Socio-Economic Impact of Medical Lower-Limb Exoskeletons*

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***Abstract*— A constructive debate is ongoing among experts and academics about the social and economic impacts of advanced robotics. Exoskeleton robotic suits represent one of the most significant examples of what Human-Oriented Robotics is. After recent technological advances, the range of application fields of these devices has widened with respect to the first applications about teleoperation and power amplification. The aim of this paper is to contribute to the ongoing discussion by offering a vision of the possible future developments in terms of socio-economic impacts, resulting from the increasing use of Exoskeleton Robots, especially with regard to their applications in lower limb medical rehabilitation. In order to provide a concrete contribution to the current state-of-the-art, we are working on an alternative exoskeleton design approach to overcome the identified limits to the diffusion of this new technology. The achieved results are presented in the final part.**

I. INTRODUCTION

When we consider Human-Oriented Robotics, we immediately think about robotic devices designed to collaborate with humans in every-day-life tasks. One of the most important examples come from Exoskeleton devices which can be regarded as wearable robots, i.e. a mechatronic system designed around the shape and function of the human body, whose segments and joints kinematically correspond to those of the person they are externally coupled with. As the technological solutions improved and the scientific interest towards these robots grew, their fields of application have widened, making it possible to use them for power amplification, teleoperation and neuromotor-control research and rehabilitation [1]. Since the early 1960s, the US Defense Department, the Air Force through the Cornell Aeronautical Laboratory, and the General Electric were pioneers in expressing interest in the development of a human-amplifier powered suit for military purpose. These studies pointed out several issues in duplicating human motions by using a master-slave control strategy in which the operator is in a master suit which controls the slave suit. This last one takes care of the work load. However, difficulties in human sensing and system complexity kept it from walking [2]. Any attempt to use a full body exoskeleton resulted in an uncontrollable motion, and so it was never tested with a human.

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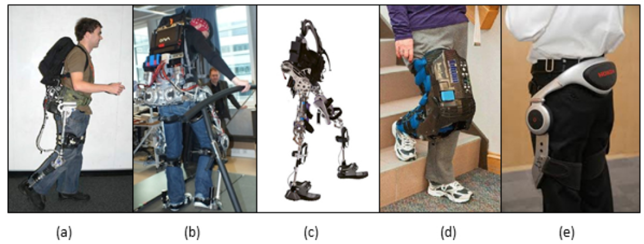


Fig. 1. (a) MIT Exoskeleton; (b) MindWalker; (c) Austin Exoskeleton; (d) AlterG Bionic Leg; (e) Honda Walk Assist Device.

A next generation of exoskeletons came from the active orthoses for paraplegics, projected to give back the user a real autonomy in the execution of the walking task. Commonly, these systems include hydraulic, pneumatic or electric actuators to drive the hip, knee, and ankle joints along a predefined trajectory in the sagittal plane. After more than thirty years of research and development, the ideal scenario is to be met by a combination of a rehabilitation robot and an environment modification. This approach integrates users into a comprehensive system in which they are in control of the rehabilitation robot, and they can exert control on the environment whenever it is not fully provided by the robotic device. In more recent approaches, the robotic assistant mediates between the user and the environmental controls [3].

Today, many exoskeleton suits are available for different application [4]. Fig. 1 shows some design examples. *MIT Exoskeleton* [5], [6] has been developed at MIT laboratories and produces motion using magnetic fluid which changes viscosity under the effect of electricity. *Mindwalker* [7], which had the first demonstration in 2012, took shape at University of Twente in Netherlands and includes a new electroencephalographic signals (EEG) bio-sensor system. *LOPES* [8] has been developed at University of Twente since 2001 when the suit project was started. *Austin Exoskeleton* [9], by UC Berkeley, has been projected to ease the design and promote smart computation and elegant programming in order to keep down the production costs and make the system more affordable. *NASA X1* [10] has been planned by NASA to be used in space or for medical purposes. It is very flexible and can provide additional force for astronauts during surface exploration. *Power Loader* [11] is the first industrial exoskeleton suit designed by a Panasonic subsidiary venture called Activelink. It has been designed to be released on the market starting with 2015. *AlterG Bionic Leg* [12] is a single-leg robotic aid worn during therapy sessions to help patients in sit-to-stand, overground walking

