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Proceeding of Human Exoskeleton Technology and Discussions on Future Research

LI Zhiqiang[1, *], XIE Hanxing[2], LI Weilin[1], and YAO Zheng[1]

1 *State key Laboratory of Reliability and Environmental Engineering Technology, Beihang University,*
Beijing 100191, China,
2 *School of Reliability and System Engineering, Beihang University, Beijing 100191, China*

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Abstract: After more than half a century of intense efforts, the development of exoskeleton has seen major advances, and several remarkable achievements have been made. Reviews of developing history of exoskeleton are presented, both in active and passive categories. Major models are introduced, and typical technologies are commented on. Difficulties in control algorithm, driver system, power source, and man-machine interface are discussed. Current researching routes and major developing methods are mapped and critically analyzed, and in the process, some key problems are revealed. First, the exoskeleton is totally different from biped robot, and relative studies based on the robot technologies are considerably incorrect. Second, biomechanical studies are only used to track the motion of the human body, the interaction between human and machines are seldom studied. Third, the traditional developing ways which focused on servo-controlling have inborn deficiency from making portable systems. Research attention should be shifted to the human side of the coupling system, and the human ability to learn and adapt should play a more significant role in the control algorithms. Having summarized the major difficulties, possible future works are discussed. It is argued that, since a distinct boundary cannot be drawn in such strong-coupling human-exoskeleton system, the more complex the control system gets, the more difficult it is for the user to learn to use. It is suggested that the exoskeleton should be treated as a simple wearable tool, and downgrading its automatic level may be a change toward a brighter research outlook. This effort at simplification is definitely not easy, as it necessitates theoretical supports from fields such as biomechanics, ergonomics, and bionics.

Keywords: exoskeleton, robot, biomechanics, ergonomics, bionics

1 Introduction

The human exoskeleton is a kind of electromechanic system originally coming from comic stories. It can give human an extra strength to resist fatigue or to take more weight, to run faster or to jump higher. These kind facilities are drawn to be a lightweight armor worn by human, and its power system will output energy instantly whenever any muscles need some assistance to perform hard works than usual. Conceivably, the achievement of exoskeletons will be actively involved in life, especially for peoples disabled or wounded, and it might be evolved to be sport or amusement tools with great commercial value.

Inspired by this promising outlook, studies of the fantastic wearable equipment have been going on for more than fifty years. Among the most enthusiastic are defense departments, who were willing to invest millions to such development. The more a soldier could carry, the more combat ability he had. According to the US military standard, a soldier is allowed to carry up to 30% of his overall weight when marching, and this limit is set to 245 N for PLA[1]. However, thanks to modern powerful firearms and equipment, soldiers' loads tend to significantly exceed these limits. This is particularly true in the case of Special Forces, who usually carry out tasks in difficult situations with little logistic support.

In the late 1960s, the *General Electric Research* developed and tested a body amplifier prototype based on master-slave system, called "Hardiman"[2–3]. It was a huge hydraulically driven system (weighting more than 5900N), and was only able to raise one arm. This system remained incomplete at the time of its termination. Several research projects were conducted by Prof. Vukobratovic in *Serbia* in around 1970s[4–5], and similar works were done at *MIT* beginning from around 1980s[6]. However, few studies were done during the next 20 years because of fundamental technological insufficiencies, especially in control hardware.

At the end of the 20th century, with the rapid progress in computer science, as well as control and drive technologies, *DARPA* believed that the technological basis was already

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* Corresponding author. E-mail: leezhq@buaa.edu.cn

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sufficient to restart the exoskeleton project. They launched a 7-year project called EHPA[7], with a total investment of 50 million dollars, and expected it to enter service within the next decade. Since then, the research of exoskeleton has seen a major revival.

Besides the U.S. army, many other colleges and institutes in Japan, Russia, the U.K., German, Korea and Singapore also started their own projects. Hundreds of exciting results were published during the first several years of 21st century, which fostered a general optimism that the "Iron Man" would soon be seen walking the streets.

