The Proceeding of the Research on Human Exoskeleton

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Abstract—Human exoskeleton robot, also named as wearable robot, is a man-machine automatic electromechanical device, which can enhance the wearer 's athletic ability and assist the wearer doing some work with the aspects such as high strength and high-speed without feeling tired. This paper presents an overview of the technology in the recent decade at home and abroad, sorted by kinds of driven methods, and focused on several sophisticated devices. The key technologies and obstacles are also discussed in the paper.

Keywords-exoskeleton;biped;robot;biomechanics; rehabilitation

I. INTRODUCTION

The exoskeleton, whose initial definition comes from biology, is a hard shell surface covering insects or beetles body, and it plays a role in protecting and supporting the animal. The human exoskeleton, which first appeared in the works of science fiction, is a special armor with power and is dressed in human body to improve the fighting capacity of the people. The exoskeleton not only can play a considerable role in the medical, industry, mining and other fields, but also can play an important role in the disaster relief, battlefield rescue, logistics readiness and other military applications. For example, it can rehabilitate the disabled and rejuvenate the old.

Exoskeleton technology, which belongs to the humanoid robot research, is a long-term research focus in academic circles. In recent years ,study on exoskeleton technology is very active and has a number of exciting results. This paper classifies and summarizes the current research results, and discusses the main problems of the technology.

Because there is no authoritative classification to the exoskeleton technology, so it is often classified according to the general structure, function, energy and different actuation type: upper and lower extremity exoskeleton based on structure, the exoskeleton of bearing type and the exoskeleton of speed type based on function, hydraulically, pneumatically, electrically and newly actuated exoskeleton based on actuation type. The current study is mainly the bearing lower extremity exoskeleton, and the related research results are relatively abundant, so this paper mainly introduces the representative achievements.

II. HYDRAULICALLY ACTUATED EXOSKELETON

A. BLEEX

Among hydraulically actuated lower extremity exoskeletons ,the research result of America University of California at Berkeley is the most significant . Under the support of D APA (America national defense pre research agency) ,Professor Kazarooni and his research team developed the BLEEX exoskeleton system[1] in 2007,which was an active lower extremity exoskeleton, walking for 4 hours at the average speed of 1.3 miles per second while carrying a load of 34kg.

The BLEEX has a total of 15 degrees of freedom, and each BLEEX leg has 7 degrees of freedom[2] to achieve the hip abduction adduction and flexion and extension, knee flexion and ankle toe stoop flexion, of which only four are powered by the hydraulic cylinder and the other joints are passive elastic elements to reduce muscle endurance.

In the energy selection, BLEEX researchers made many attempts and eventually they selected the small internal combustion engine used in project. Kazarooni considers that the fuel is still the energy which has the greatest energy ratio. The drive system weighs 27kg and its pressure is 6.9MPa, but its execution efficiency is only 14%[3].

Figure 1. BLEEX system of University of California , Berkeley, USA

The control of BLEEX system selected the known sensitivity amplification control (SAC)[4] method, defining the transfer function of force applied by human to the exoskeleton output as sensitivity function,obtaining and controlling human motion state by sensors. The shortcoming of SAC is high sensitivity and low robustness of the system ,leading that this method is strictly dependent on the dynamic model of system. Therefore, the research team conducted a number of experiments to get the parameters of system [5][6]. In order to fully perceive body state, the system used a large number of sensors: a total of 16 accelerometers, 10 encoders, 6 force sensors, 12 foot pressure switches, 1 pressure unit and 1 inclinometer.

The success of BLEEX system once caused a sensation, widely reported by the media, because it was the first active leg exoskeleton to actually work. Although BLEEX is quite complex, has low efficiency in the implementation of the system, greatly constraints human motion, and has no practical value both from the structure or the control and drive system, the engineering level of the whole system is high and all components are closely together. In addition, the wearer ,wearing BLEEX with a load, does not need special training, also does not need to make any changes to the control algorithm, and its creative explore is very commendable.

B. ExoHiker

After the BLEEX system, the research team conducted a number of experiments on the system, made comprehensive improvement of the system and launched two exoskeleton systems ,having more practical value: ExoHiker and ExoClimber ,respectively in January and October, 2005[7].