and stair-climbing exercises. *Honda Walk Assist Device* [13] has a peculiar hip design to help people walking or climbimg stairs. *KobaLab Exoskeleton* [14] has been developed by the Koba Lab from Tokyo University of Science and can allow the user to lift heavy loads by using pneumatic artificial muscles. *Agricultural Exoskeleton* [15] designed by Tokyo University of Agriculture and Technology has been made to help out with tough agricultural work, since about 40 percent of agricultural workers in Japan are aged 65 or over. *HULC* [16] has been built by Berkeley Bionics and Lockheed Martin for military use. *XOS* 2 [17] is another military exoskeleton built for soldier to carry up to 90 Kg (200 lb) of loads. Other exoskeletons examples will be discussed in section 3.
This paper doesn't concentrate on technical aspects of modern exoskeletons design but would give a useful contribution to the evaluation of their socio-economic impact, analyzing the related market too. In section 2, considerations about social impact are given, providing up-to-date statistics about Spinal Cord Injury (SCI) and a speculation about the benefits deriving from the usege of these new technologies. The issues involved into this field of research and development justifies the number of companies that are emerging all over the world, as described in section 3. Section 4 is about economical aspects, considering both the lifetime costs in SCI and the emerging market of medical lower limb exoskeletons. A prototype of a new exoskeleton on which we are working is presented in section 5. Finally, section 6 concludes the work by discussing significant future developments.

II. SOCIAL IMPACT

Medical lower limb exoskeletons are used to assist people with lower extremities paralysis or weakness in walking. They can be used with subjects with complete or incomplete SCI or other kind of neurological diseases such as stroke, multiple sclerosis, amyotrophic lateral sclerosis and Parksinson's Guillain Barre [18]. The following considerations concern the spinal cord injured population.

A. Spinal Cord Injury Facts

According to the *International Spinal Cord Society (ISCOS)* [19], global informations about the number of people living with SCI are minimal. The data reported here allow to make a comparison between some different geographical areas as regards Traumatic Spinal Cord Injury (TSCI). For a full analysis considering all the *World Health Organisation (WHO) global regions*, refer to [20]. Considering SCI facts, it must be noted that regional data are available only for North America (USA and Canada), Western Europe (Denmark, Greenland, Iceland, Sweden, Ireland and Germany) and Australia. For the areas with no published data, the incidence reported were estimated by using regression modelling as detailed by [21]. Considering the data about global prevalence (i.e. the number of people living with TSCI), the range of the reported value is between 236 (India) and 4,187 (USA) per million. However, data for many developing countries

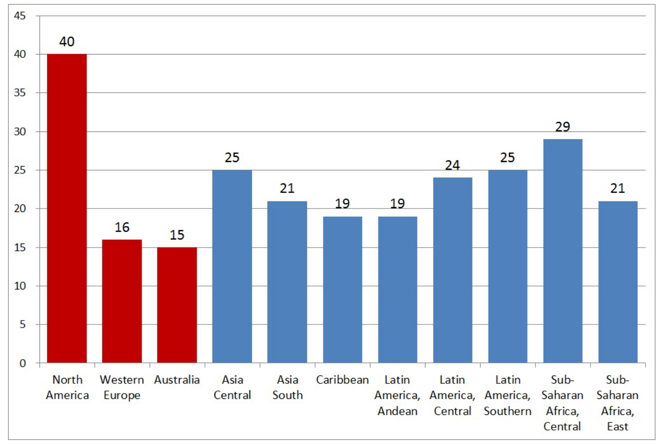


Fig. 2. TSCI annual-incidence per million people. The red bars refer to areas for wich regional data ara available, whereas the blue ones are for the areas whose results were estimated by using regression modelling. Source: adapted from [20].

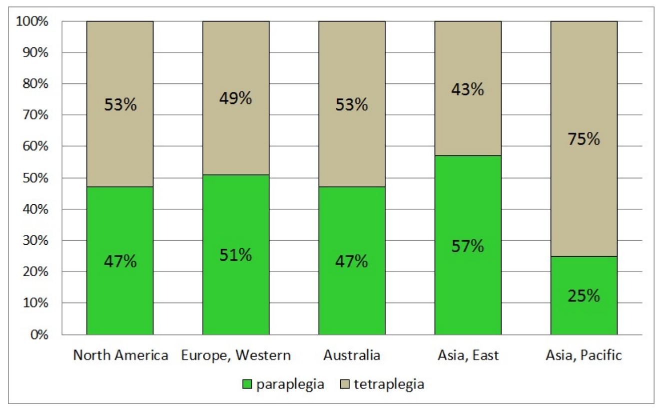


Fig. 3. Percentage of TSCI cases resulting in paraplegia and tetraplegia. Source: adapted from [20].

