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I DISABILITY STUDIES: ASPETTI CLINICO-TERAPEUTICI

*DISABILITY STUDIES: CLINICAL AND THERAPEUTICAL ASPECTS*

# Lower limb wearable robots for physiological gait restoration: state of the art and motivations

## *Robot indossabili per arti inferiori per il ripristino della camminata fisiologica: stato dell'arte e motivazioni*

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Wearable robots are a class of mechatronic systems intended to exchange energy with the environment and the human body in order to attain performance augmentation as well as for assistive, prosthetic or rehabilitative purposes. In this scenario a safe physical human-robot interaction assumes a crucial role both from hardware and software points of view. Whereas the conventional design methodology is effective in several robotics fields, issues arise in the case of wearable robots. The goal of the authors is to develop a novel wearable robots design methodology exploiting the concept of embodied intelligence.

The paper starts from the description of what is a wearable robot and what are the design objectives to achieve. Then a state of the art of lower limbs wearable robots is reported. The adoption of a novel design methodology based on embodied intelligence is finally described and motivated. In conclusion, an example of the application of these new methods to a non-anthropomorphic wearable robot for gait restoration is reported.

**Key words:** Wearable robotics, robot-assisted neurorehabilitation, gait assistance

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*I robot indossabili sono una classe di sistemi biomeccatronici che scambiano energia con l'ambiente e il corpo umano allo scopo di aumentare le performance motorie dell'utente, o di assistere e riabilitare la camminata fisiologica in soggetti con problemi di deambulazione. In tale scenario è cruciale poter garantire una sicura interazione fisica uomo-macchina, sia dal punto di vista hardware che software. Le metodiche di progettazione convenzionali, sebbene siano efficaci in vari campi della robotica, non risolvono completamente le problematiche tipiche che riguardano lo sviluppo di robot indossabili. Per superare questa difficoltà, gli autori intendono sviluppare una nuova metodologia di design per robot indossabili che tragga beneficio dal paradigma della embodied intelligence.*

*Il presente articolo parte dalla descrizione generale di un robot indossabile, illustrando quali siano gli obiettivi progettuali da soddisfare. Successivamente viene riportata un'analisi dello stato dell'arte, raggruppando i robot indossabili per arti inferiori in due classi: sistemi autonomi e sistemi fissi. L'adozione di una metodologia di design innovativa basata sul concetto di embodied intelligence viene quindi descritta e motivata. Si riporta infine un esempio applicativo di tale metodologia applicata alla progettazione di un robot indossabile non antropomorfo per il ripristino della camminata umana.*

***Parole chiave:*** *Robotica indossabile, neuroriabilitazione robot-assistita, assistenza alla camminata*

## Introduction

Wearable robots (WRs) are robots worn by human operators. WRs may operate alongside human limbs, as in the case of orthotic robots or exoskeletons, or they may substitute for missing limbs, for instance following an amputation. Wearability does not necessarily imply that the robot is ambulatory, portable or autonomous (Pons, 2008). A WR can be seen as a technology that extends, complements, substitutes or enhances human function and capability or empowers or replaces (a part of) the human limb where it is worn. The exoskeleton is a species of WR. The definition of exoskeleton has been given in (Dollar et al., 2007) as "an active mechanical device that is essentially anthropomorphic in nature, is worn by an operator and fits closely to his or her body, and works in concert with the operator's movements". Robot kinematic chain is not a free design parameter for robotic exoskeletons, while WRs can be designed to have even a possibly non-anthropomorphic kinematic structure. This is in agreement with the classification given in (Guglielmelli et al., 2009). The purpose of such devices is to enhance the performance of the person wearing it, where performance can be speed, coordination or some other desired attributes. Potential uses of a WR are therefore in assistance, rehabilitation, training, and human augmentation. The strict cooperation between WR and the human body (HB) poses the accent on safety, because the physical human-robot interaction (pHRI) requires a continuous mechanical energy exchange between the human and the robot. Indeed, pHRI represents the most critical form of interaction between humans and machines in general. Under the peculiar point of view of man-machine interaction, the design of robot structure, sensors, actuators and control need to be holistically considered.