However, development of the exoskeleton was bogged down and few achievements were reported during the following years. Several reviews in 2008 and 2009 introduced latest progress[8–10], and discussed directions of future developments in an optimistic tone still. However, the technological difficulties were far greater than expected: many engineering problems previously regarded as nonessential turned out to be major challenges.

So what exactly is exoskeleton? Why are there always some "small" problems keeping it from being practical relevant? It is time to look back and critically reconsider the researching routes that have led to this predicament. The concept of exoskeleton and the range of its research should be redefined to adapt accurately to the current human science and technology level.

This article maps the developing history of exoskeletons, both active and passive, focusing on several most important achievements. Some key difficulties in control algorithm, driver system, power source, and man-machine interface, which, from the very beginning, have prevented researchers from creating the perfect exoskeleton, have been summarized and discussed. At the end of the article, a critical assessment of the traditional robotics-oriented researching methods and contemplations about possible future directions of research are presented.

2 Researches on Exoskeleton

At present, research directions of exoskeletons can be divided into two categories: active and passive, based on the criterion whether the system has a portable power supply or not. This section introduces developments in both categories.

2.1 Active exoskeletons

The active exoskeleton is actually a biped robot system bound to human body, and perfectly synchronized with the body's movements. Theoretically, the ability of this kind of exoskeleton is "infinite" and ideally, it could even be designed to work driven by the human mind only. The majority of current research has been focused on active exoskeletons, the most remarkable of which have been done in the US and Japan.

In 2004, the group headed by Prof. KAZAROONI from *UCB* announced the "BLEEX" (Fig. 1) system supported by EHPA project from *DARPA*. This system was sensational and widely reported, as it was the first practically functioning exoskeleton with a human being inside it.

Fig. 1. BLEEX of the University of California, Berkeley

One of the distinguishing features of the BLEEX was that it could support 333N and walk at a speed of 1.3 m/s for over 4 hours. The BLEEX featured 15 DOFs in total[11–12], covering most of the degrees of freedom of the human lower-limb joints. Therefore, its frame could perform almost all the movements the legs were capable of. Its control system adopted the SAC[13] method, defining the body force as the key sensitive factors. The controller determined the movements of the exoskeleton based on data gathered by the sensors, and thus reduces the force endured by the human body to minimum. Therefore, there were totally 46 sensors of various kinds incorporated in the system[14]. While this control strategy led to high sensitivity, its robustness tended to suffer, which rendered the system highly dependent upon active models, and which necessitated a large number of experiments to optimize all the parameters[15–16]. The BLEEX used a small diesel engine as power supply, and was packed a 4 L fuel tank[17], because the team leader believed that hydrocarbon fuel was still the lightest energy source available. The entire power system weighted about 265 N (27 kgf), working pressure was 6.9 MPa on average. However, the power efficiency of BLEEX was only 13%[18].

The BLEEX was rather complicated in terms of structure and control system, which limited its user's movements to no more than walking in a rigid gait at a very low speed. Even with further optimization, it was unlikely that the BLEEX could enter people's daily life. Still, the BLEEX was designed and produced at such a high engineering level that it was felt like a consumer product rather than a rough prototype come out of a laboratory. Also, the BLEEX was easy to wear, and its control system could learn the wearer's pace, and therefore no special adjustment was needed to adapt the system to suit individual wearers. Even though its awkward gait kept people worried that they might fall down, and so a safety rope had to be tied to the ceiling all the time in testing, it was really the first genuinely functional exoskeleton. The originality of the team should be highly appreciated.

After numerous experiments on the platform of the BLEEX conducted by the same team[19–20], the system was improved comprehensively and evolved into the ExoHiker, in January 2005[21].

The ExoHiker was driven by hydraulic-pressure, same as the BLEEX, but its control strategy was greatly simplified. The active control strategy had been redesigned as a joint follow-up control. This simplification reduced the weight of the system by more than half. As the number of active driven joints were reduced and the control system focused on the knee joint, the ExoHiker could work for 4 hours with a Lithium-ion battery weighting only 39 N (4 kgf).

