The Research on Exoskeletons with Focus on the Locomotion Support

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Abstract: This paper summarizes the research on exoskeletons focusing on locomotion support and presenting their general features including the general control approaches. The major fields of exoskeleton applications are focused, namely the military and medical fields. The results of our research on muscles activation during human walking are shortly described. The current developmental trends are outlined in the conclusions part.

Keywords: lower limb exoskeleton, EMG, gait analysis

1. Introduction

The concept of an artificial exoskeleton is inspired by biology. Many living creatures possess external skeletons covering their soft bodies, the classic example are insects. Animal exoskeletons are not only introducing the rigidity of the body but make the safe covering of soft organs, moreover through reconfiguration of the rigid segments, the reshaping of the body, that supports the locomotion, is obtained. Interesting example are the worms covered by segmented shell which can take a ball like form for rolling down the inclined surfaces (see Fig.1)

The human exoskeletons we are not yet reached such advanced stage however those devices have quite long research history, and the recent challenges in this field are impressing. The study on human exoskeletons started in 19th century. The first exoskeleton-like devices were invented by Nicholas Yagin [26] (1890). These devices offered for the wearer the faster running and higher jumping ability. The era of modern exoskeletons started in late seventies of 20th century together with the progress in digital control systems and sensing technologies [25].

Exoskeletons are regarded as a wearable robots or a wearable intelligent devices. They can be categorized as a full-body, upper-body and lower-body supporters. The exoskeletons are used in rehabilitation, they prevent of motion system injuries, they increase the power or enhance the human motion abilities. Moreover, they are used as intelligent prosthesis for amputees, they also allow the locomotion of the persons with different motion impairments.

In this paper we focus on human lower limb exoskeletons. However, the representative example of advanced full body exoskeleton is also mentioned. The walking ability is very crucial for normal functioning of the human being and is required for many working activities. The paper is organized as following: first the lower limb exoskeletons for military and medical applications are shortly presented; next the basic features of a human gait together with outline of our research on muscles activation signals are given. The paper is ending with conclusions.

Fig. 1. Armadillidiidae, also known as a pill bug, can reshape its body spherically. Left: pill bug in walking posture [20], photo by Peter O'Connor aka anemoneprojectors on Foter.com/CC BY-SA; right: pill bug taking the ball shape [19], image courtesy of membio at FreeDigitalPhotos.net

Rys. 1. Armadillidiidae, znane również jako kulanka, potrafi zwinąć się w kulkę. Po lewej: kulanka w postawie podczas chodzenia [20], fot. Peter O'Connor znany jako anemoneprojectors na Foter.com/CC BY-SA; po prawej: kulanka przybiera kształt kuli [19], fotografia dzięki uprzejmości membio na FreeDigitalPhotos.net

2. Exoskeletons for military applications

The modern exoskeletons augment the force and strength of soldiers carrying the loads to supports the longtime marching. The research on full-body exoskeletons for military applications started more than fifty years ago with the works on HARDI-

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MAN. The HARDIMAN was built within General Electric project named "Human Augmentation Research and Development Investigation" [25]. HARDIMAN was equipped with hydraulic and electric motors. Unfortunately, the HARDIMAN project was not successful, because the actuators were producing violent and uncontrolled motions. In 2001, the Defense Advanced Research Projects Agency (DARPA, USA) started its own research on exoskeletons launching the program "Exoskeletons for Human Performance Augmentation" [16]. It aimed the design of exoskeletons augmentating the user forces. Between others, the Sarcos company was appointed to this project, and in 2006, DARPA successfully accepted the exoskeleton prototype by them. In 2010, Sarcos company delivered XOS exoskeleton. XOS is a full--body exoskeleton that enhances user's strength by hydraulic actuators. XOS allows to carry the armor and other heavy objects [10]. The company progressed farther the exoskeletons development what lead to the very advanced Guardian XO exoskeleton suit for industrial workers, presented recently (2019) [17]. Another example of the DARPA supported designs is the Berkeley Lower Extremity Exoskeleton (BLEEX). The project was ordered in 2000, immediately after launching "Exoskeletons for Human Performance Augmentation".

