SOFTER
SMARTER
STRONGER

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FROM EXOSKELETONS TO EXOSUITS

LORENZO MASIA

For thousands of years and across cultures, tales like those of Icarus and his wings made from wax and feathers testify to the universal human desire to overcome the physical limitations imposed by nature by using wearable technology. Today, this desire finds expression in robotics, where significant technological advances have opened up new possibilities that were once confined to the realm of science fiction. Robotics is used, for instance, in fields such as human assistance, rehabilitation, or to enhance human performance. A current research area that Heidelberg scientists are also working on is wearable technologies such as exosuits, which have the potential to completely transform rehabilitation and enable people with physical impairments to lead more independent lives.

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When we think about robots, our imagination often conjures up images of sterile environments with multiple mechanical arms working together to assemble cars.However, the field of robotics has expanded greatly in recent years, encompassing a wide range of applications that are becoming increasingly integrated into our daily lives and redefining what we think of as automation. Over the past decade, robotics has undergone a transformation, growing and branching out in new directions. One of the most promising areas of robotics research is wearable robotics, which is making rapid progress in both medical and industrial domains. In the past, robots and humans existed in separate spaces, but the future of robotics seems to involve a more symbiotic interaction between artificial and biological systems.

In the 1868 novel “The Steam Man of the Prairies”, author Edward Ellis depicts a massive iron robot controlled by its creator, who sits in a carriage behind it. The robot is capable of running at incredible speeds; it is a product of the excitement surrounding the first industrial revolution and the potential of steam power. As the decades passed, advances in technology were matched by bold visions of wearable robots that could boost human strength and protect humanity from extraterrestrial threats. Drawing on the automated machines used in the manufacturing industry, early designs for wearable robots typically featured a metal frame modelled after the wearer’s skeleton, connected by mechanical joints.

The beginning of the exoskeleton era
In 1967, General Electric brought this vision to life through the Hardiman project led by Ralph Mosher. The Hardiman exoskeleton captivated science fiction fans all over

the world, but due to technological limitations it was never tested with a human wearer. Despite its failure, the project sparked lasting interest in robots that could enhance or aid human movement through a mechanical structure that mirrors the anatomy of the wearer. This marked the beginning of the exoskeleton era.

The Hardiman exoskeleton was a bulky device that consisted of a metal frame that was attached to the body using straps and other supportive devices. It was powered by hydraulic actuators that enabled the user to move their legs and arms. Despite its limited capabilities, the first exoskeleton provided a glimpse into the future of wearable technology and its potential to enhance the physical abilities of humans. With the advent of robotics, significant advances have been made in the field of wearable technology. Modern exoskeletons are lighter, more compact, and offer more sophisticated capabilities.

Institut für Technische Informatik

Die Forschung am Institut für Technische Informatik (ZITI) beschäftigt sich im Bereich „Innovative Computing“ mit der Funktionsweise, dem Aufbau und der Nutzung von Hardware- und Software-Architekturen zur Erfassung und Verarbeitung von Daten, um Algorithmen an die Stärken und Schwächen der verwendeten Architektur anzupassen. Das Institut ist mit vielen Forschungsbereichen der Universität Heidelberg vernetzt, in denen Daten erfasst oder rechenintensive Aufgaben bewältigt werden. Übergeordnetes Ziel ist in der Regel eine substanzielle Steigerung der Rechenleistung sowie der Energieeffizienz oder eine Reduktion der Leistungsaufnahme. Für die Lösung von Problemstellungen im Bereich von Sensorik oder Datenkommunikation kann das ZITI auch Mikrochips von Grund auf neu entwerfen.

Neben dieser Spezialisierung befasst sich das Institut mit effizienter Programmierung, verfügt über eine Vielzahl von verschiedenen Rechenbeschleunigern und untersucht so Methoden und Arbeitsflüsse für hocheffiziente Datenverarbeitung. Weiterhin werden im Bereich Biorobotik und Biomechanik disziplinenübergreifend neue Technologien entwickelt, die Biologie und Robotik symbiotisch miteinander verbinden, um eine effizientere Kommunikation zwischen Maschinen zu ermöglichen, die mit biologischen Systemen interagieren. Ziel sind robotische Geräte, die beispielsweise in der neurologischen Rehabilitation oder zur Unterstützung des Menschen in der Arbeitswelt eingesetzt werden können.