According to a independent tests performed by the *NATICK Soldier Center*, the ExoHiker system was excellent in terms of movement diversity and robustness: it could follow almost all of the body's movements, including even sudden strides, squats and crawls. Another test in 2006 showed that, when wearing the ExoHiker and walking at speed of 3.2 km/h, the wearer consumed 5%–12% less oxygen without any burden, and 15% less oxygen when carying a 360 N load. The ExoHiker is the most outstanding lower extremity exoskeleton system up to now, and its marvelous advance encouraged DARPA to bring it from laboratory to battlefield.

It was unfortunate that Prof. KAZAROONI who had been the front runner in exoskeleton research discontinued his work, and all the documents and patents were packed and transferred to the large defense contractor *Lockheed Martin* in around 2006.

In early 2009, the ExoHiker was renamed as HULC[22] (Fig. 2) and announced to the public again. Though an upper-limb function was added in, few genuine improvements could be find in the sytstem. Afterwards, not much progress of the HULC had been reported.

Fig. 2. HULC from Lockheed Martin

Another important project supported by DAPAR, XOS, a full-body exoskeleton system (Fig. 3), was announced by the *Sarcos*(U.S., laterly purchased by the *Raytheon*) in 2005[23–24]. It employed rotary hydraulic actuators located directly on the joints instead of linear hydraulic actuators, and its controller could acquire the wearer's states with the aid of information gathered by sensors located in arms, feet and backpacks, so that the system could output corresponding inverse forces. These compensatory forces could be amplified more than ten times. For instance, with the aid of the system, people could carry a 882 N (90 kgf) load as if weights no more than 88 N (9 kgf).

Fig. 3. XOS from Sarcos

In September 2010, *Raytheon* presented a new version, XOS-2. This new system used hydraulic driven system like its predecessor, and included a large number of sensors, execution units and controllers. Wearing the system, tester could lift a 890 N (200 pounds) weight repeatedly for hundreds of times without feeling a bit tired. Testers could also smash wooden boards 76.2 mm (3 inches) in thickness. In addition, the new system was lighter, faster and stronger than ever, and reduced energy consumption by 50%. However, the main disadvantage of the XOS-2 was that it was still energy guzzler, which made a built-in energy source impossible. A ridiculous- looking tail was attached at the lower back, which kept the wearer from wandering freely. Its designer, however, believed that it was an unimportant engineering issue and could be overcome in the days to come. Up to now, reports on the XOS-2 have showed that it has been bothered by the tail all the time, and has been demoted from a universal-function field exoskeleton to a brawny aircraft loader.

Compared with the hydraulic-driven exoskeleton, those driven by electric motors possess advantages in terms of weight, price and reliability. Therefore, researches on motor-driven exoskeletons were carried out at many institutions, among which, the *University of Tsukuba* has achieved some respectable results (Fig. 4).

Fig. 4. HAL series of the University of Tsukuba

The HAL-1 was announced by the university back in 1999[25]. Its successor, the HAL-3 was finished in 2001[26], and in 2005, a commercial version of the HAL-5 was introduced in *Aichi Expo*[25]. The HAL-5 was a full-body exoskeleton with a weight only 147 N[27]. Its frame was made of aluminum alloy, with steel components in the joints. The HAL-3 had six joints, the knees and hips were driven by DC motors, and the ankles were support by passive springs, which served to stabilize the body[28]. The degree of movement allowed for each joint was restricted in accordance with the human joint's capability to prevent injury. HAL-5 had a lower-limb structure similar to that of HAL-3, and newly added upper-limb loading function.

The HAL series chiefly used the EMG sensors as inputs. Based on the signals, servo motors produced a same torsion as that caused by the tension of human muscle, which synchronized the movement of the exoskeleton with that of the body[29]. The controller of HAL used battery-powered small PCs that were equipped with wireless network cards, and located in the back of the exoskeleton. The HAL was mainly used for civil, such as nursing, and assisting the disabled in waking.

Already on the market, the HAL system was the first commercially available exoskeleton. Its defects might come from the EMG sensors, which were used to acquire bioelertric singals from muscles. Since it must be attached to the human skin, it would be influnced by body's movement and sweat, which would result in seriously affected signal quality. In addition, the DC motors could not output enough power when wearer walked at a faster speed. Technically, at the same weight level, the power output of motor-driven systems cannot compare with that of hydraulic-driven systems.