ExoHiker weighs 14.5kg and could carry a load of 90kg,having little noise. It is suitable for the human whose height is between 1.65 ~ 1.91m,and the pilot could walk for 68km at the average speed of 4 kilometers per hour while carrying a load of 68kg. In the walking , ExoHiker can achieve all control through a simple LCD controller. ExoClimber is actually a high power version of the ExoHiker, and it could not only help people transport heavy loads over flat terrain for long distance, but also be used for the rugged mountain road. Further more, ExoClimber ,whose noise size is similar to the office printer, weighs 23kg and could carry a load of 90kg. The researchers conducted a snow walking test on the exoskeleton ,and when wearing the ExoClimber and carrying a load of 45kg, the distance of snow walking increased by 900%.

(a)ExoHiker (b)ExoClimber (c)HULC

Figure 2. The second generation exoskeleton of Berkeley and HULC

The performance of ExoHiker and ExoClimber was confirmed by Natick soldier Center, having an independent third party test on ExoHiker and ExoClimber. At the end of 2006,the researchers had the oxygen consumption test on ExoHiker and ExoClimber, and it indicated that when the soldiers walked at a speed of 3.2km/h ,wearing exoskeleton without load ,the oxygen consumption was reduced by 5% ~ 12%;when walked at a speed of3.2km/h, carrying a load of 37kg, the oxygen consumption was reduced about 15%.

TABLE I. THE COMPARISON BETWEEN BLEEX AND EXOHIKER

	BLEEX	Exohiker
weight	70[kg]	14[kg]
load	34[kg]	90[kg]
Working time	3[hours](4[L] diesel)	96[hours](0.6[kg] battery)
speed	1.4[m/s]	5.3[m/s]
The types of action	Walking slowly	walking at different speed and then running

From the public information, we know that Exohiker is quite good at variety of locomotion and robustness, and can almost follow any action of the human body, or even deliberately sudden step, squat, creeping and other movements.

After finishing the Exohiker study, the team packaged all technology to the Lockheed Martin ,who carried out technical transformation of military engineering. In 2009, the system was renamed HULC (Human Universal Load Carrier)[8] and released. On the other hand , it had some upper limb function and was expected to form the Army soldiers' equipment in a few years. Since then ,the progress of the research went into secrecy.

Exohiker (or HULC) has been the most outstanding one of all lower extremity exoskeleton systems , although there is still a certain gap to the ideal in the weight and working time etc. But the appearance of Exohiker (or HULC) makes the exoskeleton really be out of the laboratory and people see the possibility of its practical application.

C. XOS

In 2008, the USA Sarcos company (later acquired by Raytheon) developed a full body exoskeleton XOS[9]. This system weighs 68kg,and the controller judges the state of human body and gives the corresponding force feedback information to make the body get auxiliary power based on the sensor information of arm, foot, and backpack. These auxiliary power can be enlarged by several times, and the wearer with XOS could carry a heavy load of 200 pounds , while feeling only a 20-pound load.

(a)XOS (b)XOS-2

Figure 3. XOS system of SARCOS company

In September 2010, Raytheon company developed the second generation of the exoskeleton ,XOS-2, having a heavy-fisted hydraulic drive and many sensors, actuators and controllers. The system can make the wearer repeatedly lift a weight about 200 pounds (90kg) hundreds of times, without feeling tired, and repeatedly breakdown a wood block ,whose thickness is 3 inch (76.2 mm). It is lighter, faster, and stronger than the first generation system, and its power consumption is reduced by 50%. But the biggest problem is still that the energy consumption of the system is too large and the power can not be integrated into the system by researchers. However, the leader of the project is always optimistic and considers that it is an engineering problem and can be solved completely with the improvement of the system.

III. ELECTRICALLY ACTUATED EXOSKELETON

Compared with the hydraulically actuated exoskeleton, the electrically actuated exoskeleton has following characteristics: energy conservation and simple control .There are many research institutions making research on this aspect and the research achievements of University of Tsukuba in Japan is significant.

University of Tsukuba developed HAL-1 type exoskeleton early in 1999, HAL-3 in 2001, and the commercial HAL-5 appeared at the Aichi Expo exhibition in 2005, which was a full body exoskeleton and has a total weight of only 15kg[10].