In this framework the WR design goals should be:

*Safety*: the WR should avoid unnatural or arbitrary movements, for instance excessive excursions that could hyperextend or hyperflex human joints;

*Acceptability*: the WR should adapt itself to the specific needs and ergonomic particularities of humans (Schiele et al., 2006).

## State of the art of lower limbs wearable robots

During the last five years several review papers and books on wearable robotics have been published (Pons, 2008; Dollar et al., 2008; Herr, 2009; Guizzo et al., 2005; Pons, 2010; Bogue, 2009) proving the high interest of the scientific community towards this research area, which is not as recent as one may think. Indeed, the earliest recorded mention of a device resembling an exoskeleton is described by Yagn in the U.S. Patents granted in 1890 (Yagn, 1890). This concept consisted of long bow/leaf springs operating in parallel to the legs and was intended to augment human running and jumping capabilities. Each leg spring was engaged and deformed during the stance phase of the gait and disengaged during the swing phase, thus releasing the elastic energy to the human leg. To the best of our knowledge, Yagn's device was only a smart concept, and no prototype was built. Several years later, General Electric Co. worked on the concept of human-amplifier (*Hardiman* project, 1966-1971). The Hardiman robot was more of a robotic master-slave than a real WR in the sense we intend it.

Coming to our days, lower limbs WRs can be grouped in three main categories: *stand-alone* devices, *treadmill-based* devices and *hybrid architectures*.

## Stand-alone WRs

The "stand-alone" WRs can in turn be divided in two subcategories, respectively intended for *human performance augmentation* and *mobile medical applications*.

Regarding the first class, the DARPA program, started in 2001, has encouraged the development of exoskeletons helping soldiers to carry heavy backpacks during military missions. These exoskeletons are thus for human augmentation and four of them were reported in literature as working prototypes: the Berkeley exoskeleton, the Sarcos exoskeleton, the MIT exoskeleton and the HAL (Fig. 1).

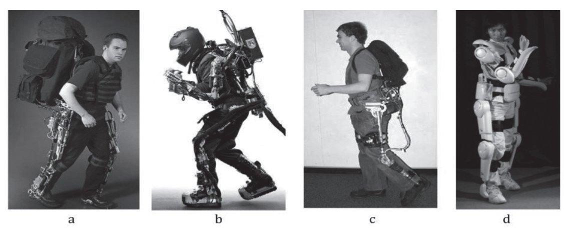



*Figure 1. Exoskeletons for human performance augmentation. (a) BLEEX, (b) Sarcos, (c) MIT exos, (d) HAL-5.*

The Berkeley Lower Extremity Exoskeleton (BLEEX), developed by the group of Prof. Kazerooni at the University of California at Berkeley (Kazerooni et al., 2006) (Fig. 1) is energetically autonomous and features three degrees of freedom (DOFs) at the hip, one at the knee, and three at the ankle. Of these, four are actuated: hip flexion/extension, hip abduction/adduction, knee flexion/extension, and ankle flexion/extension. Of the non-actuated joints, the ankle inversion/eversion and hip rotation joints are spring-loaded, and the ankle rotation joint is completely free (Zoss et al., 2006). In terms of performance, users wearing BLEEX can reportedly support a load of up to 75 kg while walking at 0.9 m/s, and can walk at speeds of up to 1.3 m/s without the load.

Similar to the BLEEX project and the Berkeley Robotics & Human Engineering Laboratory exoskeletons, Sarcos (recently purchased by Raytheon) has developed the *Sarcos XOS* designed to encompass the entire body (Fig. 1). The device, still under development, according to the goals set by the company, will walk at 5.6 km/h with a 68 kg load, run at 8 km/h, walk up a 25% grade carrying a 45 kg load, and use less than 6.5 kg of fuel to travel 100 km on level ground (Jakobsen, 2007).