Besides of the comerical available HAL, many institutions around the world developed their own electrical exoskeletons, including LEE[30], IHMC[31], PAS[32], and WWH-KH[33–34]. These systems had their own characteristics, but they still remained experimental prototypes in labortaries (Fig. 5).

Fig. 5. Experimental devices driven by electric motors

Pneumatics is another engineering option for driving exoskeletons. The chief advantage of the pneumatic driver is it its elasticity may be helpful to prevent body from impact injury.

In 2002, WPAS[35] was presented by *Kanagawa Institute of Technology, Japan*. It was used for helping nurses take care of patients who are overweight or unalbe to walk. With the assistance of the system, nurses could carry 294 N (30 kgf) loads. The WPAS was driven by a micro pumps, which were powered by portable SN-Ni batteries and controlled by embedded micro processing units. The arms, waists and tighs were all supported with rotational pneumatic drivers[36]. A nurse equipped with the WPAS, however, turns out to be obviously too ungainly and cumbersome to work in the hospital environment.

A team at *University of Salford*, *UK*, started their researches since 1990s, and distributed an pneumatic lower limb exoskeleton in 1999[37]. An unpdate version was introduced in 2006. It applied pMA as drivers whose operative properties were similar to those of the human muscles. The diameter of pMA was only 2 cm and its length could be stretched from 50 cm to 70 cm. The whole system had 10 degrees of freedom, and its weight merely 117 N[38]. The controller gathered data from verious sensors and directed the pMAs to operate softly. Its work frequency was around 200 Hz, which enable the system to move smoothly.

In about 2008, the *Vrije University Brussel, Belgium,* announced an exoskeleton based on PPAM[39]. The two knee joints were only motor-driven component, and the control algorithm was based on PSMC method. This system was still in experimental stage: only one leg has been developed.

A team at the *University of Michigan*[40–42], *USA*, presented an ankle joints with a carbon-fiber frame driven by artificial pneumatic muscles. It weighted only 17 N, and the wearer could easily accommodate to it. Experimental tests indicated that the system could improve the ability of ankle joint muscles.

Politecnico di Torino, Italy, presented the 176 N PIGRO system in 2010[43]. This exoskeleton was driven by six air cylinders located at ankles, knees and hip joints. The drivers were independently controlled by close-loop method, in a relatively simple fashion. It was designed to be used for rehabilitation, not for active walking (Fig. 6).

Research work in China began in around 2005. With the support of the *NNSFC*, a group in *Harbin Engineering University* did some research on lower limb rehabilitation robot [44–45]. In the recent 3 years, many groups at different universities and institutes, such as the *Chinese Academy of Sciences*, *Hefei Institute of Intelligent Machines* [46–47], *University of Electronic Science and Technology of China*[48–49], *Zhejiang University*[50–51], and *Shanghai Jiao Tong University*[52–53] , have been involved in this field, and numerous papers were published at various conferences.

These projects have had some success, with their work mainly focused on the study of control methods, but few of their results were on an equal level with the world's leaders in the field.

Fig. 6. Experimental devices driven by pneumatic system

In about 2006, the project of developing of practical battlefield exoskeleton was launched by the *National Defense Department*. Teams from *Naval Aviation Engineering College*[54–55], *East China University of Science and Technology*[56–57] and *Beijing University of Aeronautics and Astronautics*[58] have joined the project successively. Hydraulic and DC motor driven systems had been developed separately for the project. The hydraulic system could walk for 2 h continuously, carrying a 294 N load, which represented the most advanced level in domestic research (Fig. 7).

Fig. 7. Engineering attempts in China

However, it is worth pointing out that the best performing domestically developed systems are still 5–10 years behind the world's more successful ones.

The main features of four of the remarkable systems described above are listed and compared in Table 1. These four represent the latest achievements in active exoskeleton development.