BLEEX allowed the soldier to carry the heavy loads over the long distances [23]. The force augmenting actuators were increasing the leg joints power and the waist holder allowed to distribute properly the loads carried by soldiers. The example of partial exoskeleton is ONYX, which developed from motorized knee brace. It was the work of Lockheed Martin company financed by U.S. Army Natick Soldier Research, Development and Engineering Center (NSRDEC). Within this project started in 2018, the basic version of ONYX was enhanced to the advanced exoskeleton. ONYX uses artificial intelligence for predicting the joints movement. Another U.S. program called Tactical Light Operator Suit (or TALOS) [14] delivered a "superman" suit which is bulletproofed, weaponized and is strength enhancing. The project was started in 2013 and the advanced prototype was planned for demonstration in 2018, however it seems that the project was not so successful as it was assumed. Besides of some problems the research on exoskeletons for special applications is continuing. The actual developmental trends are focusing on soft, light weighted devices with long-lasting endurance. Their control strategies are discussed in the later part of this paper.

3. The exoskeletons for medical applications

Exoskeleton for medical application are dedicated for two groups of users, the disable persons and elderly. According to [7], there are 15 million disabled persons with lower limb motor disorders. Moreover, just in USA, in each year almost 800 000 brain strokes occur, and such patients critically need rehabilitation. The modern research on exoskeletons for medical application was started by M.Vukobratović [32] over 60 years ago. His team developed an active exoskeleton for rehabilitation of paraplegics. Till now, researchers had developed many active exoskeletons assisting patients in rehabilitation or supporting their walking [2, 9]. The exoskeletons usually apply the electrical motors powering the ankle, knee and hip joints for assisting palsy or stroke patients in walking. The exoskeleton called Lokomat (launched 2016) [3] is used to rehabilitate the patients on a treadmill. It provides a stable walking pace and secures the body balance. Some studies are indicating that the exoskeletons supporting the body weight improve the speed of gait recovery after the brain stroke [1]. The aging population is a common global issue. Unfortunately, the muscle strength is weakening with the age, moreover in the old age the problems with keeping the postural balance are also appearing. Therefore, the exoskeletons as a daily support are needed. A Japanese company (CYBERDYNE) developed Hybrid Assistive Limb (HAL) which assist the wearer walking, standing up and sitting down [21, 22]. The works on HAL precursor started in 1997 and the first demonstration of HAL took place in 2012. Another example is Unplugged Powered Suit (UPS), a lightweight, highly flexible exoskeleton invented also in Japan [11] and launched in year 2015. UPS uses pump drives and a pneumatic gel muscle (PGM) for augmenting the user forces. This device is soft, lightweighted, it can be used for enhancing the strength of athletes and for rehabilitation as well. Our list of most relevant projects, closes the Brain-Controlled Adaptive Lower Limb Exoskeleton for rehabilitation of post-stroke paralyzed (BCLLE) [33] currently being under development within the Institute of Electrical and Electronics Engineers EPICS grant.

In the end of this part it should be emphasized that the needs of patients are very diverse, however, the common requirement are the robust, and reliable systems which is easy to wear.

4. Actuation and motion generation: the main features

4.1. State of the art

Exoskeleton are the wearable robots. They integrate sensors, mechanics and control systems. The basic control strategies are listed in Table 1 where the examples considered the medical, and military applications are summarized. The types of actuators and active joints are listed. The control system of exoskeleton BLEEX increases the closed loop system sensitivity to its user forces and torques without any direct measurement. In the position control mode, the information from several inclinometers was used for deciding about required joints position [35]. BLEEX has few sensors and is driven by hydraulic actuators powering the hip, knee and ankle joints. Differently than BLEEX, ONYX and exoskeleton X1 (2012–2017) dedicated for human assistance and space missions, are using many sensors which are mounted in the feet, knees and hips collecting the motion data which are used for predictive control. ONYX applies miniaturized electric actuators [13]. X1 utilize series elastic rotary actuators in hip and knee joints [30]. Electromyogram based (EMG based) control creates the human--machine interface where the exoskeleton works according to user's intention. EMG based control strategy was firstly used in HAL-3 (2000) and was farther refined in the HAL-5 version (2009). Most recent version of HAL exoskeleton has two modes of operation. In one mode, the device supports (stimulates by firm forcing) the predefined normal gait. When the patient wears HAL regularly, the gait pathologies are vanishing, and the gait is improving [6]. In the other mode of HAL operation, the EMG signals collected by surface electrodes are used as the templates for producing the gait support. The control system associates the EMG patterns with specific movements. Those patterns are used for producing the motor control commands [28, 21]. Therefore, the system is capable to predict the next required position and drives accordingly the actuators [34, 36, 6]. It is possible under the assumption that the user is able to produce clear (not blurred) EMG signals.