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Despite this, exoskeletons are still primarily limited to research labs or expensive clinical treatments offered at high-end rehabilitation facilities. One of the major factors limiting access to exoskeletons is their complexity, which leads to higher costs, weight, and size. This complexity arises from the need for a rigid exoskeleton to precisely match the intricate movements of the human body. Misalignment between the exoskeleton and the wearer's joints can result in uncontrolled interaction forces that negatively impact the wearer's mobility and metabolism, causing discomfort.

The evolution of wearable technology

Recently, new approaches shed light on the progression of wearable technology, highlighting the trend towards less restrictive and more bio-mimetic wearable robots. This paradigm-shift favours the use of compliant materials that better conform to the anatomy of the human body. With technological progress in soft materials, compliant control algorithms, and non-linear modelling, a growing number of research groups in academia and industry are designing wearable robots made of textiles and elastomers instead of rigid links. This approach allows the devices to be portable and to enhance movements without hindering human biomechanics. These new wearable robots are referred to as “exomuscles”, “soft exoskeletons”, or “exosuits”.

Exosuits are a more flexible and lightweight alternative to exoskeletons. Unlike exoskeletons, exosuits are created to augment human movements by working in tandem with the wearer's body. They utilise materials such as textiles and soft actuation to provide assistance and amplification, rather than relying on metal frames. They are typically worn like clothing and utilise sensors and algorithms that respond to the wearer's movements. This technology makes exosuits well-suited for tasks that demand a high level of dexterity and mobility, such as industrial labour, construction, or search and rescue operations.

With advances in sensors, artificial intelligence, and materials, exosuits offer a new level of freedom and capability, making them a superior alternative to exoskeletons in many cases. The potential for exosuits to revolutionise work, life, and movement makes them a technology to watch out for in the future.

What powers an exosuit?

The classification of exosuits involves dividing active devices into those actuated by tensile units and those actuated by expansive functional units. Tensile soft robotic suits transfer positive power to human joints by tightening a functional unit, similar to the way skeletal muscles work. These suits can be made to contract through four different mechanisms: electric motors that wrap an artificial tendon around a pulley, McKibben

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"The future of robotics seems to involve a more symbiotic interaction between artificial and biological systems."

pneumatic artificial muscles, twisted string actuators, or shape-memory alloys. Expansive soft robotic suits boost human movements by expanding a folded bladder filled with fluid. Although soft artificial muscles use a wide range of principles and actuation mechanisms, only a subset of these meets the requirements of bandwidth, safety, and power density needed to support human movements.

For example, electric motor-tendon units are the most commonly used mechanism for powering soft robotic suits, due to factors such as the ability to route artificial tendons between two distant points, the availability of technology for controlling electric motors, and the ability to turn the suit into a passive garment when necessary. However, the drawbacks of this mechanism include high shear forces on the skin and low mechanical efficiency. Nevertheless, there is a significant body of literature on how to achieve accurate control of position, velocity, and force delivery with electric motor-tendon actuators.

Moving symbiotically with the wearer

An effective control system is critical to the success of exosuits as it determines their ability to enhance the user's physical abilities and to operate in a safe and intuitive manner. Control is achieved through a combination of advanced sensors, algorithms, and actuators: the sensors are responsible for capturing information about the user's movements, such as the position and orientation of the limbs (using gyroscopes and accelerometers like those in our mobile phones), or their muscle activity (using electromyography, which extracts low-voltage signals generated by the opening of the ion channels in sarcomeres).

The algorithms process this information and translate it into commands for the actuators, which are responsible for driving the movement of the suit's limbs. The software must be able to integrate the various sensors and actuators, and provide the user with a simple and intuitive interface for controlling the suit. It must also be able to manage the power and energy usage of the suit, ensuring that it can operate for an extended period of time without needing to be recharged.

One of the key challenges in controlling exosuits is ensuring that they respond in a manner that is both safe and intuitive for the user. To achieve this, the algorithms used to control the suit must be able to accurately interpret the user's intentions and translate them into appropriate movements. This requires a deep understanding of human anatomy and biomechanics, as well as the development of sophisticated control systems that can respond in real time to changes in the user's movements.

