A preliminary study of the military applications and future of individual exoskeletons

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Abstract. In today's battlefield, soldiers are increasingly more mobile, better protected and relying heavily on information. The price to pay is that they also have to carry more and more when they are out in the field. In a harsh and hostile environment, the increasing loads can be too much or even fatal for soldiers. As a result, exoskeletons that help make faster, stronger and more endurable soldiers have become a focal point of research. With an eye on its applications in the military, we have categorized exoskeletons as two types, namely, active and passive, and examined its research status quo. We suggest that efforts be taken to further categorize exoskeletons for soldiers. And typical military scenarios where five different exoskeletons can be used are elaborated. In conclusion, we have looked into the future of individual exoskeletons in terms of its technology and roadmap of development. It is now clearer where individual exoskeletons can be used and in which direction should research efforts be made.

1. Introduction

Rapid change is seen throughout the military world and individual soldiers are the most elementary and important combat platforms in future information-based warfare [1]. In order to maintain the edge in the integrated performance of equipment, and adapt to the needs of different combat missions. Soldiers are carrying more and more combat gear, their loads being heavier and heavier. Data have shown that soldiers normally carry 20kg~30kg of equipment in their daily training. According to US Army data, soldiers carry loads of 59~68 kg in Iraq and Kuwait. However, that figure can be 59~68 kg for three-day missions in high-altitude areas like Afghanistan. They need to serve a combat tour lasting for 15 months in mountainous areas as high as 2500m to 3000m which is too much for them [2]. The penalty is that troops are greatly limited as they manoeuvre. With the development of information and digital equipment, the burden for soldiers is still increasing. The penalty is that it causes injury and leads to a large number of non-combat casualties [3]. US military personnel reported 257,000 leg strains and knee injuries in 2007. 70% of the soldiers had neck and back problems. This brought down the number of deployable soldiers. Over the past 10 years or so, the number of US soldiers discharged from active duty because of musculoskeletal problems saw a 10fold increase. Every year, more than 500 million US dollars are spent on treating soldiers suffering from...
osteoathritis, spinal injuries and other orthopaedic problems.

2. Status Quo of Exoskeleton Research
Exoskeletons are wearable robotic devices that attach to the human body and work in synchrony with the limbs. These devices make it possible to realize a coupled human–robot system that assists the human user with the capabilities and reliability of a machine while the wearer supervises the system using his intelligence and aptitude [4]. Research into exoskeletons has lasted for half a century. With the rapid development of new computers, materials, techniques and control algorithms, individual exoskeletons have also achieved remarkable progress. Because of different technologies and applicable scenarios, individual exoskeletons take different forms too. In terms of the interaction of the exoskeleton with the movement of the human body, they fall into two categories, namely passive and active. If the user and the exoskeleton is seen as a closed system and there is no consistent and steady path of energy transfer, either from the exoskeleton to the user or vice versa then the exoskeleton is passive [5,6]. Otherwise it is active [7,8]. As shown in figure 1 and figure 2.

Figure 1. Passive exoskeleton: Without a continuous path of energy transfer from man to exoskeleton.

Figure 2. Active exoskeleton: With a continuous path of energy transfer from man to exoskeleton.

2.1. Status quo of passive exoskeleton research
With this type of exoskeletons, no external power supply is needed thus it can keep operating for a long time. Supported by biological mechanics and human movement and burden mechanisms, the passive exoskeleton shifts soldier's burden to a better position by mechanical levers. Therefore, soldiers are able to carry more equipment without interfering their tactical movement.

Some developed countries have come a long way over the past years in terms of the development of passive exoskeletons. They have tested and matured passive exoskeleton technologies in field conditions. The Canadian Company, Bionic Power, developed a new passive wearable flexible exoskeleton called Power Walk [9]. It extracts energy when the knee bends for power generation with an output power up to 12W, barring the need for carrying heavy batteries when the user is out for missions in the field. The UPRISE exoskeleton developed by Canadian company MAWASHI redirects 50%~80% of the load carried by soldier's shoulders down to the ground so as to lessen the burden [10]. Soldiers equipped with the exoskeleton can crawl and climb and perform other tactical movements without being much hampered. DST Group of Australia has developed the unpowered OX non-rigid exoskeleton [11]. Weighing less than 3kg, the system uses two Bowden cables to transfer backpack loads to the ground in a non-rigid way. The average efficiency of the system is more than 50%. The K2 passive soft exoskeleton system developed by Russian company JSCGB distributes evenly the weight on shoulders to other parts of the body. Soldiers equipped with this exoskeleton system can easily carry out their missions with a 50kg backpack. Lockheed Martin of the United States successfully developed the FORTIS passive exoskeleton [12], which sends weight directly to the ground and reduces the soldier's loads of equipment. The unpowered ankle exoskeleton developed by Carnegie Mellon University and North Carolina State University can make soldiers more efficient at walking [13]. US company Suit X developed an unpowered mechanical exoskeleton—MAX
The MAX mechanical exoskeleton features a modular design. It gives robust support to the user's musculoskeletal system, enabling them to complete repetitive and intensive tasks with ease. Robo-Mate, an unpowered exoskeleton system developed by a German engineering research establishment based in Stuttgart aids the user when they are carrying out heavy-lifting tasks [14]. As shown in figure 3(a)–(h).

