increase the height (additional energy required) or decrease the height (energy is released) of the object.

For a lift-support exoskeleton like the Auxivo LiftSuit, the energy we are talking about is the potential energy of the mass of the human upper body. If a person stands upright, the upper body is at the highest point, and the mass of the upper body carries potential energy in it. When the person leans forward, which moves the center of mass downwards, potential energy is released, and most of it is lost through energy dissipation. When we want to go back up, our muscles must invest additional energy to restore the potential energy.

When we place the LiftSuit with its mechanical springs on the back of the person, then this spring is stretched when leaning forward, and at least a part of the potential energy that is released by the body is transferred to the spring and remains stored in the system instead of being dissipated and lost. The energy of a spring is expressed by the following equation: $E_{spring} = 1/2 \cdot k \cdot x^2$, with k being the spring's stiffness and x being the displacement of the spring from its equilibrium position. When the human upper body then moves back to the upright position, the stored mechanical energy in the spring is converted back into potential energy of the upper body. This process is repeated with every lift, and the stored energy is transferred and converted back and forth between the human body and the exoskeleton.

Of course, typically, the spring cannot store all the potential energy of the human upper body, and the process is also not 100% efficient, e.g., due to friction. Otherwise, we would recuperate all the energy during each lift in a zero-sum energy balance, and we could basically do it forever. However, even if only a certain percentage of the potential energy is stored and recuperated after each lift, this process significantly reduces workload.

The energy recuperation principle is why spring-based exoskeletons are so highly energy efficient and can provide a good level of support while being small, lightweight, and cost-effective.

Section 3
Common Misconceptions

In this last section, we want to address some common misconceptions that we hear frequently and which are often a source of confusion. If you have read the previous sections, you will quickly be able to identify the wrong assumptions on which these misconceptions are based.

Misconception One: Only active exoskeletons provide real support because passive systems require you to invest energy first.

The main misconception is that with a passive exoskeleton, your muscles must provide the force to tension the exoskeleton's springs. So, you first need to provide the energy that supports you later. Therefore, this is not "real" support since you must still do all the work yourself first. Active systems, on the other hand, provide additional force and energy. Therefore, it is logical that only active systems can support you.

This misconception relies on several wrong assumptions that can quickly be resolved when applying the concepts of gravity compensation, energy recuperation, and the differences between engineering mechanics and biomechanics.

The first wrong assumption here relates to the forces.
It is assumed that the human muscles actively need to tension the springs of the passive exoskeleton. As we know, as long as the passive springs only offset the gravitational load on your body, you do not need to invest any additional force to pretension the spring because gravity does it for you! When designed well, the spring support will never overcompensate your body weight in any position, and you never have to use your muscles to tension the spring.

The second wrong assumption relates to the energy balance.
It assumes that, with a passive system, you always need to invest energy and, if lucky, only get some of it back. As a result, this is, at best, a zero-sum energy balance, which means there is no real support or load reduction.

One aspect of this energy misconception is that a zero-sum energy balance is something bad and inefficient. In reality, a zero-sum energy balance would be an amazing outcome. It would mean that we could do endless bodyweight squats without breaking a sweat because, during every repetition, we get all our energy back through energy recuperation.

The reality of lifting and forward-leaning is much worse. Our body burns energy every second we remain in a forward-leaning position. Every time we squat down, the potential energy of our body almost completely dissipates and needs to be built up again using muscle strength.

As a result, a passive, spring-based exoskeleton using energy recuperation to restore even a small percentage during each lift can make a significant difference. It is true that this exoskeleton does not add additional energy to the system. Still, it prevents us from losing and wasting energy during work, which is a much more efficient way of providing support.

Another aspect of this wrong energy assumption is that the differences between a mechanical and biomechanical system are ignored. The human can save much more energy than is stored in the mechanical spring simply because, as discussed above, a permanent supporting force from a pre-tensioned mechanical spring will save the human user additional energy every second because of the human muscle metabolism.

Misconception Two: Exoskeletons reduce the load of one body part by transferring it to another and increasing it there, which is actually dangerous.

First, let's acknowledge that parts of this statement are not categorically incorrect. As discussed above, exoskeletons can utilize load redistribution in different ways. But when stated as cited above, it implies that load redistribution is always necessary and leads to increased strain on body parts that were previously not under load. It also implies that load redistribution from one part to another is something intrinsically bad and unhealthy, which is the misconception we want to address:

First, local strain can be reduced without increasing strain elsewhere:
Utilizing the above-described concept of load bypassing, reducing the strain on the human body and individual body parts is possible without necessarily increasing it elsewhere. The external exoskeleton simply provides an alternative load path toward the ground, where, eventually, all gravity-induced load on the body will arrive. So why not skip the parts of the body that are at risk of overload?

Second, spreading a load over a larger body region can be helpful:
Load redistribution, which consciously accepts load increases in other parts of the body, is an approach that can be utilized intentionally. And yes, this means the load in some body parts is increased, but if used correctly, load distribution is not, by default, something bad. The same load can be spread more equally over a larger part of the body. Load redistribution can also mean better load balancing, so it can, e.g., distribute an asymmetric load more evenly between the left and right sides of the body. A load of 120% and 50% maximum capacity on the body's left- and right sides will be unhealthier than a 90% - 80% split.

Summary and Final Words

We hope you enjoyed reading this White Paper and that it helped you understand which support concepts are utilized in modern occupational exoskeletons.

It likely became apparent that there are many concepts that one can choose from when designing an exoskeleton, and a good understanding of mechanical and biomechanical principles is essential to ensure the resulting design provides the best possible performance and maximum benefits to its users.

Most of the principles discussed can be utilized by all types of exoskeletons and are, in a sense, universal. So, no matter if you have an active or passive, rigid or soft exoskeleton, they all, in one way or another, will use some of the concepts described above.

This is also why none of these categories of exoskeletons are, by default, better or worse than the others. They all rely on the same basic ideas, just implementing them using different technologies.

If you want to learn more about exoskeletons, we encourage you to visit our website. There, you can explore our occupational exoskeleton offering for various industries. If you are interested in learning more about exoskeleton technology, our educational exoskeletons of the EduExo series can help you to learn how to design and build your own exoskeleton

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Volker is Co-Founder and CEO of Auxivo. With a PhD in exoskeleton robotics and more than 15 years of experience in developing, researching, and commercializing exoskeletons, his goal is to develop high performance exoskeletons and make them accessible to more people.

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Rachel is Head of Research at Auxivo. With a PhD in Neurosciences and a Master in Movement Sciences, her work aims to understand and optimize the interaction between wearable exoskeletons and the user, making sure the human body can take full advantage of the exoskeleton support.

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Roger is a Co-Founder and Scientific Advisor at Auxivo. He is also Full Professor for Rehabilitation Engineering at the Swiss Federal Institute of Technology Zürich. His research focuses on the development and clinical validation of wearable technologies such as exoskeletons.

About Auxivo
Auxivo AG is a leading developer and manufacturer of exoskeletons, founded in 2019 as an ETH Zurich spin-off. The company's mission is to enhance worker safety and well-being by providing innovative and accessible solutions that reduce physical workload and the risk of injury. The company's fast growing exoskeleton portfolio offers practical solutions for industries like logistics, manufacturing, construction, or healthcare.

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