(such as Africa and South America) are poor and may underestimate the number within this regions. As regards the TSCI global-incident rate (i.e. the number of TSCI annual cases), in 2007 its value was estimated to be 23 case per million (179,312 cases per annum). The bar graph in Fig. 2 summarizes the global-incident rate of TSCI.

As to concern the level and the extent of lesion, Fig. 3 represents the percentage of TSCI cases resulting in neurological impairment.

According to the National Spinal Cord Injury Statistical Center of the University of Alabama [22], in the USA most of injuries occur between the age of 16 and 30, mainly among males (80.7%). Considering the etiology of SCI, 36.5% of the reported cases since 2010 refer to motor vehicle crashes, 28.5% are caused by falls, following by acts of violence (14.3%), sports accidents (9.2%) and other causes (11.4%). The data show also an increase of TSCI related to falls in elderly people (older than 60 years). For this reason, it would be important the design of the new generation exoskeletons to be suitable also for elderly people.

As regards life expectancy (i.e. the average remaining

TABLE I

LIFE EXPECTANCY IN SCI. THE REPORTED VALUES ARE EXPRESSED IN YEARS. SOURCE: ADAPTED FROM THE NATIONAL SPINAL CORD INJURY STATISTICAL CENTER, FACTS AND FIGURES AT A GLANCE, 2013. HTTPS://WWW.NSCISC.UAB.EDU/. *: STANDS FOR "IF SURVIVING THE FIRST 24 HOURS" WHEREAS #: STANDS FOR " IF SURVIVING AT LEAST 1 YEAR "

SEVERITY OF INJURY	AGE AT INJURY					
	20		40		60	
No SCI	59.0		40.0		22.7	
AIS D - Motor Functional at Any Level	52.0	52.4	33.7	34.0	17.5	17.7
Para	44.6	45.1	27.2	27.7	12.7	13.0
Low Tetra (C5 - C8)	39.6	40.4	23.1	23.7	9.9	10.3
High Tetra (C1 - C4)	35.3	36.6	19.7	20.7	7.8	8.4
Ventilator Dependent Any Level	18.6	24.9	8.4	12.3	2.0	3.7
CONDITION	*	#	*	#	*	#

years of life), it is useful to compare the values for the SCI population with these for the normal one. The highest 1-year mortality rates concerns developing countries (particularly Sub-Saharan Africa), whereas 10-years mortality rate data are only available for USA, - Southeast region 16.2%; Canada, Manitoba region 10.7% and Australia, 14.3%. Data suggest that life expectancy for subjects with SCI is still low when compared to the general population and didn't get better since the 1980's. Considering USA data [22], as shown in Tab. I, the highest mortality rate is during the first year after injury and considerably decrease with the severity of the damage. Therefore, the gap in life expectancy between SCI and the general population of comparable age, sex, and race, is increasing: in fact, although general population life expectancy is increasing, for persons with SCI who have survived the first year after injury it has remained constant. With respect to the main causes of death, while in the past most of the people with SCI died of renal failure, nowadays the leading cause of death concerns the diseases of the respiratory system (especially pneumonia) followed by infective and parasitic diseases (especially septicemia) which are usually associated with decubitus ulcers and urinary tract or respiratory infections.

B. *Improving the quality of life*

To understand the real improvement in quality of life deriving by the usage of lower limb exoskeletons, it is useful to consider what kind of aid devices are nowadays available for subject with SCI or other severe motor impairments. What is clear is that at the present, there are no systems able to substitute the wheelchair for daily life usage. Although powered wheelchairs have been introduced into the market since many years ago, also allowing a standing up position, no active walking device has been proposed until the development of lower limb exoskeletons. What medical exoskeletons offer for now is an alternative way to do clinical rehabilitation but in a future not too far they will be probably used not only in a clinical contest, but also in a daily life environment. From a clinical point of view, the use of medical robots offers many advantages compared to traditional rehabilitation methods. First of all, robotic devices allow clinicians to carry out objective measures of the progress achieved by the patient, enabling to schedule a customized training plan. The trajectories followed by the robot at each step are more accurate than that manually obtained, allowing a high repeatability of the correct movement within the single exercise. Furthermore, depending on the implemented control strategy, the system can even guarantee a patient's active role during the motion, serving not only as a walking aid, but also as a real mean of physical rehabilitation. This kind of application should involve a bioelectric trigger signal in the actuation scheme, using for example electromyographic (EMG) signals as for Robot Suit HAL [23], [24].