Another important aspect of exosuit control is ensuring that the suit is comfortable and easy to wear, with careful design of the frame and attachment points, and a selection of materials that are lightweight and flexible. The user must also be able to adjust the fit of the suit to ensure that it is snug and secure, without causing any discomfort or restriction of movement.

Pushing the boundaries

The ARIES Laboratory, specialising in Assistive Robotics and Interactive Exosuits, was founded in 2019. Since its establishment, our team has been pushing the boundaries of wearable technology. It is diverse, comprising individuals of multiple nationalities, genders, and backgrounds, each contributing a unique set of skills in fields including Biomedical Engineering, Mechanical Design, Biomechanics, and Machine Learning. What sets us apart is our ability to handle all aspects of the design process in-house. We manufacture and assemble our sensors and actuators, create our textile components, and use 3D printing technology to fabricate all parts that make up an exosuit. We are dedicated to full-body assistance augmentation and are one of few groups in the world with the ability to apply soft wearable technology to a wide range of human movements.

The central focus of our research is to provide motor assistance in rehabilitation. To achieve this goal, we have established strong partnerships with leading institutions and hospitals in Germany, such as the Universitätsklinikum Hamburg-Eppendorf and the Spinal Cord Injury Center of Heidelberg University Hospital, as well as with renowned rehabilitation centres in Italy. Our exosuit technology is versatile and can be applied in various clinical fields, including treatment for multiple sclerosis, spinal cord injury, and stroke. The results have been promising so far, with patients showing approval for and satisfaction with the use of these devices during their rehabilitation. However, the effectiveness of our technology is largely dependent on the extent of the patient's physical limitations. Patients with some residual mobility can benefit from our exosuits, which enhance their movement, improve their range of motion, and help them regain motor functions they wouldn't be able to otherwise.

Recently, we integrated functional electric stimulation (FES) into our exoskeleton technology, combining the benefits of soft robotics with electrical muscle activation. This approach not only assists motion but also prevents muscle atrophy, a common side effect of reduced mobility. Additionally, our team at Heidelberg University is part of two consortia funded by the Carl Zeiss Foundation, which conduct research on aging populations. Here, the ARIES Laboratory is responsible for designing devices to aid walking, while also increasing the wearer's metabolic efficiency.

Moreover, at a time where Artificial Intelligence is a highly discussed topic, we also specialise in incorporating the latest advances in machine learning to enhance the intelligence and adaptability of our exosuits. Recently, we used vision algorithms for the first time to instantaneously recognise and adapt to events in the environment. A camera, which is an integrated component of our wearable robots, can detect stairs and obstacles and increase the robotic assistance to help a person climb or descend stairs with reduced metabolic effort. Our experimentation extends beyond the laboratory because we firmly believe that testing our system in real-world scenarios is essential to demonstrate its effectiveness and to involve the public in our endeavours.

To demonstrate our capabilities, we recently assessed one of our walking assistance devices on the Philosophers' Walk ("Philosophenweg") in Heidelberg, which generated interest among many individuals. The City of Heidelberg then invited us to participate in its "Science in the City" initiative, giving us the chance to exhibit our work to the public in Heidelberg's Old Town for a period of three weeks. ●

Fakultät für Ingenieurwissenschaften
Als 13. Fakultät hat zum 1. Oktober 2021 die Fakultät für Ingenieurwissenschaften der Universität Heidelberg ihre Arbeit aufgenommen. Ihre Forschungsthemen sind breit angelegt und reichen von biogenen Verpackungstechnologien für mRNA-Impfstoffe über künstliche Zellen als Transportsysteme im Körper bis zu „tragbaren" Technologien wie Exoskeletten, die Menschen beim Heben oder Gehen unterstützen und in der Industrie, in der Rehabilitation oder für eine generelle unterstützende Hilfeleistung eingesetzt werden können.