A quasi-passive exoskeleton, the MIT exoskeleton (Fig. 1), has been designed in the Biomechatronics Group at the Massachusetts Institute of Technology Media Laboratory by the group of prof. Hugh Herr. This concept seeks to exploit the passive dynamics of human walking in order to create lighter and more efficient exoskeleton with the aim of replicating in WRs the achievements obtained in the field of passive bipedal walkers (Collins et al., 2005). The MIT exoskeleton employs a quasi-passive design that does not use any actuator for powering the joints. Instead, the design relies completely on the controlled release of energy stored in springs during the negative power phases of the walking gait (Walsh et al., 2007). Experimental work with this quasi-passive exoskeleton demonstrated a working device that successfully supported a 36 kg load during walking at 1 m/s. However, metabolic studies with the quasi-passive exoskeleton showed a 10% increase in walking metabolic transport cost for a subject carrying a 36 kg load via the quasi-passive exoskeleton versus a standard laden backpack (Walsh et al., 2007). While this is an undesirable result, it is thought to be the first reported study on the metabolic cost associated with exoskeleton-aided walking and, furthermore, no one has yet demonstrated an exoskeleton that reduces the metabolic cost of transport when compared to the load-carriage with a standard backpack.

The group of professor Yoshiyuki Sankai at the University of Tsukuba in Japan has developed an exoskeleton that is targeted for both performance-augmenting and rehabilitative purposes (Kawamoto et al., 2003; Suzuki et al., 2005). The leg structure of the full-body *HAL-5* exoskeleton (Fig. 1) powers the flexion/extension joints at the hip and knee via a DC motor with a harmonic drive placed directly on the joints. The ankle dorsi/plantar flexion DOF is passive. The lower limbs components interface with the wearer via a number of connections: a special shoe with ground reaction force sensors, cuffs on the calf and thigh, and a wide waist belt. Reportedly, it takes two months to optimally calibrate the exoskeleton for a specific user (Kawamoto et al., 2003). HAL-5 is currently commercialized by the spinoff company Cyberdine (Tsukuba, Japan).

The second family of stand-alone WRs is represented by rehabilitation and assistive robots called *mobile medical exoskeletons*, intended for assistive and/or rehabilitative purposes. Different from the performance-augmenting exoskeletons, which are used by healthy humans, this kind of devices is designed for persons with gait disabilities. Compared to treadmill-based rehabilitation robots, where a body weight support system keeps balance and helps supporting body weight, mobile medical exoskeletons require the patients to balance themselves, which means the patient must have a healthy upper body. The mobile medical exoskeleton should provide enough external joint torque to compensate for the lack of force in the lower body joints.


*Figure 2. Mobile medical exoskeletons. (a) Ekso, (b) ReWalk, (c) Indego, (d) REX.*

The first device is *Ekso,* designed and commercialized by Ekso Bionics, see Figure 2. The robot is intended for people with lower extremity weakness or paralysis due to neurological disease or injury (spinal cord injuries, multiple sclerosis, Guillain Barrè syndrome). The system requires the user to have sufficient upper extremity strength to correctly use crutches and the ability to self-transfer from wheelchair to a regular chair. Battery pack is attached to the system. Hip and knee joints are actuated in the sagittal plane (the main direction of the walking motion). The other DOFs at those joints are locked out or passively supported by a spring. These DOFs allow the exoskeleton to sit, walk, and stand while minimizing uncontrolled DOFs (Strausser et al., 2010; Strausser et al., 2011). Tests on the device were performed on four paraplegic patients with complete or incomplete paralysis (Swift et al., 2010) and on three chronic stroke patients (Strausser et al., 2010).

Founded in 2001 Argo Medical Technologies (Israel) has developed a robotic ambulation system for wheelchair users named *ReWalk* (see Figure 2). ReWalk is a wearable robotic device which helps paralyzed people walking. It is actuated by DC motors at hip and knee joint level assisting only the movements in the sagittal plane. The ankle joint is not actuated. Battery and controllers are attached at the back of the user. The system is designed with a remote controller, which can be used to change the motion mode of the system, such as ground walking or climbing stairs. There is a posture detection sensor at the torso to detect the upper body movement. This information is used to estimate users' walking intention and drive ReWalk accordingly. The wearer also has to use crutches for stability and safety reasons. No technological detail of the system has ever been published in the scientific literature. However the system is currently undergoing clinical trials at MossRehab (Philadelphia, PA, USA).

