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DESIGN CONCEPTS AND FUNCTIONAL PARTICULARITIES OF WEARABLE WALKING ASSIST DEVICES AND POWER-ASSIST SUITS – A REVIEW

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Abstract
In all likelihood, robotics will lead to a revolution in our lifestyle similar to internet or mobile phone. In this context, the assistive robotics is currently one of the most invested fields which leads to the design of new products with large diversity. Among of these products may be well distinguished the walking assist robotic systems which improve daily life. Therefore, it is not accidental that during the last few years a tendency to develop the robotic systems for different applications of walking and handling assistance emerged. This paper provides a design overview of wearable assist devices. We attempt to cover all of the major developments in these areas, focusing particularly on the development of the different concepts and their functional characteristics.

Key words: *assistive robotics; wearable walking device; power-assist suit; exoskeleton*

INTRODUCTION

Assistive robots have application in industrial field as well as for patients and the elderly with mobility impairments. They free people from much labor and the burdens of many kinds of manual work. There have been many approaches to the reduction of labor that do not only fully assist but also partly aid workers, such as in the use of extremely heavy payload-oriented construction equipment, which are manipulated by humans. Manual or semi-automatic machine tools are mostly used in contemporary industries. In particular, without manpower, especially without the manipulability and mobility of human limbs, full automation will be incompatible with today’s technologies. The assistive robotized devices have strong advantages given their unique features such as their outstanding physical performance, exceeding that of humans, and their agility. As a result, attempts to adopt these devices in the industrial field, especially at construction sites, indicate the use of feasible approaches to factory automation (*Okamura, et al., 1999; WRITING, et al., 2010*).
Locomotor disability is the most commonly reported type of disability. It is defined as a person's inability to execute distinctive activities associated with moving both himself and objects, from place to place and such inability resulting from affliction of musculoskeletal and/or nervous system. All over the world, several dozen million people suffer from the effects of post-polio, multiple sclerosis, spinal cord injury, cerebral palsy, paraplegia, quadriplegia, muscular dystrophy etc. and could benefit from the advances in robotic devices for rehabilitation. The temporary or permanent loss of human motor functions can be compensated by means of various rehabilitation and assistive devices. Robotic systems for rehabilitation or for assistance in daily living offer real advantages. In the last decade, the interest in this field has raised mainly due to the growing demand caused by increasing number of stroke patients. Stroke is the third most frequent cause of death worldwide and the leading cause of permanent disability in the USA and Europe. One-third of surviving patients from stroke do not regain independent walking ability and those ambulatory, walk in a typical asymmetric manner.
Worldwide statistics about locomotor disability show that in Australia: 6.8% of the population had a disability related to diseases of the musculoskeletal system, which is 34% of the persons with any kind of disability; in USA: there are more than 700.000 Americans who suffer a stroke each year, making it the third most frequent cause of death and the leading cause of permanent disability in the country. 10.000 suffer from traumatic spinal cord injury, and over 250.000 are disabled by multiple sclerosis per year; in Italy: 1.200.000 people have declared the locomotor disabilities (*Williams, et al., 1999*). The number of people with locomotor disabilities is growing permanently as a result of several factors, such as: accidents, population growth, ageing and medical advances that preserve and prolong life. Besides, it is necessary to take into account that the world population is rapidly ageing. This problem

is quite serious also in France. In 2005, one Frenchman by five was aged 60 years or older. In 2050, this ratio will be one by three. It is therefore most likely that the research in the development of wearable walking assist devices will be intensified because undoubtedly today there is a great demand for such robotic systems.

WEARABLE WALKING ASSIST DEVICES

The given wearable walking assist devices are described via innovation and technical achievements. It is also disclosed the particularities of some kinds of modern electroactive polymer actuators and McKibben type fluidic actuators which can be served for development efficient walking assist devices.
Hybrid Assistive Limb (HAL) (CYBERDYNE Inc, Japan) is an exoskeleton that is targeted for both performance-augmenting: heavy works, physical training support and rehabilitative purposes (*Hayashi, et al., 2005; Suzuki, et al., 2007*). HAL employs controller, computer, harmonic drive motors at the hip, knee, and ankle joints. Power for the motors is supplied by a battery pack mounted on the backpack. HAL system utilizes a number of sensors for control: skin-surface EMG electrodes (Electromyographic electrodes for measuring the activation level of the muscles), potentiometers for joint angle measurement, ground reaction force sensors, a gyroscope and accelerometer mounted on the backpack for torso posture estimation.
These sensing modalities are used in two control systems that together determine user intent and operate the suit. It requires AC100V electricity and can operate continuously approximately 2 hours 40 minutes. The total weight of the device is 21kg. HAL supports activities like standing up from a chair, walking, climbing up and down stairs, holding and lifting heavy objects up to 70kg. However, to date was not reported the effectiveness of the exoskeleton's lower-limb components for the improvement of locomotory function. Reportedly, it takes two months to optimally calibrate the exoskeleton for a specific user. It requires much patience to wear and difficult to maintain the quality of EMG signal for every wearing.