2.2 Passive exoskeletons

The term "passive exoskeleton" refers to the type of exoskeleton that can partially improve the ability of the body, relying solely on the energy obtained from the human body instead of any external power source. Essentially, the passive exoskeleton is a kind of spring mechanism bound to the body. It can gather the energy wasted in the walking cycle (or other body movements) and release it when needed. Because the energy supply has been dropped, passive exoskeletons are light and armor-like, easy to use, and require less maintenance.

Table 1. Features of selected systems

Parameter	BLEEX	HULC	XOS	HAL
Release time	2004.3	2009.2	2010.9	2011.1
Driver type	Hydraulic	Hydraulic	Hydraulic	Motor
Weight /N	490	235	931	216
Load /N	333	882	882	1568
Walk speed /(km • h^{-1})	4.7	11	5	4.5
Working time /h	2.0	2.0	8.0	1.5

The research on passive exoskeleton has received increasing attention from the U.S. Army in recent years. In the second stage of EHPA program[8], the *NATICK Soldier Center* launched a FFW project and drew a conceptual blueprint for 2030 (Fig. 8), which was chiefly based on passive exoskeletons. Aiming at improving soldiers' mobility and survivability, this project was probably classified. Little information on the design was available, and only several conceptual images could be found so far. The *Russian Army* has been believed to launch a secret project, Brave-21, about which very little has been reported.

Fig. 8. Conceptual exoskeleton and long term plan of U.S. Army in 2030

Springlike strength-improving devices have been widely researched and produced. Designed based on the theory of energy recycle, these products can also be categorized as passive exoskeletons.

The *APL* Company(USA) invented a kind of shoe, which had been banned by the NBA[59]. No obvious difference in shape could be spotted between these shoes and ordinary ones. But with the help of these shoes, the wearer could jump 10 cm higher. The secret of the APL was merely the four short and rigid springs located in the heel.

The *OSSUR* Corporation invented a prosthesis named Cheetah Xtreme[60] which helped the famous disabled South Africa athlete Oscar Pistorius competed in the 2012 Olympic Games (Fig. 9). It was a sleekly shaped carbon-fiber spring without any artificial control. A test comparing disabled people wearing the artificial limb with able-bodied people was conducted by Prof. Peter Burgerman from *German Sport University in Cologne*[61]. The result showed that, when running at certain speed, the wearer of this spring-like artificial limb consumed 25% less energy than able-bodied people. When up to a specific speed, the return energy from this prosthesis was close to three times higher than from the human ankle joint. The energy loss of this blade-shaped artificial limb was 9.3%, compared to the 41.4% of the human ankle joint, which means it boasted a higher than 30% mechanical advantage over the healthy ankle joint.

Fig. 9.　APL shoes and OSSUR elastic artificial limb

It is important to point out that the artificial limb is an orthotic device designed to substitute for certain abilities of the body, which is totally different from the augmentative function of the exoskeleton.

Based on the same elastic method, a new kind of plastic pad attached to sport shoes was invented by a group from the *Wolfson School of Mechanical and Manufacturing Engineering*[62]. By modifying the hardness of the pads, mechanical efficiency could be doubled when the wearer was sprinting. Unfortunately, as the stiffness of the pad could not be adjusted once they had been made, the pads were too hard for walking and slow running.

People suggest that the energy normally wasted in the course of the body's movements can be collected to generate electricity and thus power exoskeletons. A "generator shoes"[63] was designed based on this idea, but the result was disappointing. Though the power was improved to over 1.0 W, it was still too low to drive an exoskeleton.

A biomechanical energy harvesting device was published by *Simon Fraser University, Canada,* in *Science* in 2008[64]. It was a small electric generator mounted on the knee, whose frame was braced to the thigh and lower leg. It could generate an average of 5 W of electricity on each leg with minimal user effort (Fig. 10).

Further statistic results showed that the upper limit of power that could be generated without affecting the body's normal walking was no more than 15 W. In our opinion, biomechanical electricity generators have not demonstrated any genuine possibility to function as power sources for exoskeletons.