Electroencephalograms (EEG) are the signals providing the information about electrical activity of the brain. These electric signals are used for the motion control of paralyzed persons. The electrical activity of the brain is measured by small surface electrodes attached to scalp. In this case, the EEG signal patterns are associated with different movements. The patient needs an exercising for such type of control using the mind (the will) [27]. In 2005 the Media Lab's Biomechatronic Group from MIT delivered their first prototype with EEG controlled motion [18]. The project was farther developed. MIT exoskeleton applies

Table 1. Lower limb exoskeletons: list of selected features
Tabela 1. Egzoszkielety kończyny dolnej: wykaz wybranych cech

Usage categorization	Device name	Starting year of the project	Application	Control method	Type of the actuators	Active joints
Military application	BLEEX	2000	Strength augmentation and movement endurance	Sensor-based position/force/ torque control	Hydraulic actuators	Hip, knee, ankle joints
	ONYX	2018	Increase wearer's mobility and reduce fatigue	Sensor-based predictive control	Electrical actuators	Hip, knee
	MIT Exoskeleton	2005	Load-carrying augmentation	Quasi-passive force/torque control	No active actuators but springs and variable dampers	Hip, knee, ankle
Medical application	Hybrid Assistant limb (HAL-3)	2000	Assist disabled and elder or rehabilitation	EMG sensor-based predictive control	Electrical motors	Hip, knee, ankle
	X1	2012	Gait rehabilitation, and assisted walking, astronaut's resistance training	Sensor based predictive control	Series elastic rotary actuators	Hip, knee
	BCLLE	2016	Rehabilitation of post-stroke paralyzed	EEG based predictive control	High torque electric motors	Hip, knee, ankle

quasi-passive control which means that no active actuators are used but springs at ankle and hip joints and a variable damper in the knee joints. The EEG-based control strategy is also applied in BCLLE [33] the exoskeleton which is currently under development, the motions are predicted using the gait patterns recovered from measured EMG or EEG signals.

The recent research on EEG based control [24, 31] delivers very promising results. However, such control method is still in the early stage of development and it strongly depends on sensing and sensor's quality.

Table 1 is giving the short overview of the properties of the most representative exoskeletons discussed in this paper.

4.2. EMG signals analysis for EMG based control: research example

It is obvious that the researchers designing the exoskeletons must be familiar with the human motion properties [5]. Such knowledge allows to design the joint motion ranges, to select the actuators and motion transmission systems and finally to design the control system such that it will support and not obstruct the intendent movements without forcing the wrong positions or the extreme motion speed. Accordingly, when developing the lower limbs exoskeletons, the knowledge of human gait features is necessary.

The leg motion during normal walking gait is divided to the swing and stance phase. The swing phase is the speed demanding, the leg-end moves along curve trajectory and it must be fast enough for avoiding obstacles and being placed on the ground according to the gait pattern. The supporting phase is torque demanding, the leg must absorb the landing impact and support the body weight. In the normal gait seven stages are distinguished, namely the 'heel strike', 'foot flat', 'mid stance', 'heel off', 'toe off', 'mid swing', 'heel strike'. The recognition of the gait stages basis on the measured EMG signals is needed for EMG based motion control as it was already mentioned. In our project, we investigated the muscles activity during normal slow walking of a female subject [34] considering barefoot, sneakers shoes and high heel footwear. The EMG signals were recorded for the main muscle groups of the lower limbs according to standards defined in gait monitoring systems.

The simple competitive network which not needs the training was clustering the pre-processed discretized EMG signals to the several groups (clusters). It was proved that those clusters are well associated with the gait stages. Fig. 3 is showing the EMG clustering results, in this case the left leg was considered, the gait phases together with visualization of leg position are also given. Showing the results for the left leg allows us to illustrate the stages shift between two legs in the normal, slow gait (note: in both Fig. 2 and 3 the drawings are starting from the double support phase however in the first case the leg goes next to the swing phase, while the left leg stays in support what is shown in Fig. 3). As it can be noticed (Fig. 3) the changes of classes occur mainly in the moments of change of the gait stages (indicated by vertical dotted line) or near to it. It confirms that clustering artificial network can be used for gait stages recognition. Considered gait is fundamental for the exoskeletons dedi-