The material of the skeleton of HAL is aluminum and steel and the HAL-3 has a total of 5 degrees of freedom,:3 degrees of freedom at the hip joint, 1 degrees of freedom at the knee and 1 degrees of freedom at the ankle joint. The knee and hip joint of HAL-3 are actuated by a DC motor and the ankle joint is a spring type passive joint, which plays a role of stabilizing the human body. Moreover ,each actuator has a torque limiter to prevent excessive flexion and extension of the joint. The structure of the leg of HAL-5 is similar to the structure of HAL-3, but the difference is that it increases the load capacity of upper limb.

Figure 4. The HAL system of University of Tsukuba in Japan

The control signal of the HAL is from the EMG sensor, which is on the skin near flexor and extensor of various joints to control actuator to generate a torque equal to the muscle contraction torque so that the movement of the exoskeleton is similar to the movement of human muscle. The HAL controller is a small PC machine and uses a wireless network card. Moreover, the PC machine and the battery are arranged in the waist and back.

At present, HAL is mainly applied to civilian, such as medical care and assistive walking. It is the first commercial exoskeleton robot in the world, but the signal measurement of EMG sensor is not stable, motor drive method greatly limits the output power of the HAL, and its bearing capacity can not be compared with the bearing capacity of hydraulic system.

Besides HAL, Nanyang Technology University of Singapore[11], Hanyang University of Korea[12] ,America Florida human cognitive Institute[13], Tokyo University of agriculture and technology[14], Tohoku University of Japan[15] ,respectively developed electric exoskeleton system of their own during 2005 ~ 2009, and their implementation technology have different characteristics, but are at the exploratory research stage.

(a) Singapore (b)America (c)Korea

Figure 5. Kinds of experimental devices of electrically actuated exoskeleton

In addition to the exoskeleton, which is used to enhance exercise capacity of the health, there are electrical prosthetic systems developed by research institutions. Strictly speaking, the disabled limb does not have the basic ability to exercise, this is why prosthetic system cannot be called an exoskeleton and can only be counted as a biped robot system. However, the research on electrical prosthetic system and the exoskeleton only have differences in their control systems, so it still has a very good reference value in structure, energy and other aspects.

IV. PNEUMATICALLY ACTUATED EXOSKELETON

Pneumatic is another commonly industrial drive method and has been used in the exoskeleton. The biggest characteristic of the pneumatic system is that the actuator itself has certain elasticity, good coordination with body movement and small impact.

In 2002 ,Japan Kanagawa Engineering University developed the Wearable Power Assist Suit (WPAS)[16],which was mainly used to help the nurse to take care of the the patient who had a larger weight or was unable to walk. The nurse could hold the patients of 30kg ,if he wore the Wearable Power Assist Suit. It was composed of a miniature air pump, a portable Ni Sn cell and an embedded microprocessor, and the upper arm, waist and leg joints were rotary pneumatic actuators.

In 2008, the exoskeleton studied by Brussels University in Belgium adopted pleated pneumatic artificial muscle (PPAM)[17] and only the knee had a actuator. In addition， the control method was PSMC based on agency. But this is in the research stage at present, and only one leg has been developed.

(a) WPAS (b) the exoskeleton of University of Salford (c) PPAM

Figure 6. Kinds of pneumatically actuated exoskeletons

University of Michigan of America developed a ankle prosthesis[18] in 2005 , whose shell was made of carbon fiber material and whose weight was only 1.7kg, and the wearer could quickly adapt to the prosthesis. Experiments showed that this exoskeleton could improve the ability of the ankle muscles.

In 2010, Polytechnic University of Turin of Italy developed a pneumatic interactive gait rehabilitation orthosis (PIGRO)[19] and its total weight was 18kg. The control method was fixed gait, relatively simple, and it could only be used for the assisted recovery, not active walking.

V. PASSIVE EXOSKELETON

Passive exoskeleton is a kind of exoskeleton ,not relying on external energy, but only relying on the allocation of body's own energy to enhance part of the motor ability . Due to lacking of energy system , passive exoskeleton has a light structure and its theoretical work time can be infinite, but the drawback is that it need to change the way of human locomotion in most cases, and could not achieve the enhancement of the full range of sports ability.

In 1992,Applied Motion company of America developed a walking exoskeleton device ,Spring Walker[20]. The Spring Walker adopts spring as power and can jump forward. The fastest speed is up to 35 miles per hour (about 56 km), and the height of its jump is up to 5 feet (about 1.52 meters). This achievement provides new ideas for the structure design of the exoskeleton device.