Fig. 10.　Generator shoes, energy harvesting device, and the diagram of total energy could be gathered by human

The passive exoskeleton is a relative new concept, which has been proposed to overcome the disadvantages of the active exoskeleton. The passive skeleton's ability to store energy in the course of body movements and release energy to help it wearer jump higher or run faster would be especially valuable on the battlefields, where it may increase the soldiers' chance of survival much more significantly than the ability to carry more equipment in long marches. At the same time, the passive exoskeleton's frame can be designed as a set of body armor to protect the solider who is wearing it.

Passive exoskeleton can gather "negative work" during human walking or running, and then release it when needed. Although their passive working method cannot realize our dream to become the infinite powerful superman, they have many interesting characters: structural simplicity, lightweight frames, biomechanical power supply, and direct human control. These advantages will predictably help it enter both military and consumer markets much sooner than the active exoskeleton. These advantages will predictably help it come into life much earlier than active exoskeleton, both in military and consumer markets.

If the concept is to be expanded, any kind of tool that can enhance people's physical ability can be regarded as passive exoskeleton. Shoulder pole, crutches, trampolines, springboards and vaulting poles, all these tools may provide valuable experience for the designing of passive exoskeletons. Actually, also can be regarded as passive skeletons are some kinds of entertainment and sports devices (Fig. 11), about which there are much patent literature.

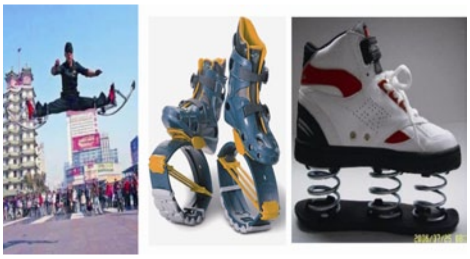

Fig. 11.　Elastic shoes and sport devices

Related studies started at least five years ago, but the achievements have been kept in secret, because of the huge potential value in both the military and consumer areas.

2.3 Key technologies of exoskeleton

2.3.1 Clinic gate analysis

Clinic gait analysis (CGA) offers the most important biomechanical support for exoskeleton designing. The movement consistency between the frame and the human limbs must be guaranteed to ensure there is no interference occurring at any time. The energy consumption of muscles when walking should also be analyzed for the designing of exoskeleton. However, gait patterns vary from person to person, and even the gait of the same individual may vary depending on one's health condition and moods. It is almost impossible to design a comprehensive working method for the exoskeleton. Therefore, the analysis of lower-limb movements is the basis for designing a walking exoskeleton system.

2.3.2 Control algorithm

Maintaining gait stability is another crucial issue in exoskeleton research. Miomir Vukobratovic from Belgrade University of Yugoslavia established the biped walking stability theory: Zero Moment Point(ZMP)[65], which is widely used in the control of biped robots. The ZMP is the point where the action line of the external resultant force intersects with the ground surface. In order to maintain the balance of the robot's body, the point should fall within the area where the supporting foot is in contact with the ground. ZMP is the only precise rule obtained from CGA and it is the most important theory in control algorithm, but it is not enough for the designing of exoskeleton control algorithms that can ensure smooth movements.

2.3.3 Power and driver issues

Power supply is always a challenge in exoskeleton research. Generally speaking, all active exoskeletons, hydraulic or pneumatic, are driven by DC motors and use batteries as power source. Limited by the current battery technology, power supplies cannot last as long as people would like them to, neither can DC motors provide enough power to drive the exoskeleton with extra loads, especially in the case of those designed for heavy military duty.

The XOS series are good examples. They are successfully both in design and control algorithm, but their development is forced to remain in the current stage until the invention of a revolutionary portable power source in the future.

Driver device is another crucial problem. All the research projects are working on efficient power and driving technologies to improve load capacity and stand-by time. Several devices can generate enough power to drive the exoskeletons, but are still troubled by problems such as oversize and lack of flexibility. The vibrations caused by hydraulic or pneumatic systems are not ignorable, and the liquid and gas storage is too heavy to carry. Up to now, none of the existent drivers can compared with the human muscles in terms of efficiency and weight.

