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LOWER LIMB EXOSKELETONS: BRIEF REVIEW

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Abstract

The paper provides a brief review on structural and technological features of Lower Limb Exoskeletons that have been manufactured until recently and the description of their disadvantages. Exoskeleton is a device designed to compensate for the lost functions of a human operator by increasing muscle strength and expanding movement amplitude with its outer frame and driving parts. Lower Limb Exoskeletons are developed to support people who have partially or completely lost lower limbs dynamics. The research and development background dates back to 1960s. Over the years, great progress has been made by scientists and researchers from all around the world. However, despite various strategies and attempts to achieve perfection in operating an exoskeleton in the current state of science and technology, it is still a challenge to develop an auxiliary model that endows with both super-efficiency and naturalness. Consequently, the paper intends to highlight the problems to be resolved and the future trends in this field. Exoskeletons have been limited in their availability for wider application by general population because of their high cost. Moreover, technological and structural issues related to design, safety, framework deterioration and optimization remain open-ended. As a technological breakthrough is an evolving process, this review can assist in conducting current research and making recommendations for perspective developments in the field of Lower Limb Exoskeletons.

Keywords

exoskeleton, lower limb exoskeleton, robotics, robots, review, rehabilitation, legs, orthosis, assistive device

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ЭКЗОСКЕЛЕТЫ НИЖНИХ КОНЕЧНОСТЕЙ: КРАТКИЙ ОБЗОР

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Аннотация

Приведен краткий обзор по теме экзоскелетов нижних конечностей, выпущенных до настоящего времени, с описанием их конструкционных и технологических особенностей, а также недостатков. Экзоскелет представляет собой устройство, предназначенное для восполнения утраченных функций человека-оператора, увеличения силы его мышц и расширения амплитуды движений за счет внешнего каркаса и приводящих частей. Экзоскелеты нижних конечностей разрабатываются учеными для поддержки людей, утративших частично или полностью работу нижних конечностей. История исследований и разработок этой области берет начало в 1960-х годах. За долгие годы учеными и исследователями всего мира был достигнут высокий прогресс. В условиях современного состояния науки и техники существуют различные стратегии и подходы к управлению экзоскелетами, однако сложно разработать тот подход, который наделит эти устройства сверхэффективностью и естественностью. В статье показаны проблемы, которые необходимо решить, и будущие тенденции в этой области. Ключевым недостатком экзоскелетов долгие годы остается ограниченная доступность их использования широкому слою населения в связи с высокой стоимостью устройств. Остаются открытыми вопросы проектирования, безопасности, уменьшения конструкции и оптимизации.

Поскольку эта технология является относительно развивающейся, данный обзор может помочь в проведении текущих исследований и составить рекомендации для проведения будущих разработок в области экзоскелетов нижних конечностей.

Ключевые слова
экзоскелет, экзоскелет нижних конечностей, робототехника, роботы, обзор, реабилитация, конечности, ортез, вспомогательное устройство

Exoskeletons generally known as electromechanical devices were designed to increase the physical performance of human operator by the drives located on the outside skeleton. The term "exoskeleton" is understood as a supporting frame located outside the body. A Lower Limb Exoskeleton (LLE) has proved to facilitate people with disabled/leg injuries in acquiring or recovering their walking abilities.

The research into LLEs has been carried out for the past five decades. It is believed that the first stepping active exoskeleton was created in 1969 under the leadership of Miomir Vukobratovich, a Yugoslav and Serbian scientist in the field of biomechanics and robotics at the Institute of Mikhail Pupin in Belgrade [1–5].

In the 1960s, the efforts of General Electric resulted in developing Hardiman[1], i.e. an exoskeleton that could lift a weight of 110kg, while the required human effort accounted solely 45 Newtons.

Exoskeleton Hybrid Assistive Limb (HAL)[2], devised at the University of Tsukuba in Japan, was created as a motor apparatus for rehabilitating people with support problems. It enables them to return to a fully active life. And those people, who used to be dependent on wheelchairs, can walk again and even climb the stairs.

In 2000, a device called Walking Assist Device (WAD) appeared which was intended to restore walking skills after injuries during the rehabilitation period. When creating such an exoskeleton, the experience accumulated by the Japanese corporation Honda in developing the robot Asimo Walking Assist Device in the Center for Wako Basic Technical Research was applied. The walking ability on various surfaces (stairs, rugged terrain, etc.) demonstrated by Asimo has progressed steadily over the past decade, which has also affected the Walking Assist Device. A WAD is controlled by information coming to an on-board computer from various sensors, thus facilitating a patient in moving to a sufficiently large distance[3]. Then the Japanese company Cyberdyne developed an exoskeleton HAL-5, whose name stands for Hybrid Assistive Limb or simply a hybrid auxiliary limb[2]. A similar device was developed and developed by Berkeley Bionica. The ELEGS-exoskeleton can be used by people with physical disabilities suffering from paralysis of lower limbs, to achieve a certain mobility level[4] [6].

The Lockheed Martin Company has created universal exoskeleton called HULC (Human Universal Load Carrier). It is based on two "legs" made of a light titanium alloy[5].