![Figure 3](image_url)

**Figure 3.** Unpowered exoskeletons: Based on bio-mechanical and human body dynamic loading principles, these exoskeletons transfer loads carried by the user to a better position on the body without hampering the user's movement.

### 2.2. Status quo of active exoskeleton research

Using electrical, hydraulic and pneumatic solutions, active exoskeletons power human joints in place of muscles. Based on the energy conservation law, it has the potential to lower human metabolic cost.

Active exoskeleton research has started from scratch and now entered a phase of optimization. The United States is a world leader in terms of active individual exoskeleton research. The Human Universal Load Carrier (HULC) is a lower limb exoskeleton system jointly developed by HEL, Berkeley and Lockheed Martin. The system weighs 32kg with a payload capacity of 91kg [15]. The Raytheon XOS is a wearable exoskeleton. The second generation XOS 2 system is about 50% more energy efficient than the XOS 1[16]. The Onyx system developed by Lockheed Martin weighs 6.4kg in total [17]. Its control system can sense the terrain on which the user is marching and provide effective joint assistance, no matter he is carrying anything or no. U.S. Special Operations Command introduced the Tactical Assault Light Operator Suit (TALOS) program [18]. The suit not only features an exoskeleton, but also includes liquid protection kits that can be solidified instantly, a temperature regulator, life monitoring and saving device as well as situational awareness device that strengthen the soldier's comprehensive combat capability significantly. The Guardian XO Max exoskeleton built by
Sarcos Robotics makes the user 20 times stronger [19]. There is no delay between human operation and response of the exoskeleton, which reflects the operation of the user in a direct and real-time manner. The Soft Exosuit is a typical prototype developed by Wyss Institute of Harvard University under the Warrior Web program. An evaluation conducted by the US Army Natick Soldier Centre found that the suit reduced the soldier's metabolic cost by 7.3%, and joint positive accumulative work by 13.1% [20]. The Russian Ratnik-3 individual exoskeleton system is powered by the hydraulic unit in its backpack. It can carry 95 percent of the external loads when the user is walking on flat or tilted surfaces. The Hercules exoskeleton system developed by French company RB3D is mainly composed of electro-mechanical legs, arms and back support. It can carry a load of 100kg and its battery enables the wearer to walk 20km at a moving speed of 4km/h [21]. The ASYA exoskeleton system developed by Turkish company Aselsan has its knee powering motors and transmission mechanisms placed outside the hip, thus lowering the weight of moving parts and enabling the soldier to move rapidly with the smallest resistance. The system can improve soldier's capability by 25% [22]. South Korean company LIG NEX1 has demonstrated the LEXO exoskeleton with a maximum payload of 90kg and endurance of 4 hour [23]. Japan has also attached great importance to exoskeleton technologies as part of military frontier technology research. It has proposed research plans and roadmaps. The Japanese HAL full-body exoskeleton has already evolved to its 5th iteration. It can help the user lift loads and walk[24]. As shown in figure 4(a)–(l).

![Powered exoskeletons](image)

**Figure 4.** Powered exoskeletons: After years of R&D efforts, remarkable achievements in the area of exoskeleton technology have been made in terms of power, control, materials, ergonomics. Some exoskeletons with good performance such as HULC, Onyx, HAL5 have been field tested and trialled.

### 3. Scenarios and Areas for Exoskeleton Use

It is reported that the US Soft Exosuit has been evaluated by the military. Russian K2 exoskeleton system has seen action in mine detection operations in Syria. The Canadian UPRlSE exoskeleton system also demonstrated its EOD capability and appeared in the 2019 French military parade. All of these are evidence that military exoskeletons in developed countries are moving out of laboratories to
the battlefield. China has also kept tapping into the potential of exoskeletons. After the 2015 "Unlimited Power Assistance" wearable exoskeleton contest. In October 2019, the Super Warrior-2019 Exoskeleton Contest was held in Beijing. The contest included light manoeuvring, loaded march, ammunition loading, materiel handling, obstacle climbing, trench crossing and weapons operating. All of these have pointed to the future of exoskeleton application. Future exoskeletons will have finer areas of application. Various specialized exoskeletons will see rapid development. Exoskeletons with different configurations will be used in different areas.