It should be noted that the current exoskeletons are not to intend as plug-and-play devices, but require a careful clinical analysis of the patient in order to define the correct conditions of usage. In fact, becoming familiar with an exoskeleton requires some training. An example comes from Ekso Bionics who provides a specific process of learning, which starts from the building up of the upper body strength on the parallel bars and continues by the use of a walker and then crutches with the exoskeleton, both while attached to a tether. It takes about 12 hours of walking to get ready for independent walking [25]. From a physiological point of view, with reference to the quality of life and the issues discussed in the previous section, greater mobility would bring the subject important health benefits, reducing problems deriving from sitting for long periods e.g. bone loss, urinary-tract complications, pressure sores, diabetes and obesity. Considering the psychological aspects, allowing the subject to assume the standing position and walk, would improve his well-being, giving him a new perspective of life. Using these devices in everyday life would also increase the social participation of the subject. If we try for a moment to imagine a future in wich everybody will use an exoskeleton system, for example for heavy work activities or simply for energy consumption saving, no differences will be notable between general population and motor impaired people.

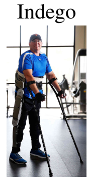
III. EMERGING COMPANIES

According to Keith Maxwell, business development manager for Lockheeds program "*We are now seeing a golden age in which we can produce this technology and derive benefit from it*" [26]. The interest in this emerging field is also demonstrated by the number of companies that are springing up in the world. Tab. II compares the features of five exoskeletons already on the market.

Ekso Bionics [27] is one of the leading company of the sector. It was founded in 2005 with the name of Berkeley ExoWorks (in 2007 became Berkeley Bionics and in 2011 changed in Ekso Bionics). During the years, it has developed some advanced exoskeletons both for military and medical purpose such as ExoHiker (2005), ExoClimber (2005), HULC (2008), and Elegs (2010) [28], now called EksoSuit. Currently the EksoSuit is intended for use in specialized

TABLE II

COMPARISON BETWEEN THE DESIGN OF EKSO SUIT BY EKSO BIONICS, INDEGO BY PARKER HANNIFIN, REWALK BY ARGO MEDICAL TECHNOLOGIES, HAL BY CYBERDINE, REX BY REX BIONICS. (N.A. STANDS FOR NOT AVAILABLE DATA)

	Ekso Suit	Indego	ReWalk	HAL	Rex
					
step trigger strategy	push a button	tilt sensor	tilt sensor	EMG sensor	joystick
N. motors per leg	2	2	2	2	n.a.
mass	about 30kg	about 12 kg	n.a.	n.a.	about 38 kg
forearm crutches	yes	yes	yes	no	no
backpack	yes	no	yes	no	no
available on market	yes	2014	yes	yes	yes