The safety and reliability of the hydraulic and pneumatic systems are also important issues. Though right now they do not figure high on the researchers' lists of priority, the potential danger of ignoring them will materialize sooner or later.

All the problems mentioned above are still dismissed as soon-to-be-overcome technical obstacles by most researchers. Unfortunately, different from a cell phone or a radio, an exoskeleton must be a perfect piece of equipment when it enters production. Even if an exoskeleton system is capable of fulfilling its duty, it is impossible for the users to tolerate its defects in aspects such as weight, shape, endurance, reliability and safety.

3 Discussions on Current Issues and Future Development

Based on the analysis of the more than 400 papers we have examined, we can now map the current researching routes and major developing methods of exoskeletons. Current researches on active exoskeletons have been almost exclusively based on robotic technology. Follow-up control has been the focus of the study, and system integration(SI) the major method of implementation (Fig. 12).

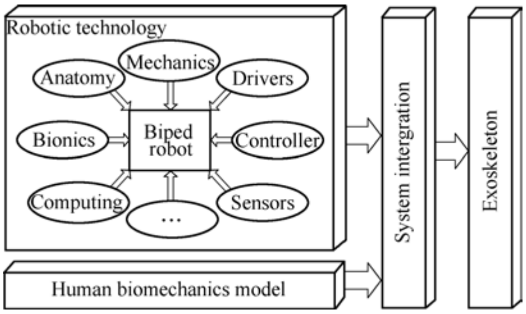

Fig. 12. Researching route for most active exoskeletons

However, the big problem here is that the exoskeleton is definitely not a kind of robot.

The biped robot is a kind of automatic electromechanical system capable of standing and walking independently, it merely "looks like" a human being. The crux in designing a biped robot is to maintain its balance when it is standing or walking. But controlling target for exoskeleton is total different from robot. The exoskeleton is a kind of strong-coupling assistance system, the controlling target of which is the accurate following of every movement of the human limbs in terms of location, velocity and acceleration. Its output power spectrum must also totally match that of the working muscles. Tracking almost unpredictable movements at multiple targets is very difficult for the controller. The control algorithm is different from, and much more sophisticated than that of a biped robot.

The algorithm of gait planning and navigating of exoskeleton is also different. Although many gait patterns have been summarized from sports biodynamic studies, it is determined by the nature of the brain that the human gait is random and unrepeatable in detail. Therefore, while these statistically obtained patterns may be of value in gait identification and stage division, they are of little help in the designing of exoskeleton control algorithms. Robots, on the other hand, can be designed to operate exactly according to these patterns, without taking any motion matching problems into account.

Researchers have found that not much can be learned from the achievements of biped robot research. Many attempts at using robot control methods have already reached the ceiling. Unfortunately, many studies are still oriented toward this direction. In our opinion, this may be the main reason for the stagnancy in exoskeleton technology.

Another major problem with current research method is the oversimplification in the biomechanical aspect. In the biomechanical studies related to exoskeleton research, the human body has always been treated as a rigid mechanical frame, and a passive target to be tracked. The interaction between human and machine is seldom taken into account. In a coupling system, sophisticated human mind shall certainly play more important roles in control strategy. This defect in the research, we believe, certainly does not result from the researchers' negligence. It is very difficult to offer a clear description of the division of work between human and mechanical system in this coupling system, and it is even questionable whether such clear descriptions exist. In this situation, the more complex the control system gets, the more difficulty it is for the user to learn to use.

Most researchers are shackled by the idea that exoskeleton should closely follow the motion of the "rigid" human frame and interference between them is strictly forbidden in design. Seldom is this question asked: "If it is too difficult to get the exoskeleton to follow the movements of the human body, why not reduce its complexity, and design it as a simple tool that people can learn to use, even if it means they need to change their gaits a bit?" We can ride a bicycle by stepping on the pedals and drawing circles with our feet repeatedly, and with the help of a pair of roller skates we can move faster by making some modifications to our usual walking gait. Human beings' ability to learn to use tools always surpasses our own expectation of ourselves. The designs in most projects still focus on the structural duplication of the human body. This tendency makes the structure and controller of exoskeleton more and more complicate, and more and more hard to be achieved.