Fig. 1. Hybrid Assistive Limb.

BLEEX system provides a versatile load transport platform for mission-critical equipment, so it has several applications without the strain associated with demanding labor such as that of soldiers, disaster relief workers, fire-fighters, industrial and construction workers and so on.
The Berkeley Lower Extremity Exoskeleton (BLEEX) is powered by an internal combustion engine which is located in the backpack (*Chu, et al., 2005; Kazerooni & Steger, 2006*). The hybrid engine delivers hydraulic power for locomotion and electrical power for the electronics. The exoskeleton is actuated via bidirectional linear hydraulic cylinders. BLEEX consumes an average of 1143 Watts of hydraulic power during level-ground walking, as well as 200 Watts of electrical power for the electronics and control. In contrast, a similarly sized, 75 kg human consumes approximately 165 W of metabolic power during level-ground walking. The control system utilizes the information from eight encoders and sixteen linear accelerometers to determine angle, angular velocity, and angular acceleration of each of the eight actuated joints, a foot switch, and load distribution sensor per foot to determine ground contact and force distribution between the feet during double stance, eight single-axis force sensors for use in force control of each of the actuators, and an inclinometer to determine the orientation of the backpack with respect to gravity. This control algorithm essentially minimizes the interaction forces between the human and the exoskeleton and instead, utilizes mainly sensory information from the exoskeleton. BLEEX can 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. This development continues with the HULC prototype, under Lockeed Martin license.
Sarcos is a full-body exoskeleton designed for load-bearing, that results in decreasing the wearer's metabolic cost (*Huang, 2004*). Sarcos has a portable internal combustion engine to deliver the hydraulic power necessary for locomotion. The exoskeleton comprises hydraulic actuators located at the hip and knee and a linear hydraulic actuator for the ankle. The onboard computer processes data delivered from twenty sensors on each leg. Sarcos control algorithm is similar to BLEEX's where the exoskele-

ton senses what the user's intent is and assists in performing the task. The Sarcos exoskeleton is able to carry a 90 kg load.

A drawback for both the BLEEX and Sarcos exoskeletons is that an internal combustion engine may be undesirable for military applications, since the noise from the engine may give away the position of soldiers in a covert operation. Even though they can be utilized in industrial field, where the noise from the engine is not crucial, or the service personnel who is wearing the exoskeleton can be located close to the immobile power source.

Hercule (figure 2) is an exoskeleton designed for accompanying persons and providing assistance to carry and manipulate heavy loads, developed by the French company RB3D and CEA LIST Interactive Robotics Laboratory (*Garrec, et al., 2013*). It uses highly efficient electric actuators allowing the current prototype to carry a 40 kg load at 4 km/h speed with an electric autonomy of 4 hours. Only the flexion /extension joints of knee and hip are actuated.

Fig. 2. Hercule (LIST, CEA)

The controller principle is that actuated joints are providing torques to counteract the load weight. The high back-drivability of the actuators (CEA patents) is a key feature to have machine following the user smoothly. The back of the exoskeleton can transmit the load carried by the arms to the exoskeleton legs.

ReWalk (figure 3, ARGO Medical Technologies Ltd.) is a wearable, motorized quasi-robotic exoskeleton that can be used for therapeutic activities (*Goffer, 2006*). ReWalk comprises light wearable brace support suit, which integrates DC motors at the joints, rechargeable batteries, an array of sensors, and a computer-based control system. Upper-body movements of the user are detected and used to initiate and maintain walking processes. ReWalk allows paraplegic patient to walk, sit and stand-up, climb up and down the stairs. It lacks of body weight support and stability, hence for that reason there is a need to utilize crutches, to maintain upright position and balance. It might be insecure for paralyzed patient wearing ReWalk exoskeleton; in case of losing balance he/she will just fall on the ground. Similar to ReWalk by application and actuators technology is the EKSO exoskeleton, developed on Kazerooni laboratory (*Strausser & Kazerooni, 2011*).