clinics but a new personal version will be available in 2014. Collaborative centres are placed within a support program which provides physiotherapists with training certification for the selection and assessment of potential patients as well as a specialized engineering support within a program of periodic maintenance, and access to Ekso Research Network for the consultation of data acquired from Ekso. *Parker Hannifin* [29] has recently licensed the Indego exoskeleton technology [30] developed at the Center for Intelligent Mechatronics of the Vanderbilt University, and is targeting commercial launch in 2014. Indego is 40-50% lighter than competing devices, has no bulky backpack or footplates and is easy to use and transport thanks to its modular design. Furthermore, it is the only wearable device that incorporates a proven rehabilitation technology called Functional Electrical Stimulation (FES). Since the year of founding in 2011, *Argo Medical Technologies* [31] has growth from a small research and development start-up based in Israel to an international company with headquarters in the US, Germany and Israel. The company has developed two alternative version of the ReWalk exoskeleton [32]. The Rewalk Rehabilitation is projected to be used in a clinical context and is currenly available in Europe and United States. On the other hand, the ReWalk Personal is available throughout Europe since 2012 and is awaiting FDA clearance in the USA. At the time of this paper, Argo Medical Technologies is seeking strategic partners who will be able to effectively provide marketing/sales, training, technical support and any other customer support function. *Cyberdyne* [33] is a venture firm aiming to utilize accomplishments by Prof. Sankai and his laboratory at University of Tsukuba. The study for the development of the Robot Suit HAL started in 1992 and in 1997 the first prototype was ultimated. In 2002 the HAL-3 was completed and in 2004 Cyberdyne Inc. was founded. Being the unique device using EMG signals to control the joints actuators [23], [24], HAL-5 is one of the most advanced available exoskeletons. Currently a collaboration between Cyberdyne, the Center for Cybernics Research and the Johns Hopkins University is in progress in order to further improve the effectiveness of the system. *Rex Bionics* [34] was founded in New Zeland in 2007, at the end of the design phase of the Rex exoskeleton (that began in 2003). After having passed the validation/safety tests and the regulatory trials established by the New Zealand National Ethics Committee, the Rex is available on the market since 2010. Unlike other existing exoskeletons, the user selects the desired movement through the use of a joystick. Because it doesn't require the use of crutches, the system can be used even by subjects with low strength in their upper limbs.

IV. ECONOMIC IMPACT

The reported data would give an idea about the SCI-related costs. As it can be noted, the occurrence of SCI does not only influence the social life of the subject, but has a strong economic impact too.

A. Lifetime costs in SCI

The average yearly health care and living expenses and the estimated lifetime costs vary not only depending on the severity of the injury, but also on education, employment history and age of the subject. Tab. III shows the average yearly expenses and the estimated lifetime costs for the tratment of a person living with SCI. These figures do not include any indirect costs (i.e. losses in wages, fringe benefits and productivity) which averaged $70,575 per year in February 2013. As you'd expect, higher level of injury and lower age at time of injury correspond to higher costs [35]. The lifetime cost of an injury causing paraplegia in a 25 years old person is about $2,250,000. This is an high amount if we compare it for example with the cost of an heart attack. In fact, according to the *National Business Group on Health*, the average total cost of a severe heart attack is about $1 million, whereas the average cost of a less severe heart attack is about $760,000 [36]. Introducing exoskeletons would give the medical staff an effective device which could speed up the rehabilitative treatment allowing a significant cost cutting. The median days hospitalized in the acute care medical/surgical unit immediately following injury was 11 in 2010 (this number was 24 between 1973 and 1979) while the number of days in the rehab unit is descreased from 98 to 36. Considering the intensive and accurate exercise that can be done by using an exoskeleton, the introduction of these devices could further decrease the convalescence within the rehabilitation facility, allowing the patient to continue the physical therapy at home after discharge. In fact, once discharged from the hospital, 87.1% of all persons with SCI are sent to a private, noninstitutional residence (in most cases their homes before injury). Only 6.5% are discharged to nursing homes. The remaining are discharged to hospitals, group living situations or other destinations.

TABLE III

AVERAGE YEARLY EXPENSES AND ESTIMATED LIFETIME COSTS IN SCI. SOURCE: ADAPTED FROM THE NATIONAL SPINAL CORD INJURY STATISTICAL CENTER, FACTS AND FIGURES AT A GLANCE, 2013. HTTPS://WWW.NSCISC.UAB.EDU/

SEVERITY OF INJURY	AVERAGE YEARLY EXPENSES		ESTIMATED LIFETIME COSTS BY AGE AT INJURY	
	First Year	Each Subsequent Year	25 years old	50 years old
High Tetraplegia (C1-C4)	$1,044,197	$ 181,328	$ 4,633,137	$ 2,546,294
Low Tetraplegia (C5-C8)	$ 754,524	$ 111,237	$ 3,385,259	$ 2,082,237
Paraplegia	$ 508,904	$ 67,415	$ 3,265,584	$ 1,486,835
Incomplete Motor Functional at Any Level	$ 340,787	$ 41,393	$ 1,547,858	$ 1,092,521

Reading this data makes clear the necessity to develop a product easily usable by the patient also at his own home, and not only within a clinic. Considering then the occupational status of the subjects, 57.1% reported being employed at the time of the injury but only 11.8% of people with SCI are employed one year after the injury. By 20 years postinjury, and similarly 35 years postinjury, 34.9% are employed. These data have a key role in the decision process about the sale price and the components complexity for such devices. Actually, since they are too expensive, only a small portion of the potential users will be able to afford buying them. This would be an essential aspect, because it would deprive a large part of the population of the actual benefits deriving from this kind of technology.