A significant breakthrough compared to the devices described above is made by the company Rex Bionics, which created the REX exoskeleton. The robot, created by experts from New Zealand, allows patients who have suffered from paralysis of lower extremities to walk. However, the most significant drawback of the above described developments is the high cost of these exoskeletons[6].

MINDWALKER, the powered LLE was designed in 2009 by European Commission-funded for paraplegics to regain locomotion capability [7–9]. The wearer is able to hold bags or anything else with the MINDWALKER, while walking without any external walking support. This can be achieved by controlling the frontal plane. This exoskeleton has totaled 10 DOFs and the weight of about 28 kg excluding batteries. Six healthy and four Spinal Cord Injury (SCI) participants took part in the ground-level walking experiments wearing MINDWALKER [7]. To keep balance SCI patients needed to hold the handrail: electromyography (EMG) patterns of their upper-limb muscles that were measured and showed to be augmented for stepping, whereas leg muscles were lowly activated if any. When tried on healthy subjects, EMG activities of leg muscles were similar or even larger during exoskeleton-assisted walking compared to free level walking, but comparatively smaller than walking under unassisted mode. Consequently, the experiment has showed that, stable walking without crutches is achieved for healthy subjects with the current prototype and control implementation but not for SCI paraplegics.

MoonWalker (2010) is the next LLE, which is capable of sustaining a part of a user's body weight. This orthosis can be used for rehabilitation, to assist people who have weak legs, or those ones who have broken legs, to walk. The main characteristic of the MoonWalker is application of a passive force balancer that can provide the needed force to sustain body weight. It is controlled by using an actuator that requires very low energy to

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[1] Hardiman. URL: http://cyberneticzoo.com/man-amplifiers/1966-69-g-e-hardiman-i-ralph-mosher-american/ (дата обращения: 10.10.2017).

[2] HAL. URL: https://www.cyberdyne.jp/english/products/HAL/ (дата обращения: 10.10.2017).

[3] WAD. URL: http://world.honda.com/Walking-Assist/ (дата обращения: 10.10.2017).

[4] eLEGS™. Berkeley robotics and human engineering laboratory. URL: http://bleex.me.berkeley.edu/research/exoskeleton/elegs%E2%84%A2/ (дата обращения: 10.10.2017).

[5] Lockheed Martin. URL: http://www.lockheedmartin.com/us/products/exoskeleton.html (дата обращения: 10.10.2017);
HULC. URL: http://bleex.me.berkeley.edu/research/exoskeleton/hulc/ (дата обращения: 10.10.2017).

[6] REX. URL: https://www.rexbionics.com/ (дата обращения: 10.10.2017).

work on those terrains, as it is used only to shift that force to the same side as a leg in stance. That motor also provides an energy portion to climb stairs or slopes. The authors believe that this approach can help to improve LLEs energetic autonomy [10].

In 2011, Russia began to step up its practical efforts to research exoskeletons. Within the ExoAtlet project that creates an exoskeleton for people's rehabilitation three versions of the exoskeleton are being developed: ExoAtletP, ExoAtlet-A and ExoAtlet Med. Patients can walk even using stairs, sit down and get up without help by means of ExoAtlet[1]. A soft pneumatic exoskeleton was created by a team of researchers from Carnegie Mellon University, Harvard University, University of South Carolina, Massachusetts Institute of Technology (MIT) and the Bioscience wearable sensor developer. It houses flexible artificial muscles, lightweight sensors and the control software. The device is made of a soft elastic polymer. At present, it can be worn only on the low leg, the biological structure of which is diligently replicated in the device. According to the laboratory tests, this device can move the ankles of the examined people within a 27-degree range of motion, which is considered sufficient enough for a normal walking gait. While this is a sole prototype, scientists are still in process of improving construction, so that patients with movement disabilities will find it more convenient to use [11–13].

Exoskeletons of this type reduce a metabolic rate, which usually rises while walking, and, therefore, these devices are successfully used to teach people walking and restore lost functions in post-stroke patients and in those who need rehabilitation after cerebrospinal traumas [14–17].

In the past several decades, intensive studies are being conducted by means of the LLEs creation in many countries of the world (the United States of America [18–21], Japan [22], Israel[2], Korea[3], France[4], New Zealand[6], Zealand[6], Serbia [1, 5], Italy [23]). LLE is a complex technical device, which includes a large number of different devices, such as motors, sensors, digitizing units and a processing and control module. The most critical parameters in the exoskeleton design are: the mass-dimensional characteristics limitations, its ability to overcome obstacles of a given height, the ability to perform walking on a flat surface as well as stairs, and also to overcome inclined planes. In addition, one of the most important parameters in the exoskeleton design can become the time of its autonomous operation.

Some researchers faced the issues of designing and modeling exoskeletons and anthropomorphic robots [24–27]. In their studies, attention is given to gait synthesis and controlling mechanism organization in the walking process. At the same time, the problem of synthesizing adaptive control systems that can be used to improve one's management strategy in association with the individual characteristics of a person wearing an exoskeleton remains insufficiently studied. This task is of particular importance as body mass of a person ranges significantly, and the loads experienced by the mechanism during operation can be estimated only approximately.