In the second stage of DARPA EHPA project, Massachusetts Institute of Technology put forward the concept of passive exoskeleton[21] and made a number of researches. One of passive exoskeletons weighs 11.7kg, and it only consumes power of 2W when walking with a load. When it carries a load of 36kg at a speed of 1m/s , 80% of the load will be transmitted to the ground through the exoskeleton, but the oxygen consumption will increase 10%.

In 2008, this exoskeleton was modified to be a passive exoskeleton for knee joint[22], which weighed about 2.5kg and adopted the SEA actuator. Therefore, this exoskeleton needed to consume electric power about 150W, which belonged to the passive exoskeleton partly.

VI. THE CURRENT PROBLEMS AND FUTURE DEVELOPMENT OF EXOSKELETON SYSTEM

It took nearly half a century for the exoskeleton system from the birth of the concept to practical exploration. Although the current development of the exoskeleton system is in the ascendant and the distance to the ideal of human is more and more closer, there always seems to have a few problems unresolved because of not having a clear understanding to the difficulty of the development of the exoskeleton system.

The exoskeleton system is a subsidiary system of human body, and its motion control method must be able to strictly follow the movement of the human body without interference and provide the auxiliary energy when needing power output of the muscle, as we know this is actually a very high demand for the control system. But the law of human movement involves the advanced brain thinking, and the understanding in this area is still very superficial. Even though we adopt the latest control theory , any summarized law of motion may be deliberately broken. Therefore ,the control of exoskeleton system is not simple transplant of robot control system which is independently working, and it need to be thoroughly studied. This is the core problem in the current development of the exoskeleton system.

Besides the control system, an important bottleneck is the driving technology. All kinds of mature driving schemes, which we know, have defects such as large volume, heavy weight, large noise and high energy consumption, and drivers can't be compared with human muscle, so the research and application of new drivers are imminent problems for the exoskeleton system. At present, the electro-strictive polymer artificial muscles, which is still at the laboratory stage, is the hope ,and the development of this technology is very worthy of attention. In addition, the study on elastic passive energy storage device and piezoelectric, magnetic drive technology also has a strong reference value.

The problem of Energy system is that the density of the battery energy is too low. It is generally thought that it is very useful that the battery quality is controlled within 5kg and the work time of the power supply is more than 8 hours for the body carrying system . Although the energy density of lithium ion battery and fuel cell continues increasing, having exceeded 300Wh/kg,it is still far from the demand. The requirements of the exoskeleton system for battery power is rather special, and the battery not only can ensure long time output of small power (such as traveling, loading), but also has the ability of instantaneous high power output (such as running, jumping, etc.) .In the current technology level, the composite systems of lithium ion battery and super capacitor may satisfy the harsh requirements more possibly.

There are a lot of problems in the flexibility and portability of the structure of the system, and there are no systems that can really make people feel comfortable. It is now generally believed that the structure of the exoskeleton system should be same to the structure of human body, which is the premise to ensure there is no interference between the systems, but it has been found that too much freedom would not only increase the complexity of the system, but also greatly increase the system's instability. In fact, determining the number of degrees of freedom and active joint of the system not only need to have an in-depth understanding of the anatomy, also need to analyze and summarize the movement process of body, muscle work mode and the buffer process in biomechanics , but the research progress of the biomechanics is still statistical conclusions and qualitative analysis, which is difficult to provide strong technical support for the exoskeleton design. On the other hand, human body structure has typical characteristics of parallel mechanism, so the design of the structure system need to be introduced into parallel mechanism design and analysis methods. But the related research has not been reported.

In short, although the exoskeleton system has obtained a very big development in recent years, it also encounters a big problem. Even though the exoskeleton system integrates the latest achievements of sports biomechanics, kinematic of machinery, material science, as well as energy, drive, control, the technical level is still far from practical use on the whole. It is clear that the exoskeleton system is certainly more advanced than the robot system. As a external interfering system, it must be able to perceive and respond to the movement of human body, and also to convert energy into suitable power output to match the motion of human body. These challenges are more greater than the original fancy, and they need the progress in related fields as the foundation. Predictably, exoskeleton technology still has a long way to go, but the progress in any related field is likely to accelerate the pace of progress of the exoskeleton technology.

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