Fig. 3. ReWalk

Walking Assist Device with Bodyweight Support Assist (Figure 4, Honda Motor) helps support bodyweight to reduce the load on the user's legs while walking. This could lead to reduced fatigue and less physical exertion (*Koshiishi, 2010*). The device comprises of 2 motors and gears, rechargeable lithium ion batteries, control computer, shoes with foot force sensors and a seat. It weighs 6.5 kg. Honda's device lightens the load on the user's legs and helps maintain a center of gravity via special mechanisms developed by the company. Walking, crouching, climbing stairs all become easier with the help of this device.

There is plenty of use cases for this product, not the least of which would be helping industrial workers, people afflicted with mobility issues or leg problems. It can also be used for rehabilitation. Despite its' advantages, still it will be uncomfortable, limiting and aesthetic for everyday life.

Walking Assistive Device with Stride Management (Figure 5, Honda Motor) is developed for patients with weakened leg muscles who are still able to walk (*Hirata & Koyama, 2012*). It is comprised with 2 brushless DC motors, rechargeable lithium ion battery, angle sensors, control computer and operates about 2 hours. A motor helps lift each leg at the thigh as it moves forward and backward. This helps lengthen the user's stride, making it easier to cover longer distances at a greater speed. Its lightweight and simple design with a belt worn around the hips and thighs reduces the wearer's load and fits different body shapes. The device weights 2.8kg with batteries.

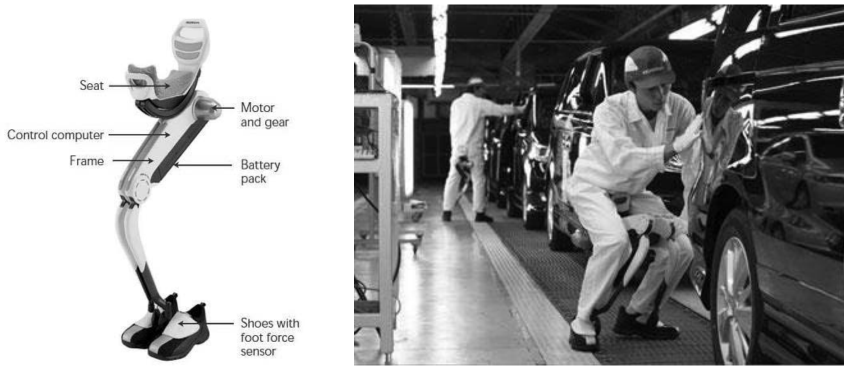

Fig. 4. Walking Assist Device with Bodyweight Support Assist.

Fig. 5. WADSM

POWER-ASSIST SUITS

Another type of wearable devices which is similar with the walking assist devices, however, the main purpose of this kind of devices is to enhance the physical competence of human instead of walking assistance. This so-called “power-assist suit” can be used for heavy load carriage, enhancement of stamina or operating heavy tools.

In some factories, workers need to operate hand tools like driller and welding gun and using these tools for long time can not only be physically exhausting but also lead to muscle fatigue and injure. An exoskeleton recently designed by Lockheed Martin named FORTIS (Fig.6) allows its operators to support heavy tools and enhancing their strength and endurance (*Lockheed Martin Corporation, 2016*). FORTIS weighs less than 12.3kg and it transfers the weight of tools to the ground through a series of joints at hips, knees and ankles. One of the great advantage of FORTIS is that it does not need any actuators (i.e. unpowered) and it can be used in different environments from factory to field work because it is a wearable device and it moves along with the operator’s natural movement while standing, bending, leaning or kneeling.

Fig.6. FORTIS

Dexterous Robotics Lab (DRL) at the NASA Johnson Space Centre in Houston developed an exoskeleton named X1 (Fig.7) in cooperation with the Florida Institute for Human and Machine Cognition (IHMC) in Pensacola (*Rea, et al., 2013*). Initially designed as a mobility device for people with paraplegia, X1 had been tailored as an in-space countermeasures device and a dynamometry device to measure muscle strength. The X1 exoskeleton currently has four active degrees of freedom (DOF) at the hips and the knees, with powered movement constrained to the sagittal plane which can assist or resist human movement. It also has six passive degrees of freedom for abduction and adduction; internal and external rotation; and dorsiflexion and plantarflexion. Any of these passive DOFs may be left free to move or locked out to intentionally constrain movement.