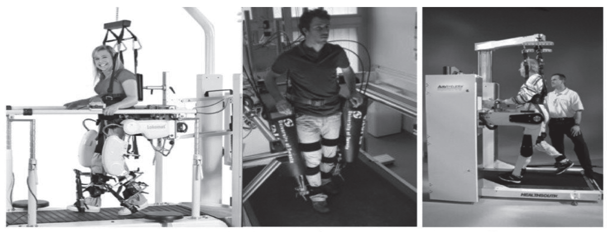
More recently, pilot clinical trials also started in Italy, at the Centro Protesi INAIL di Vigorso di Budrio (Bologna, Italy) on 18 paraplegic subjects.

*Indego* (Figure 2), produced by Parker, is the commercial version of Vanderbilt powered orthosis (Farris et al., 2011); it is a powered lower-limb orthosis that is intended to provide gait assistance to spinal cord injured (SCI) individuals by providing assistive torques in the sagittal plane at both hip and knee joints. With respect to Ekso and ReWalk, it neither includes a portion that is worn over the shoulders, nor a portion that is worn under the shoes. The orthosis has a mass of 12 kg and has to be worn in conjunction with a standard ankle foot orthosis (AFO), which provides support at the ankle and prevents foot drop during swing. A custom distributed embedded system controls the orthosis with power being provided by a lithium polymer battery, which provides power for one hour of continuous walking at approximately 0.8 km. In order to demonstrate the ability of the orthosis to assist walking, the orthosis was experimentally tested on a paraplegic subject. Experimental results indicate that the orthosis is capable of providing a repeatable gait with knee and hip joint amplitudes that are similar to those observed during non-SCI walking.

Different from the previous devices, *REX*, produced by REX Bionics (Auckland, New Zealand), is an anthropomorphic lower body orthosis designed for sit-to-stand, stair ascend and overground walking, without the use of crutches (see Figure 2). The system does not use sensors to estimate the motor intention of the user, who can control the robot by acting on a joystick. Users should have a height between 1.46 m and 1.95 m, a weight below 100 kg and a hip width of maximum 380 mm. The system has been demonstrated with healthy subjects, and for sit-to-stand of wheelchair users.

## Treadmill-based WRs

The main role of these rehabilitation therapeutic robotic platforms is to partially support the patient weight on one side and to generate symmetrical and periodic gait patterns on the other side. A technique known as "partial body weight support" usually forms the basis for lower limbs neurorehabilitation. Although not necessarily robotic, it simplifies robot-mediated lower-limbs neurorehabilitation. Partial body weight support usually requires the patient to wear a parachute-type harness that is connected to an overhead gantry and allows only a percentage of the person's weight appearing as a force on the treadmill. Data collected in (Visintin et al., 1998) showed that after six weeks of exposure to partial body weight support therapy four times a week, subjects after a stroke performed better in their ability to balance, in their motor recovery, in their ability to walk, and in their walking endurance. The disadvantage of partial body weight support is that it requires the intense involvement of the therapist, often more than one, to assist the motion of the feet. Since these are repetitive and physically demanding tasks for the therapists, robot solutions are very useful. The potential for valuable robotic assistance is further enhanced when considering the safety of the patient in a partial body weight support mechanism and the fact that an inexpert therapist may be applying higher forces and giving fewer opportunities for the task to be completed unaided. The robotic system must be designed so that it can assist on an *assistance-as-needed (AAN)* basis, much like highly skilled physical therapists perform when teaching a SCI patient to relearn to walk.



a b c

*Figure 3. Treadmill-based exoskeletons. (a) Lokomat, (b) LOPES, (c) AutoAmbulator.*

*Lokomat* developed by Hocoma, see Figure 3, has been the first mechatronic body weight support system developed to provide precise body weight unloading for patients with neurological or other impairments during treadmill training (Frey et al., 2006). The novel mechatronic design provides an active body weight support, instead of traditional fixed one. In addition, a robotic exoskeleton system support hip and knee movement in the sagittal plane, while the ankle joint is not supported (Colombo et al., 2000). Gait pattern adaptation algorithms were implemented in Lokomat to realize the AAN approach (Jezernik et al., 2004).