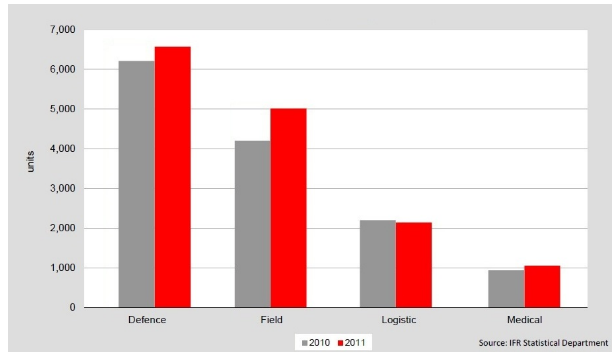


Fig. 4. Service robots for professional use. Sold units in 2010 and 2011 (main applications). IFR Statistical Department - World Robotics 2012 Service Robots.

B. Lower Limb Exoskeleton Market Analysis

Exoskeletons market have a high growth potential deriving from the capability of these devices to satisfy a need not solved yet. Some important evaluations about the economic impact of medical robots are derivable from the data collected by the *International Federation of Robotics (IFR) Statistical Department* [37]. The report gives some considerable statistics about the present and the future market of both industrial and service robotics. Compared to 2010, the total number of medical robots sold in 2011 had an increment of 13% with a total number of 1,051 units, reaching a share of 6% of the total unit sales of professional service robots. Fig. 4 shows a comparison between the number of medical robots which have been sold and the amount of other service robots for professional use. The total value of sales reached US$ 1,347 million, covering the 38% of the total sales value of the professional service robots. Considering their mean unit price of about US$ 1.5 million, medical robots are the most valuable service robots. The most relevant application remains robot assisted surgery and therapy with 994 units sold in 2011, 14% more than in 2010. As regards disabled assistance robots, in 2011 a starting point for the market seems to have been set, with 156 robots sold up from 46 in 2010. Comparing to other medical robots market, this is still a small number but with a considerable growth potential thanks to several research projects that have been set up in many laboratories during the last years. In fact, considering the projections for the period 2012-2015, sales of disabled and elderly assistance robots will reach 4,600 units. Furthermore, a strong growth of the market has been forecasted within the next 20 years.

Considering the innovative human augmentation systems (which include powered exoskeletons, upper-limb powered prostheses, and ocular sensory replacement devices), a new *Allied Business Intelligence (ABI) Research* market study [38] forecasts an annual growth rate of nearly 41% between 2010 and 2020, with associated annual revenues from $29 million to more than $877 million as show in Fig.5. In particular, more than 11,000 powered exoskeletons will be shipped by 2020 and they will make up quite a third of the market accounting for sales of $292 million, with a *Compound Annual Growth Rate (CAGR)* of 68%.

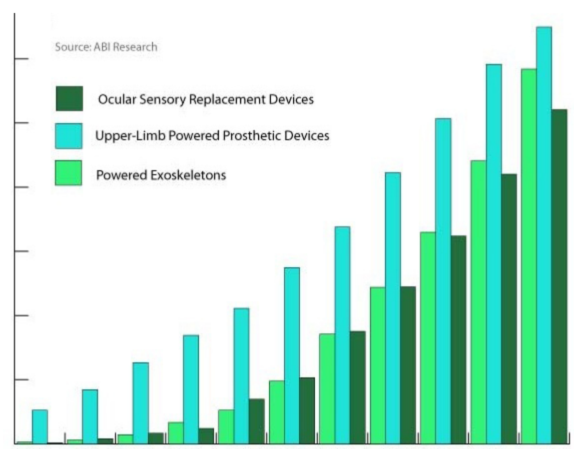


Fig. 5. Human augmentation Systems Worldwide Market. Projected Revenue 2010-2020. Adapted form: ABI Research "Exoskeletons, Powered Prostheses and Optical Sensory Devices: The Global Market for Human Enhancement/Augmentation Systems".