Fig.7. X1

These previous mentioned exoskeletons are all fabricated by rigid frames and linkages, connected with wearers at certain position on their body via pads, straps or other linking mechanisms. Therefore, these rigid links will add considerable inertia while users move their biological joints, and this impedance must be compensated by motors or by users themselves. Furthermore, during the movement, the misalignment between user’s body and exoskeleton can be up to ±10cm, even if the exoskeleton was well aligned at the start of movement, and this misalignment will cause pain or even injury to the user (*Schiele & van der Helm, 2013*).

To solve this problem, a new way of design exoskeleton is to use soft materials to fabricate a cloth-like “Exosuit” and add actuated moments to the joints which need to be assisted. Because of using soft materials like fabrics and cables, the exosuits much lighter than the exoskeletons, therefore, only a little inertia is added to the wearer’s movement. Additionally, since there is no rigid joints or frames exist in exosuits, so there is no problem relating to the joint misalignment. Unlike conventional exoskeleton, Exosuit does not contain any rigid elements which can transfer loads to the ground, hence the wearers must sustain all the compressive forces by their own bones.

Fig.8. Soft exosuit actuated by pneumatic actuator.

Fig.9. A cable-driven exosuit.

Recently, two prototypes of exosuit have been designed by several researchers from the Wyss Institute for Biologically Inspired Engineering at Harvard University. The first one is a lower-extremity exosuit actuated by custom Mckibben style pneumatic actuators (Fig.8) which can assist the hip, knee and ankle (*Wehner, et al., 2013*). The actuators attach to the exosuit through a network of soft, inextensible webbing triangulated to attachment points. Because of the use of soft material, this exosuit itself (human interface) weighs only 3.5kg, and experiment shows that it can comfortably transmit joint torques to the user while not restricting mobility. However, it also has some drawbacks like the air supplier is not portable which can limit its mobility.

The second one is a soft cable-driven exosuit (Fig.9) that can apply forces to the body to assist walking (*Asbeck, et al., 2013*). The exosuit is fixed on the body by straps and actuated cables can generate moments at the ankle and hip with magnitudes of 18% and 30% of those naturally generated by the body during walking, respectively. The geared motors are used to pull on Bowden cables connected to the suit near the ankle. Like the first design, the worn part of the suit is extremely light, hence the suit's unintentional interference with the body's natural biomechanics is negligible.

CONCLUSIONS

The review showed that there are some limitations related to the development of wearable walking assist devices. One of the largest problems facing designers of these devices is the power supply. There are currently few power sources of sufficient energy density to sustain a full-body via a wearable device for more than a few hours. Initial wearable walking assist devices experiments are commonly done using inexpensive and easy to mold materials such as steel and aluminium. However steel is heavy and the device must work harder to overcome its own weight in order to assist the wearer, reducing efficiency. The aluminium alloys used are lightweight, but fail through fatigue quickly. As the design moves past the initial exploratory steps, the engineers move to progressively more expensive and strong but lightweight materials such as titanium, and use more complex component construction methods, such as molded carbon-fiber plates. Carbon nano tubes are light weight, 10 times stronger, and more heat resistant than titanium. The powerful but lightweight design issues are also true for joint actuators. Standard hydraulic cylinders are powerful and capable of being precise, but they are also heavy due to the fluid-filled hoses and actuator cylinders, and the fluid has the potential to leak onto the user. Pneumatics is generally too unpredictable for precise movement since the compressed gas is springy, and the length of travel will vary with the gas compression and the reactive forces pushing against the actuator. Generally electronic servomotors are more efficient and power-dense, utilizing high-gauss permanent magnets and step-down gearing to provide high torque and responsive movement in a small package. There are several muscles that flex the leg at the knee joint. Thus, the flexibility is another design issue, and which also affects the design of shell space suits. It is important that the walking assist device does not interfere with the movement of a leg during walking and designed joints will be flexible enough.

Thus, several challenging topics exist with regard to the development of wearable walking assist devices

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