*LOPES (LOwer-extremity Powered ExoSkeleton)* is a treadmill-based wearable robotic device for gait training and assessment of motor function in stroke patients (Veneman et al., 2007), developed at University of Twente by the group of prof. Herman van der Kooij (Figure 3). LOPES is comprised of two parts: the adjustable lightweight frame for pelvic control actuating the two horizontal pelvis translations and the exoskeleton leg with four actuated DOFs per each leg, which assist hip flexion/extension, adduction/abduction, knee flexion/extension and ankle dorsi/plantarflexion. The development of the device started in 2001 and since then has been used with healthy subjects as a neuroscientific tool to investigate motor learning and more recently with chronic stroke patients to validate the device as a tool for neurorehabilitation. Studies were presented to demonstrate the ability of this rehabilitation tool to restore an improved kinematic walking pattern (improved foot clearance during swing) after a period of robot aided gait training (van Asseldonk et al., 2009).

The *AutoAmbulator* is a commercial system patented (Fisher et al., 2011) and developed by Healtsouth, shown in Figure c. The Food and Drug Administration (FDA) granted HealthSouth permission to begin using its own innovation in 2002. Though including a different mechanical design of the weight support subsystem, which reduces the weight and overall dimensions of the device, allowing also for faster don and doff times compared to the Lokomat, it essentially consists of an electrically actuated anthropomorphic device supporting hip and knee movements in the sagittal plane. The AutoAmbulator has already proven itself as a valuable tool in the rehabilitation of several patients: patients with multiple sclerosis, Parkinson's disease, a stroke, a brain or spinal cord injury or other neurological disorders may all be candidates for rehabilitation using this exoskeleton. Unfortunately, few details on the uses of this system could be retrieved in the peer-reviewed literature.

## Structural intelligence-based design methodology for wearable robots

Robots described in the previous paragraphs have been designed around the HB, only complying with a set of detailed functional and technical specifications in order to obtain a as safe as possible pHRI. Instead, the level of interaction between the WR and HB should be advantageously pushed ahead by designing the WR so that a *symbiotic interaction* occurs between it and the HB. The adjective "symbiotic" refers to the intimate physical interaction between the HB and the robotic artifact leading to *emergent dynamic behaviors* of the system comprised of "human body + robot". *Designing for symbiosis* is a kind of design for emergence aiming at producing dynamic behaviors that are useful to a given purpose (e.g. restoring proper motor abilities in chronic subjects, of whom elderly people are the most socially relevant example). Since a WR interacts with the HB but also with the external environment, besides pursuing a design to achieve the emergence of useful dynamic behaviors, the mechanical structure of the WR is intended to intrinsically manage low level issues related to the interaction with the external environment by showing proper zero-delay, intrinsic responses (i.e. *preflexes*) to a perturbation (Kubow wt al., 1999). The ability of a mechanical structure of producing useful emergent dynamic behaviors and of adapting itself to external perturbations through preflexes can be seen as whole as a form of *structural intelligence*, as an instantiation of EI.

Till now, such concepts have been explored and applied to the development of robots inspired by a large variety of biological systems, such as mammalians, fishes and insects. On the contrary, the HB has been poorly investigated from the structural intelligence standpoint, while this is a promising new route toward the development of useful machines intended for the strict interaction with humans, such as robots for rehabilitation, assistance and for the functional restoring for elderly and disabled people. In the scenarios where the robot and the HB are strictly interacting, the design of the artificial system must take into account the dynamics of the biological counterpart, which is highly variable and actively tuned by the human sensory-motor system. When strict physical interaction occurs, the dynamics of the HB and that of the robotic artefact are strongly coupled. If the robotic artefact is meant to compensate for lost body functionalities, such as proper gait generation, the proposed approach consists in finding how the robotic system must be designed to take advantage of the variable biomechanical properties of the HB.