Aktuell umfasst die Fakultät 29 Professuren; ihre Wissenschaftler:innen forschen am Institut für Pharmazie und Molekulare Biotechnologie, am Institute for Molecular Systems Engineering and Advanced Materials und am Institut für Technische Informatik. Darüber hinaus arbeiten Professor:innen der Fakultät am Interdisziplinären Zentrum für Wissenschaftliches Rechnen, am BioQuant-Zentrum, am Zentrum für Molekulare Biologie der Universität Heidelberg sowie am Biochemiezentrum der Universität Heidelberg. Die Fakultät bietet den konsekutiven Bachelor- und Masterstudiengang Molekulare Biotechnologie, den Staatsexamensstudiengang Pharmazie und den Masterstudiengang Technische Informatik an. Außerdem verantwortet sie den Master und das PhD-Programm Matter to Life im Rahmen der gleichnamigen Max Planck School. Weitere Studiengänge in den Bereichen Molecular Systems Engineering und der Medizintechnik sind in der Planung.

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WEICHER, SCHLAUER, STÄRKER

VON EXOSKELETTEN ZU EXOSUITS

LORENZO MASIA

Im Laufe der Jahrtausende gab es unzählige Geschichten, in denen der menschliche Körper mittels Technik verbessert wurde: etwa Ikarus mit seinen Flügeln aus Wachs und Federn oder der Keltenkönig Nuada mit dem silbernen Arm. Diese Geschichten aus unterschiedlichen Kulturen zeugen vom universellen menschlichen Bedürfnis, die Grenzen der Natur zu überwinden. In der Geschichte von Ikarus kommt ganz besonders der unerreichbare menschliche Wunsch zum Ausdruck, aus eigener Kraft zu fliegen. Heute ermöglichen uns Fortschritte in Technik und Medizin den Übergang vom Reich der Mythen in das Reich des Möglichen.

In den vergangenen Jahren gab es signifikante Fortschritte bei der Entwicklung von Aktuatoren, automatisierter Kontrolle und Miniaturisierung elektronischer Geräte, ebenso auf dem Gebiet der intelligenten Materialien. Das hat neue Möglichkeiten in der Robotik eröffnet: Sie kommt mittlerweile in Gebieten zum Einsatz, die einst der Science-Fiction vorbehalten waren, zum Beispiel als Assistenzsysteme, in der Rehabilitation oder zur Steigerung der menschlichen Leistungsfähigkeit. Ein sehr aktuelles Forschungsgebiet in der Robotik, dem sich auch Heidelberger Forscher:innen widmen, befasst sich mit tragbaren Technologien, insbesondere mit Exosuits.

Diese tragbaren Geräte sollen körperlich beeinträchtigte Menschen bei der Fortbewegung und Ausführung von Aufgaben unterstützen. Sie bestehen aus weichen oder semirigiden Komponenten, die am Körper befestigt werden und dort unterstützend und mobilitätssteigernd wirken. Exosuits können auf unterschiedliche Anforderungen wie Gehen, Stehen und sogar Klettern programmiert werden; gleichzeitig können sie Kraft und Ausdauer steigern, um Aufgaben wie schweres Heben oder wiederkehrende Bewegungsabläufe zu erleichtern. Sie haben das Potenzial, die Rehabilitation komplett zu verändern und körperlich beeinträchtigten Menschen ein selbstbestimmteres Leben zu ermöglichen. Darüber hinaus werden sie in der Industrie und beim Militär zur Leistungssteigerung eingesetzt. ●

PROF. DR. LORENZO MASIA ist seit April 2019 an der Universität Heidelberg am Institut für Technische Informatik (ZITI) tätig. Er ist Leiter des ARIES Lab, das sich mit dem Design und der Entwicklung von Exosuits für die körperliche Rehabilitation und zur Steigerung der menschlichen Leistungsfähigkeit beschäftigt. Lorenzo Masia hat einen Abschluss in Maschinenbau von der Universität La Sapienza in Rom und einen Doktortitel von der Universität Padua (beide in Italien). Vor seinem Wechsel nach Heidelberg arbeitete er am Massachusetts Institute of Technology (USA), dem Istituto Italiano di Tecnologia (Italien), der Nanyang Technological University in Singapur und der Universität Twente (Niederlande).

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„Die Zukunft der Robotik scheint in einer symbiotischeren Interaktion zwischen künstlichen und biologischen Systemen zu liegen.“