Wearable robots

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Abstract: *This seminar paper presents the technology of wearable robots, mainly exoskeletons. Several examples of exoskeletons in different fields are presented.*

Keywords: *wearable robot, exoskeleton, exosuit, HAL, EXARM, SAM, Power Suit, ONYX*

1 Introduction

The robots are mainly used to replace human workers in repetitive and physically exhausting labors. In the origins of robotics, the robots were not intended to cooperate with humans. Even at this time, many robotic platforms are separated with human workers by cages or light barriers to prevent injuries. Along with the progress in the robotics, the cooperative robots or shortly the cobots were invented to fully cooperate with humans and to help human workers with their tasks. The next step in the interaction between humans and robotic systems are wearable robots.
These innovative robotic systems are more and more common in many fields of human life. The substantial growth is mostly seen in the medicine. Prosthetic arms or legs replaces amputated limbs of patients, wearable robots help people with rehabilitation or with neural or muscle diseases that negatively affects their movability. The other field to mention is industry. Many industrial companies across the globe equip their workers with robotic exoskeletons that prevent the workers from injury. The military always adapted new technologies to gain an edge. The army mainly aims for enhancing the humans' capabilities in order to create a super soldier able to carry heavy weaponry, to cover larger distance in less time etc. The example of such experiment is Exoskeleton for Human Performance Augmentation project of U.S. Defense Advance Research Projects Agency.[1]
This paper aims for introducing the technology of wearable robots, especially exoskeletons and exosuits. Those types of wearable robots are efficient to help workers with load carrying etc., where the automation and for example usage of industrial robots is impossible or insufficient.

2 The division of wearable robots

The wearable robots can be divided into three instances according to their function.
Empowering robot exoskeletons or so called extenders are a class of wearable robots that enhances the human's strength while keeping the operator full control of the robot. These exoskeletons were defined to structure map the anatomy of the wearer.
Orthotic robots are supposed to restore the weak or completely lost function of the human limb. The robotic exoskeletons belong to this group of wearable robots and they complement the ability of human limb or restore the function of handicapped patient.
Prosthetic robots are robotic limbs that replace the human limb that was amputated.[2]
The paper focuses mainly on the robotic exoskeletons. As the terms exoskeleton and exosuit are often used as synonyms, the difference is described below.

2.1 Exoskeleton

The robotic exoskeleton is a wearable robotic system. The name exoskeleton is biologically inspired and it refers to a hard shell of insects, spiders etc. Its main function is to protect the animal. The robotic exoskeletons are designed to perform not only protection, but also other tasks. Specific systems are supposed to enhance human capabilities like load capacity. In medicine, the exoskeleton can help the patient with rehabilitation of upper or lower limbs.

The exoskeleton is a class of wearable robot that moves synchronously with the human. There is a correspondence between the joints of the human and the robotic system. The exoskeleton should attach to the part of human body that it is worn on. This feature is essential as there could appear nonergonomic interaction forces. The crucial aspect of a robotic exoskeleton is a human-robot interface (HRi) which connects human and robot. The HRi consists of two parts: physical human-robot interface (pHRi) and cognitive human-robot interface (cHRi). The pHRi resolves the flow of power between human and robot. It consists of the rigid structure of the exoskeleton and actuators. The cHRi deals with the flow of the information between the exoskeleton and its wearer. The sensors of the exoskeleton measure bioelectrical and biomechanical variables that are processed to the information passed to the human.[2]
It is worth mentioning that mainly for the industrial and construction sector the terms of passive and active exoskeleton are used. Active exoskeleton mostly refers to the systems that prevent the workers from injuries or help them with movement by using actuators and sensors. On the other hand, the passive exoskeleton is a wearable rigid structure. Its function is balance and re-distribute the weight.[3]

2.2 Exosuit

The exoskeleton's rigid structure can be a disadvantage in many cases. The exoskeleton can make the worker's movement harder if the links do not impose perfectly to their body. Also, the mass of the exoskeleton raises the metabolic rate and the metabolic cost of accelerating or decelerating the limb is increased. The soft wearable robot, the exosuit, is the answer to these disadvantages. The exosuit mainly consists of fabric. Because of that, it is much lighter than exosuit. The other benefit of using a fabric material is that it can attach directly to the body and the user is not restricted in movement and it can be worn under regular clothing.
Applying the force to the joints to move them is more difficult task compared to the exoskeleton. For example, Harvard university in their research used firstly pneumatic actuators. After more research, the scientists decided to use electropneumatic actuators and Bowden cables for transition of the force to the joints.[4]