The objective is to design the robotic system in such a way that the dynamics of the HB, especially in the case of impaired or elderly subjects, and that of the robot during interaction, symbiotically benefit from each other, exhibiting emergent dynamic behaviours which favor the performance of the desired task. This is a radically new approach, where EI is taken a step further to embrace also the potentialities of structural intelligence, in a novel yet biomimetic way. This can lead to a new generation of WRs helping HB, which are intrinsically better than those based on classical design and control paradigms.

The design approach differs from conventional methodology, in which a design is pursued that must comply with a set of detailed functional and technical specifications defined a-priori, because it is based on open-ended co-evolutionary approach shaping structure, sensory system and control. This process is performed in a simulation environment, in which the WR interacts constantly with HB, which is characterized by time-changing biomechanical properties and motor patterns, and with the external environment. To achieve the highest level of structural intelligence, topology and morphology (i.e. number of links, types of joints, links length, etc.), the dynamic properties (joints stiffness and damping, inertial properties of links), sensors number and location and the control are not defined a-priori, as it usually happens when the design starts from application based specifications. On the contrary, all these aspects are left free to co-evolve, leading to robots with novel, possibly non-anthropomorphic shapes and properties.

The chosen scenario to test the results coming from the novel evolutionary design approach is an active orthosis for the lower limbs, aimed at restoring proper walking in chronic subjects, such as aged people, because walking is a rather complex task suitable to be tackled by approaches taking advantages from structural intelligence. In this framework the authors have developed the *UCBM lower limbs wearable robot* (Sergi et al., 2011; Carpino et al. 2012; Carpino et al. 2011; Tagliamonte et al., 2013; Accoto et al., 2012) (see Figure 4) as the result of this novel methodology to design active orthoses. The robot acts in the sagittal plane actuating the hip and knee flexion/extension movements. The developed treadmill-based WR is based on a non-anthropomorphic design, and its specific kinematics provides a number of advantages, the main ones being: *i)* easier wearability: small anthropometric changes are intrinsically compensated by the capability of the robot to slightly adapt its configuration; moreover, there is no need to align robots joints to human legs joints; *ii)* dynamic advantages: the heaviest parts (actuators) can be located close to the trunk, thus reducing the oscillating masses, which would have required additional torques for dynamics cancellation. The robot is connected to the human limbs through carbon fiber cuffs able to transmit the pull/push forces from the robot to the limbs. A distributed sensory apparatus monitors the motions of the upper body to improve user intention detection. The UCBM WR integrates kinematic, dynamic and control solutions produced by a co-evolutionary optimization process, and custom compliant actuators enriching the dynamical properties of the robot so that walking arises as an emerging dynamic behaviour. The robot, furthermore, includes several mechanical regulations and cuffs sizes in order to be adapted and worn by users characterized by different anthropometric sizes. The prototype of the UCBM WR is available to be clinically tested with able-body young and elderly subjects and with subjects characterized by gait disabilities. The robot has been preliminary tested on 5 subjects in order to assess the effectiveness of the proposed design methodology and to test the different levels of gait assistance perceived by the users.

*Figure 4 The UCBM wearable robot platform during the preliminary experimental trials.*

## A shift of paradigm in robotics

While in the previous decades the approach to themes like Artificial Intelligence (AI) and more generally to robotics was dominated by a rationalistic orientation, whereby intelligence was conceived as an independent and autonomous set of instructions contained in a piece of software, nowadays a different perspective, which could be defined as a bottom-up approach, is becoming more common. The main idea of this new paradigm is to no longer consider intelligence as something restricted to the brain only, or located in a specific spot, like software, but to see it somehow spread out in the body, or, in our case, in wearable robots. This idea brings to mind the Scholastic conception of the vis aestimativa[1]: the faculty we have in common with animals to discover, without (and before) any intellectual instrument, what is good and what is bad for our welfare (Newman, 1957). In other words, the intelligence that is strongly connected to the body is a sort of art of calculating what is useful and what is dangerous in specific scenarios. This practical sense, as a specific kind of adaptive intelligence, is mostly unconscious and does not refer to logical reasoning. This does not mean it cannot be investigated by means of logic, but rather that it does not stem from superior and explicit reason.