For the development of the necessary technologies, during the last years, many funds have been committed to exoskeletons research. For example, as regards military purpose, in March 2000 the US Defense Advanced Research Projects Agency (DARPA), began a project known as *Exoskeletons for Human Performance Augmentation*. In order to develop a full body force amplification exoskeletons by 2005, DARPA has awarded $50 million in grants to Sarcos, Oakridge National Labs, Boston Dynamics, The University of California-Berkeley and The Millennium Jet group [39]. Although important results have been reached from the technological point of view, due to their high cost of manufacture this kind of devices will be primarily used in military and medical settings. In fact, the actual selling price of the most biomedical exoskeletons ranges from $60,000 to $120,000 and make them difficult to be bought by individuals.
For this reason, many emerging exoskeleton companies are addressing to rehabilitation centres and hospitals, some of them providing only leasing contracts for their robots. This is the case of Cyberdyne, whose Robot Suit HAL is not accessible to individual users, but only to medical/welfare facilities under a rental/lease contract. Furthermore, the system can only be used by the specific subject who has successfully completed the training program [40]. On the other hand, a different approach has been adopted by Argo Medical Technologies. After selling about 65 medical exoskeletons, the company has sold about 20 devices to individuals for personal use, all in Europe, for a price of 52,000 euros ($67,230) [26]. A decrease in the price of this kind of systems could be derived from Parker Hannifin who has promised that its Indego model will be available from 2014 at a competitive price [26]. Thanks to the last technical achievements as it concerns both components features and control strategy, exoskeletons are now close to become a new impact device as demonstrated by the growing number of companies which are trying to set up a new market segment.

V. OUR PROPOSAL

Considering the current use of exoskeletons, we believe that one of the biggest obstacles to a wide spread of these technologies are the very high prices which are still prohibitive for most customers, as also reported by the *UC Berkeley News Center* [9]. The aim of our project is to give back autonomy to those who suffer from lower limbs disabilities, working firstly in accordance with the principle of social equity. To achieve this goal, we are working to realize an economically accessible exoskeleton which could be bought by a single subject. To make this possible, we have started from an already existing working prototype with the aim of improving it further. The current version of the system is shown in Fig. 6 and is the result of over twenty years of research and experimental sessions[1] conducted by its inventor Benito Ferrati, father of the first author of this paper. Studies conducted over the time have brought to a patent portfolio which currently includes, among others, a U.S. Patent. Over the years, many versions of the system were realized in accordance with the evolution of the state-of-the-art and the current device was successfully validated on four subjects with complete spinal cord injury. After an accurate evaluation, we have considered the existing prototype to be a great starting point for the development of further improvements. In fact, the system already uses a semplified mechanical design which allows to exploit industrial available components (e.g. linear actuators), ensuring the maintenance of low production costs.
The existing system, which includes two actuated orthoses, a corset and a walker, is able to assist the user during the movements of standing up/sitting down and walking straight. The pseudo-anthropomorphic kinematic design allows only two flexion-extension Degree Of Freedoms (DOFs) per leg, in accordance to the two purely rotary joints at the hip and knee. Each orthosis is actuated by two ball screw DC motors opportunely linked to the thigh and shin segments in order to convert the linear motion to a rotation of the included joint. The kinematic design allows the upper actuator to substitute the hip flexor muscle (rectus femoris) and the hip extensor (hamstring muscles group) while pulling and pushing respectively. On the other hand, the lower actuator acts as the knee flexor muscles (hamstring, gastrocnemius) while pulling and as the knee extensors (quadriceps muscle group) while pushing. This design was dictated by the desire to make the system robust and easy to use and maintain. In fact, the aim of the project is not to perfectly reproduce the human motion in all its DOFs but to use a minimalistic design to provide a simple, low-cost and useful assistive device. The electronic components and two battery packs are positioned in the box fixed to the walker in order to make the legs and trunk structures lighter and more ergonomic. This make the system easier to use and make the subject more confident.

Fig. 6. A trial session of the proposed exoskeleton.

In order to easily evaluate some mechanical modifications and cut their relative executive costs, a multibody model of the system has been developed and a simulation approach has

[1] A video of an experimental session is available at: https://www.dropbox.com/s/h5nkrvdcvejufxw/TEF_video.avi

been adopted. The mechanical caracteristics and a preliminary human-machine interaction model have been described in detail in [41]. Considering the human-centered approach involved in the use of an exoskeleton, the OpenSim[2] [42] simulator was chosen to implement and analyze the model from a biomechanical point of view. An important experience in musculoskeletal structures modelling had been developed in previous works as reported at [43]. A snapshot of the walking motion of a human-body model constrained to the virtual device is shown in Fig.7. In order to obtain effective actuators force values for the real exoskeleton prototype, within the simulation process the gait cycle movement was considered and the actuators forces were computed. The modelling approach also allowed to test some potential improvements for the existing system, evaluating their results in human walking. An active DOF was added at the ankle joint in order to achieve a greater similarity in the gait kinematics. The obtained results will be applied to effectively improve the real prototype design.