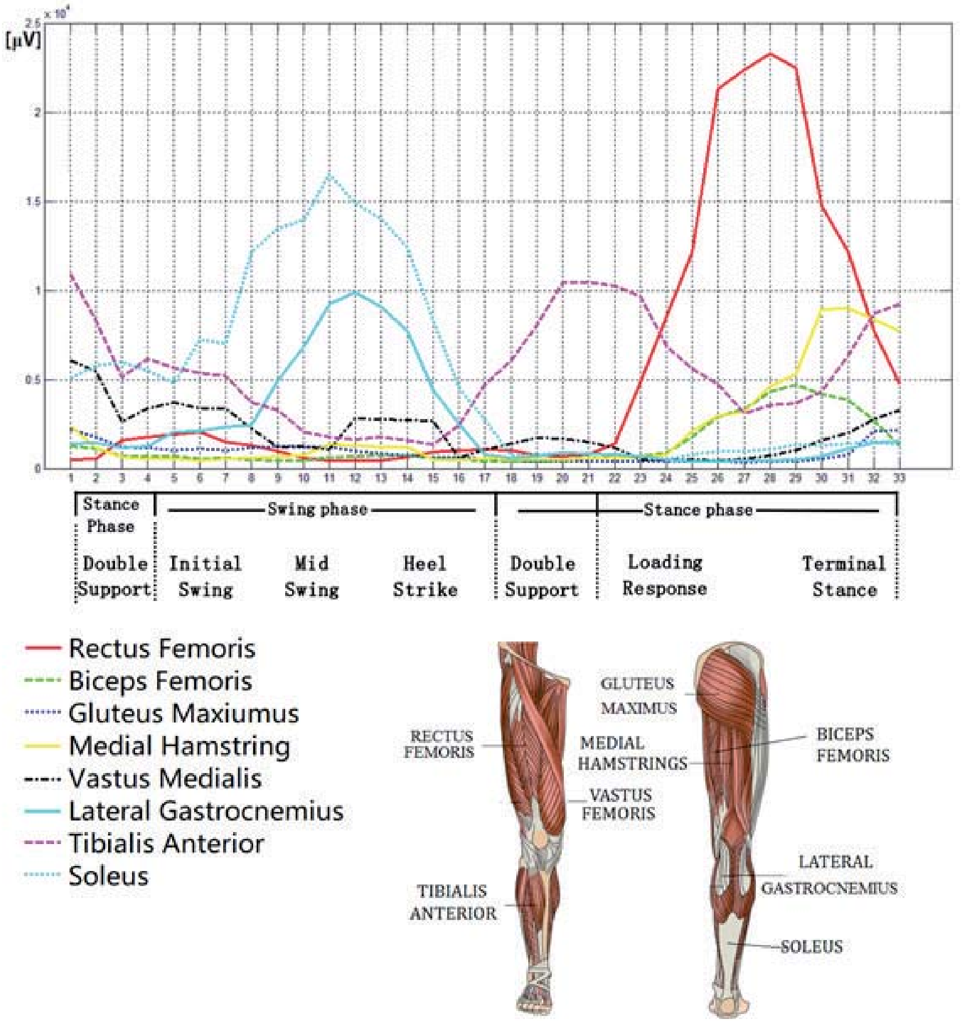

Fig. 2. Processed EMG signals for bare foot. The considered main muscle groups are pointed out

Rys. 2. Przetworzone sygnały EMG dla bosej stopy. Zaznaczono wzięte pod uwagę główne grupy mięśni