As stated by Rodney Brooks in the foreword of (Pfeifer et al., 2006), there are some tenets of modern rationalism usually involved in the metaphors adopted to talk about intelligence (i.e. “our nervous system work as a computation machine”, “there are separate control systems for our body”, “there can truly be disembodied reasoning”). Tracing the source of the still dominant model of computation intelligence back to Turing (Turing, 1950) and his famous “Computing Machinery and Intelligence”, it is worth noting that such a theory came from considering the externally observable behavior of a human computer, a person who carried out computations with pen and paper, and “is supposed to be following fixed rules”, so that Turing modeled what a person does, not what a person thinks. It is also Turing who said that such computation is independent from the medium in which it is expressed.

What can be said after almost three decades of rationalistic-oriented science and technology? Probably it did not succeed in facing the adaptation issues connected with intelligence. The field was in dire need of a real paradigm shift. This paved the way for the “Embodied Intelligence” (EI) paradigm, whose description could be summarized briefly in the phrase: “intelligence requires a body”. Scientists have dealt less with symbol processing, internal representation, and high-level cognition, and focused instead on interaction with the real world. As the orientation shifted, the nature of the research questions also changed: the community got interested in locomotion, manipulation and, in general, how an agent can successfully act in a changing world.

The rejection of the previous computational approach can be even seen in the provocative titles of papers (i.e. Brooks’ works: “Intelligence Without Representation” (Brooks, 1987), “Intelligence Without Reason” (Brooks, 1991) or “Elephants don’t play chess” (Brooks, 1990)) meant to open a new way in the field of robotics. The new paradigm stresses the attention on the system-environment interaction, rather

[1] Furthermore, for the apprehension of intentions (which are not received through the senses) the “estimative” power and the “memorative” power (which is a storehouse of such-like intentions) are mentioned (S. Thomatis Aquinatis, *Summa theologiae*, I, q. 78, a. 4).

than on sophisticated reasoning processes. From a theoretical point of view we can always see the typical goal-oriented intelligence structure in these models, although the difference between these two paradigms lies in the meaning to ascribe to the word "goal". While the classical AI approach sees the goal as an abstract calculation power, the EI approach sees it in the ability to overcome the environmental challenges.

## Conclusions

In 2000 elderly people in Europe aged 65 or over were more than 60 million (16.4% of population). The rise in life expectancy is set to continue; combined with falling birth rates, this will accelerate the aging of the population. The EU population aged 60 and over is expected to rise by 37% by 2050. This will certainly have a great impact on the development of the wearable robotic devices.

The development of efficient robotic systems for rehabilitation and assistive purposes requires the synergistic deployment of advanced solutions from multiple aspects, including the choice of the kinematic structure, actuation systems and from a comprehensive knowledge of relevant biomechanical and neural properties of the human component. The introduction in the field of wearable robotics of the concept of EI, in particular embodied and structural intelligence, and of the concepts derived from the findings in the field of passive walkers, can lead to the design of optimal solutions in terms of kinematics, ergonomics and dynamics. The embodiment of robotic artifacts has so far been intended as a principle useful to achieve a strict interrelation between cognitive and physical processes, exploiting the interaction with the environment. Many EI robots designed so far are animal-like artificial artifacts, whose physical and cognitive functions are conceived to exploit the embodied interaction with a more or less complex and variable ecological niche. If the ecological niche is the HB, an enormous, extremely variable amount of physical, dynamical and neuromuscular properties has to be taken into account, which a robot should symbiotically exploit for a positive interaction. In order to obtain this symbiotic interaction robot topology and morphology need not to be predefined but must emerge from an evolutionary design phase in which the interaction with the physical interaction with the HB is taken into account and optimized.

Furthermore, compared to upper limb retraining, gait retraining has more repeatable cyclic operations, which favors simpler control concepts. In contrast, the engineering of lower limbs rehabilitation devices needs to be more considerate of the dynamics of gait, and the forces applied to the legs and feet need to be larger. To fulfill these requirements, wearable robots performances can benefit from a careful design of robot morphology, which is open in the case of non-anthropomorphic WRs, and can allow achieving a better dynamical interaction with the HB and with the environment.

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