Figure 1: Hal-5 exoskeleton with rigid structure [5]

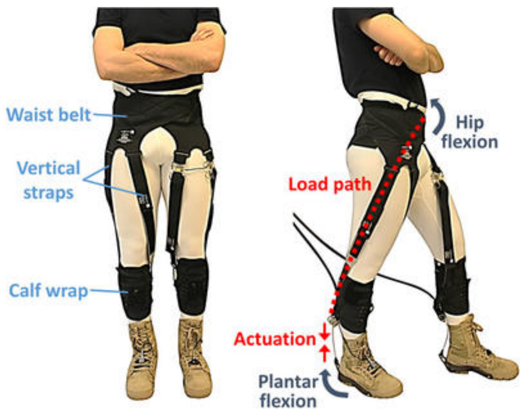

Figure 2: Harvard exoskeleton - soft wearable robot [6]

3 Examples of wearable robots

3.1 HAL

HAL (Hybrid Assistive Limb) is the robotic exoskeleton created by Japanese manufacturer Cyberdyne. The development of exoskeleton started in 1992. The first version Hal-1 for lower part of the body enhanced the walking ability of the wearer. This was achieved by amplifying the torque of the human joints. The scientists continued the research and created HAL-3 exoskeleton for lower limbs that aimed to be used in the daily life. Another type of HAL exoskeleton is HAL-5 which is a full body exoskeleton. HAL-5 Type-B specification says it can hold and lift objects up to 70 kg while the full weight of the exoskeleton is 23 kg. The battery can power the exoskeleton for approximately 2 hours and 40 minutes.

HAL exoskeleton hybrid cybernic control system that consists of two types of complementary algorithms. The first one is Cybernic Voluntary Control (Bio-Cybernic Control). The sensors of the exoskeleton measure bioelectrical signals which show the intention of the wearer to move. When biolelectrical signals estimate the intention to move limb, the torque of the wearer's joint is amplified.
The second part of hybrid cybernic control is Cybernic Autonomous Control (Cybernic Robot Control). It reacts to other measured information rather than bioelectrical signal. Those include for example joint angle or floor reaction force. Thanks to Cybernic Autonomous Control, the HAL-3 enhances many types of healthy person's motion abilities including walking or climbing stairs.[7]
As for today, Cyberdyne company offers many variants of HAL exoskeleton including non-medical types and medical lower limb type. The medical exoskeleton is used to help people with lower limb disabilities. When a nervous system of the patient is not working correctly and the patient cannot move lower limb, the exoskeleton is able to detect the intention to do so and moves the feet instead of the patient. The Cyberdyne states, that their product can even help patient's brain to learn to move their feet again when the neural paths are broken.[8]

Figure 3: HAL for medical use [9]

3.2 EXARM and SAM exoskeleton arms

The European space agency funded research of the human arm exoskeletons for their astronauts. The first project was EXARM - The ESA human arm exoskeleton. It was developed as a master-slave robotic teleoperation with force feedback. The EXARM was supposed to help the astronauts in the repairs of International Space Station by controlling the EUROBOT. The EXARM should be then used in space exploration of the solar system.
The main advantage of using the exoskeleton arm with the force feedback to control the robotic arm is that the operator manipulates the arm from a safe place while the robotic arm operates in harsh environment (space, underwater). The EXARM was supposed to be used where the preprogrammed paths for the EUROBOT could not be used due to obstacles etc.[2]
Much like EXARM, SAM is a haptic exoskeleton – it produces the force sensation to the wearer. The exoskeleton arm has seven degrees of freedom (DOF). Each of the seven joints of the arm uses brushed DC motor as actuation force.
SAM as the teleoperation system exchanges the information between master and slave device (robotic arm etc.). The position of the exoskeleton is sent to the slave and meanwhile the slave sends its measured information to the master. The slave measures and sends the force and torque to the SAM. The arm is then able to process the information and create the force feedback to the operator. The wearer can then react to the sensation of rigid contact.[10]
The SAM is currently manufactured by Belgium manufacturer Space Applications Services. The SAM or DEXO (Dual Force-Feedback Arm and Hand Exoskeletons) arm weights 7 kg. The weight is compensated by an external gravity cancellation system.[11]