Furthermore, though it seems that the problems of drivers and energy sources are technical ones, and the ever-emerging new advances and inventions seem to promise their solution, this is not the case.

Most known engineering driving apparatus suffer from defects such as oversize, overweight, excessive noise, and high power consumption. None of them can compare with the human muscles. A new study of electro-polymeric [66] seems to be offering hope, but it is still in the laboratories. As regards the energy sources, although the energy density of lithium cells and fuel cells has been continuously increased during recent years, it still cannot satisfy the requirements of exoskeleton in terms of both weight and safety. Moreover, the battery must the able to work for a long time at a low power output (while walking), and at certain points provide instantaneous high power output (while running and jumping). Also, structural frames are still far from satisfactory. Some testes show that no existent exoskeletons can really make the wearer comfortable, even the exoHiker, which is considered to be the best. Besides, factors such as flexibility, reliability, safety, maintenance and noise control should all be taken into consideration. Should any of these aspects fall short, it would become the Achilles' heel of the system.

Are the above-mentioned difficulties technical problems? If so, then the exoskeleton itself can also be regarded as a technical problem, for we already have bulky, heavy exoskeletons that can work for short periods of time. In fact, when a technical problem is too far away from being solved, it becomes a scientific problem. Solving these problems would involve so many fields that it goes beyond the scope of exoskeleton. If researchers of exoskeleton continue to follow the traditional robotics-oriented research roadmap, the only thing they can do is to sit back and wait for revolutions to take place in the related fields.

After more than 10 years of intense efforts and rapid advances, people are disappointed to find out that none of the technical problems that were present 50 years ago has been completely solved. Though some exciting advances have been achieved, the main barriers in aspects such as materials, controls, drivers, biomechanics and man machine engineering are still there. In 2005, in its mid-stage assessment, the DARPA realized that original target of development for exoskeleton was overoptimistic: Exoskeletons are much more difficult to develop than robot systems. Research work would have to continue for at least another 10 years, and its outcome would depend upon technical advances in the related fields.

Pessimistic prediction of exoskeleton development diverted researchers' attention to other kind of weapon system. Worth mentioning here is the "American Robot Solider", which has seen much media coverage recently. It is actually not a new concept, and does not differ essentially from traditional biped robots. Its study may help to achieve a better understanding of the mechanism of human walking, but as a combat unit, it has little advantage over a quadruped weapon platform.

Researchers of the exoskeleton need to slow down to reflect on the essence of the exoskeleton and review their research directions. In our opinion, given the current scientific and technological condition, it is impossible that the exoskeleton can be a magical outfit that turns its wearer into Superman. It is only a tool that can assist us in finishing tasks that are not too much beyond our physical capability.

Based on this idea, we suggest that the passive exoskeleton deserve more attention, not only because it possesses tool-specific characteristics such as low level of intelligentization, structural simplicity, and easy operability, but also because its concept sidesteps the problems of energy supply, driver system and control algorithm, which have been troubling scientists all the time. The passive exoskeleton therefore shows the greatest promise to become the system to enter people's daily life.

Bionics may play an important role in helping design passive exoskeletons. Studies show that, apart from their powerful muscles, another crucial reason why kangaroos, horses, ostriches and cheetahs are such good runners and jumpers is their long and strong tendons. They function just like springs which can store and release energy. If tendon-like structures could be properly integrated into the system, we might not have to wait long to see delicately constructed passive exoskeletons in the streets.

4 Conclusions

The exoskeleton is totally different from biped robot clearly, current researching routes and major developing methods have some fatal flaws. The human mind does not play an important role in the control cycle, and it deserves a more thorough research. The defects of inefficiency and bulk weight of exoskeletons are not simple technique problems, they disturbs system designers from very beginning, and will not be totally solved for a long time to come.

It may brighten up the outlook if the researchers can downgrade the automatic level of the exoskeleton and begin to design it as a wearable tool. This effort at simplification is definitely not easy, as it necessitates theoretical supports from fields such as biomechanics, ergonomics and bionics.