Another limit of most of the available exoskeletons is about the adopted coupling strategies to establish an active human-exoskeleton interface. In fact, the current strategy for the rehabilitation of a patient with SCI, often involves at least two physiotherapists who work togheter to support the subject's body and move his lower limbs. Besides being very tiring, both for the patient and the staff, this process is able to provide only qualitative information about the improvement of the subject, in accordance with the physiotherapist experience. To solve this limit, we are now testing a novel type of sensors network for human-machine interaction measurement, taking inspiration from [44], [45]. Being able to evaluate this quantities would give the device an additional clinic value, providing the clinician a tool through which quantify objectively the rehabilitation progress.

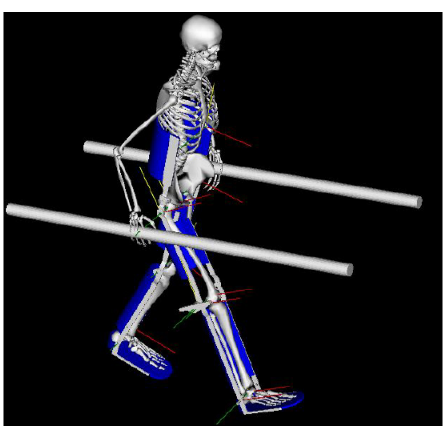


Fig. 7. OpenSim model of the human body constrained to the virtual-exoskeleton.

In order to evaluate the clinical efficacy of the device, we have already started a collaboration with the San Camillo Foundation[3] in Venice, a Research Hospital qualified as IRCCS (Institute for Scientific Care and Hospitalization) for the discipline of motor neurorehabilitation, communication and behavior. In our project we would encourage the natural constitution of a consortium of hospitals, clinic and rehabilitation facility as well as specialised companies in the perspective of creating a virtuous circle which can support the development and the market introduction of this robotic devices. A great diffusion of an economically available system would allow even smaller centres to use technologically innovative tools. Such an approach would be able to overcome the geographical barriers, allowing also patients living in outlying areas to use an advanced system, without compel them to move toward the few cutting-edge rehabilitation centers.

[2]Freely available at: https://simtk.org/home/opensim

[3]http://www.ospedalesancamillo.net/

VI. CONCLUSIONS

This paper aims to contribute to the ongoing discussion about the social and economical impacts of advanced robotics, in particular of Exoskeleton Robot devices, especially with regard to their applications in lower limb medical rehabilitation. After the introduction, which was intended as a brief summary of the state-of-the-art about the two main types of exoskeletons, for strength amplification and limbs rehabilitation, a discussion on what are the social and economic impacts that characterize these research areas in the last years was presented.

With regard to the social impact, without doubt, at the present there are no systems able to completely substitute the wheelchair for daily life usage. This because medical exoskeletons offer only an alternative way to do clinical rehabilitation, but in a future not too far they will be probably also used in a daily life environment. One of the most interesting ongoing discussion is about how we could establish an active human-exoskeleton interface in order to promote a better coupling between them with respect to the current adopted approaches. Several studies support the many benefits deriving from the use of such technology, both from a physical and psychological point of view, but also on a more general improvement of the quality of life and social participation of the subject. On the other hand, we analyzed the economical impacts. In this paper, five of the major companies all over the world, engaged in research, development and production of exoskeleton devices were considered. Moreover, the market analysis was conduced from two point of view: in the first one some data about the estimated lifetime costs in SCI were reported, and in the second one a market analysis strictly referred to the lower limb exoskeletons was provided, based on the recent data published by the main research and statistical agencies. In the last section, about our proposal, we introduced a new exoskeleton design approach intended to minimize the production costs by using a simplified mechanical structure and linear actuators already available in industry. A description of the system's virtual model was provided in order to illustrate an efficient approach to study human-machine interactions and investigate new technical solutions.

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