Currently, active elaborations are being carried out with the purpose to bridge the gap of fundamental knowledge in exoskeletons. They may be grouped according to the following main aspects:

- investigations of kinematic and biomechanical properties of new apparatuses and creation on this basis the optimal principles and scheme of their application [28–31];
- developing methods to determine exoskeletons systems parameters and their operation control, which can allow the researcher to quickly and systemically evaluate different variants of executive mechanism constructions according to the chosen criteria [32];
- applying computer analysis of virtual topographo-anatomic media while designing of biomechanical systems [32, 33];
- creating and improving the materials and the main units of exoskeletons, ensuring their effective performance [9, 34–36].

The emphasis should be focused on the paper written by the Italian researchers owing to its large value [37]. The authors performed a search in both Web of Science and Scopus and then took into account only the most relevant works and employed only the exoskeleton descriptive papers with the higher level of technology maturation. This paper provided extensive and systematically reviews of works about powered lower-limb assistive exoskeletons and orthoses. The review is divided into two blocks with multi-joint and single-joint systems involved. Each block includes chapters that classifies all exoskeleton models by assistive strategies and gives a brief analyses and discussion of each model. At the end of the paper the state of the art of assistive strategies is concluded, and the challenges in developing, tuning and validating an assistive strategy are discussed.

The next paper is the most recent and introduces a light-weight, electricity-powered lower-limb exoskeleton called Human Universal Mobility Assistance (HUMA)[5] [38]. HUMA was developed with weight-bearing assistance that allows individuals, including the elderly people, to augment their endurance/strength, so

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[1] Exoatlet. URL: https://www.exoatlet.com/en (дата обращения: 10.10.2017).

[2] Meditouch. URL: http://meditouch.co.il/ (дата обращения: 10.10.2017);
Motorica. URL: http://motorika.com/products-2/ (дата обращения: 10.10.2017).

[3] Walkbot. URL: http://walkbot2015.cafe24.com/eng?ckattempt=1 (дата обращения: 10.10.2017).

[4] RB3D. URL: http://www.rb3d.com/en/ (дата обращения: 10.10.2017);
Wandercraft. URL: http://www.wandercraft-exoskeleton.com/ (дата обращения: 10.10.2017).

[5] URL: http://dx.doi.org/10.1016/j.robot.2017.06.010 (дата обращения: 10.10.2017).

that they can support their own weights as well as an additional payload. HUMA uses a powered artificial transferring hip flexion/extension torque by means of a universal joint, a powered artificial knee structured by a double four-bar linkage, and a two-DOF spring-loaded ankle joint. The paper examines the aspects such as overall hardware configuration, the kinematic analysis of knee mechanism, control architecture, overall leg control algorithms, swing and stance control algorithms. In conclusion, HUMA was successfully tested and demonstrated walking and running using the control algorithm that was developed for this purpose.

The recent work of the Malaysian scientists is also of wide interest and gives a systematically review of the design and development of multiple joint LLEs[1] [39]. The discussion focuses on the LLEs application for augmentation, muscle weakness or gait recovery and rehabilitation. It also discussed the details of aspects such as the control strategy, actuator, safety and design, including compactness, noise, heavy structural weight, cost, mimicking of natural walking, and power sources. Furthermore, the type of a low-level controller and sensor, and the measurement parameters for the low-level controllers of each LLE are also shown. The paper leaves open a several issues that need to be improved, for example, the development of cost, safety, control system, and design aspects such as bulkiness, noise, heavy structures, natural-like walking and power supply systems.

Aaron M. Dollar, an associate professor of Mechanical Engineering and Materials Science in Yale University, is widely known for his achievements in the field of robotics. Hugh Herr works as an associate professor in the Program in Media Arts and Sciences at MIT and in the Harvard-MIT Division of Health Sciences and Technology. Being the Head of the Biomechatronics research group at the MIT Media Lab, he focuses on developing of wearable robotic systems that serve to augment human physical capability. The paper written by Aaron M. Dollar and Hugh Herr provides interest because of its large number of citations and uniqueness [40]. The described type of an exoskeleton has been specifically designed to assist in running, reducing the metabolic cost of transport and fatigue of a wearer, and in contrast to the other models of exoskeletons has not been a massive construction.

They present the design concept, describe the working principle, detail design information, and conduct a preliminary benchtop evaluation of the hardware prototypes. The authors concluded the paper by discussing the concept, identifying challenges and potential pitfalls of successful exoskeletons and how to apply them in a design. The perspectives of LLEs seem to be bright, and such devices are predicted to be in high demand to meet the needs of disabled and ageing people. Avoiding high cost of the sophisticated components, such as harmonic drives, microcontrollers, and high end Direct Current motors and looking into ergonomic mechanical innovations can assist to improve the quality of the exoskeletons delivered to the markets. Therefore, it is concluded that if proper emphasis is laid on these issues, the exoskeleton market can be developed to reach the masses to provide the needed assistive devices.

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