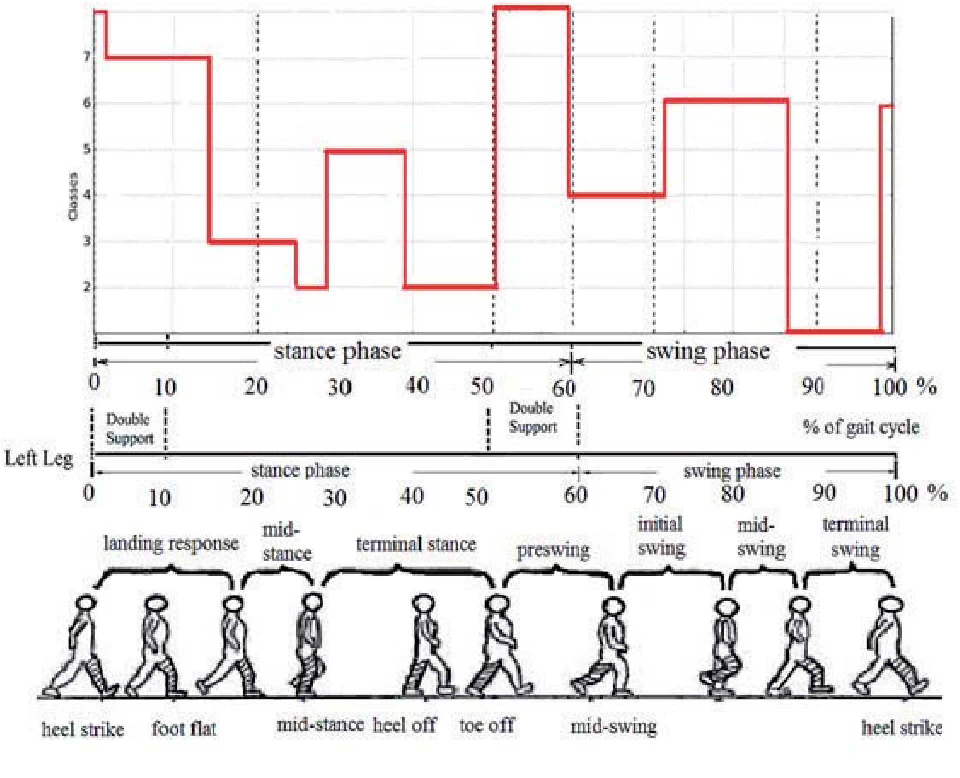

Fig. 3. The clustering results of the EMG signals. The data concern the left leg. The gait stages are also illustrated

Rys. 3. Wyniki grupowania sygnałów EMG. Dane dotyczą lewej nogi. Zilustrowane są też etapy chodu cated to rehabilitation. Such gait is also used for detecting the motion impairments and the recovery processes. The details of the methods are given in [36].

5. Conclusions

Earlier exoskeletons for military applications, were using rather big hydraulic motors, with the progress in engineering, the electric motors become popular [15, 8]. The military users need light, endurable and flexible exoskeletons. ONYX is the example of such solution; this lower limb exoskeleton is easy to wear, and it is efficient in exploitation [13]. Meanwhile, due to the progress in power supply solutions the operation time is also improving. The challenge of exoskeletons for medical applications is to overcome the system complexity and the high cost. Differently than in the military application the users of medical exoskeletons are usually motion impaired and cannot voluntary produce their movements when keeping the stable posture. They need rigid and actuated assistance for supporting their body weight. Due to the development of efficient batteries, new flexible and light materials and progress in actuating techniques [29] the better solutions are now possible. Artificial muscles [4] are more often applied what allows to adjust the devices better to the human body structure and with reducing its weight. On the other hand, the progress in the sensing techniques and control methods is also very crucial. The refined EMG of EEG sensors provide reliable readings and sophisticated, artificial intelligence-based control algorithms, are associating the sensory data with the motion commands much better than it was years ago.

Meanwhile, the cost of exoskeleton is still very high and is over the acceptance level for majority of needing persons. For example, the retail price of HAL was approximately between $14,000 and $19,000 in 2011, moreover the monthly rental fee was estimated to $1000 [12].

It must be concluded that light, durable and not expensive lower limb exoskeletons is the most fundamental demand. In medical field they support rehabilitation, or they offer the walking possibility to the persons with motion disorders. In military or other special applications, they enhance the user's strength and motion efficiency.

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Badania nad egzoszkieletami zorientowane na wspomaganie czynności ruchowych

Streszczenie: W niniejszym artykule podsumowano wyniki badań przeprowadzonych nad egzoszkieletami przeznaczonymi do wspomagania czynności ruchowych. Przedstawiono ich główne cechy, a także główne podejścia ich sterowania. Podstawowymi obszarami użycia egzoszkieletów są zastosowania wojskowe i medyczne. Opisano zwięźle wyniki badań nad aktywacją mięśni podczas chodzenia przez człowieka. Obecne trendy rozwojowe przedstawiono w podsumowaniu.

Słowa kluczowe: egzoszkielet kończyny dolnej, EMG, analiza chodu

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