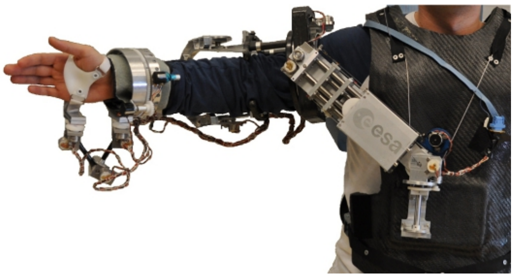

Figure 4: EXARM exoskeleton [12]

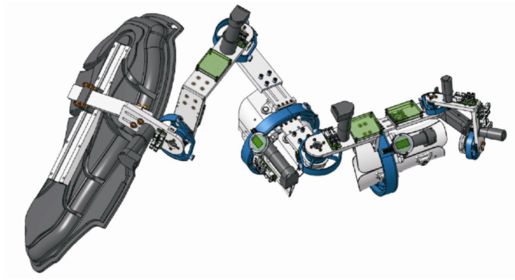

Figure 5: SAM exoskeleton [13]

3.3 Muscle suit

The Muscle Suit exoskeleton was developed at the Tokyo University of Science to help the workers with hard work where mechanization is impossible. Muscle suit uses compressed air that is stored in the cylinder at back or the pressured air must be connected externally.
The Muscle Suit exoskeleton uses McKibben artificial muscles as actuating force. The McKibben muscle is a class of pneumatic artificial muscles (PAM) and consists of inner tube and the braided mesh that surrounds the tube. The mesh provides protection to the tube and it also controls the contraction of McKibben artificial muscle.[14] The McKibben muscle in the Muscle Suit can generate maximum force 2.2 kN when the air of pressure of 0.5 MPa is used.
The air is supplied by solenoid valve in the Muscle Suit. The valve is controlled by either breath-activated switch or touch sensor switch in the commercial version of the exoskeleton. The manual operation of the exoskeleton is required because of the difficulty of installing sensors that would measure an intention to move. The researchers found that for users it is difficult to use the exoskeleton by operating the switches and a standalone version without the need of switches and compressor.[15]
The experiments showed positive effects for range of muscles in both static holding and dynamic lifting. For example, while holding a mass above head, the exoskeleton was able to decrease muscle activity of Biceps Brachii (30–70 %) and Trapezius pars transversa (40–70 %). It shows that Muscle Suit could reduce the physical load on shoulders and arms.[16]
A start-up company Innophys affiliated with the Tokyo University of Science started to sell Power Suit. As of July 2020, more than 13,000 units were sold.[15]

Figure 6: Muscle Suit exoskeleton [17]

3.4 ONYX

The military always sought new ways and technologies to gain an edge over enemy. The exoskeleton can enhance the abilities of soldiers and thus gain a desired edge on the battlefield.
ONYX exoskeleton is being developed by Lockheed Martin primarily for army purposes. It is a lower body exoskeleton which main goal is to reduce an energy for many regular and repeated tasks an infantry have to

perform. It includes crossing terrain, kneeling and more.
The exoskeleton consists of both rigid and flexible structures which should be as much comfortable for the wearer as possible. Sensors of the exoskeleton provide measured speed, direction and angle of movement to the main computer. The artificial intelligence of the computer predicts the movement and controls electro-mechanical actuators to enhance movement of knees.[18]

Figure 7: ONYX exoskeleton for army [19]

4 Conclusion

This paper aimed for presenting wearable robots, primarily exoskeletons. Exoskeletons are a growing technology in many fields including industry or medicine. The growing interest supports for example the number of sold Muscle Suit exoskeleton.
Nowadays the trend is to use automation wherever the human's work is too hard or repetitive. In many cases, the use of industrial robots or other automation devices is impossible and human workers cannot be replaced. The employment of wearable robotics might be a solution. The exoskeletons can help workers in load carrying or lifting. The exoskeletons or exosuits can also protect the workers from injury.
Wearable robots proved to help people with neural diseases or after injury. Many hospitals around the globe use several systems for rehabilitation. The amputated limb can also be replaced by more prosthetic arm or leg. EXARM and SAM prosthetic arms with force feedback were mentioned in this paper. These examples show the possibilities of usage of exoskeletons applied in harsh environments like space or depths of the ocean.

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