3.1. Marching with heavy loads on complex terrains
Heavy loads were a headache for infantry in ancient times as they still are today. During the First World War, soldiers of the belligerent countries carried 26kg on average. 100 years later, the total weight of the Land Warrior system is 45kg [25]. Moreover, the total weight of weapons system of Project-Wolf/soldier2000 (Russian) and FELIN (France) is more than 50kg [26]. Especially on complex terrains like plateaus and mountains, where it is hard for mechanical transport systems to provide timely battlefield replenishment and logistic support. Therefore, soldiers need to carry heavy loads of combat materiel and equipment, which may lead to fatigue and injury, affecting their flexibility and mobility or even causing non-combat casualty. People may think that carrying less is a solution, in fact, that is almost impossible because nobody knows what may happen next in the combat and the risks of leaving necessary equipment and supplies behind are just too high. One of the best ways for alleviating their loads is to make the same amount of loads lighter to carry via technical solutions [27]. Load-carrying mobile soldier exoskeletons are multi-functional, mobile, user-friendly and intelligent. They are suitable for carrying heavy loads on complex terrains like plateaus and mountains, where they will prove their value. And they are an effective solution for helping soldiers carry more, marching faster and longer.

It is predictable that load carrying can be used in the following occasions: individual logistic support on high altitude, mountainous and forest terrains, power assistance for high altitude border patrols, transporting important materiel through inaccessible terrains for disaster-relief vehicles, embedded chemical, radiological and nuclear defence suits which can reduce users’ labour intensity, assisted walking in low gravity environments for astronauts executing lunar or Mars exploration missions.

3.2. Light march on complex terrains
Soldiers patrolling at high altitudes have to climb mountains, which lead to fatigue and exhaustion. This affects their patrol performance and even their health. The rough terrain in mountainous areas can cause lumbar and spinal injuries as well as twisted and bruised knee and ankle joints, again disrupting soldiers’ normal patrol operations. Individual lightweight mobile exoskeletons are light, flexible and highly reliable. They can reduce soldier’s fatigue and probability of getting hurt, improve their combat capability without hampering their body movement. Therefore, they constitute an effective solution for endurance problems on complex urban, high altitude oxygen deficient and forest environments.

Individual lightweight mobile exoskeletons can be used in the following occasions: long time, long distance border patrols at high altitude, high frequency joint exercises and high intensity force-on-force drills, high intensity and long-time urban stability, counter-insurgency, EOD and other special operations as well as battlefield search and rescue operations.

3.3. Transportation of military supplies and ammunition handling
In field conditions, especially high-altitude oxygen deficient environments, it takes two times of manpower to load/unload ammunition and materiel from the truck than on low altitude areas. But the materiel is usually not suitable for being handled by multiple people owing to its size and limited working space. Soldiers lifting heavy loads repeatedly in this kind of conditions are liable to experience high altitude sickness and mood swings. As a result, they may have to leave their duty, thus affecting their unit’s combat capability. Sailors also have to lift and carry heavy loads in cramped
spaces in the ship. Materiel storage, transport and maintenance support work at logistic support bases are also more and more strenuous and frequent. Highly laborious tasks may cause occupational diseases, which reduce soldiers’ capability of providing efficient logistic support. Many artillery weapons are still loaded manually in China. And the ammunition is heavy, for example, a 155mm round can weigh 45kg. After loading several rounds like these soldiers will feel exhausted. It not only slows them down, but also may cause injury. Most small and medium sized missiles and aerial bombs are also loaded to the plane by hand. For instance, the Chinese PL12 AAM weighs 160kg and is normally loaded by 6 soldiers together. It can also cause the same problems as artillery shells. It is fair to say that how to swiftly bring military supplies to the battlefield and improve the speed of ammunition handling without causing much fatigue and strain for soldiers is a matter of success or failure. Individual exoskeletons for lifting and transporting can be used for handling of military materiel in small scale and for loading heavy ammunition. They can help soldiers lift and carry more and longer. They are highly valuable for materiel transporting (loads under 200kg), ammunition handling of big calibre guns and aircraft missile loading, especially in high-altitude oxygen deficient and cramped environments.

It can be predicted that exoskeletons of this type have the following applications: manual materiel transport along highways and railroads, small amounts of material handling in ammunition magazines, materiel handling for firing trials in test ranges and prove grounds, ammunition handling of towed large and medium calibre guns, aircraft missile loading, and shield installing.

3.4. First Aid in the Battlefield
Of those who died in the battlefield, data have shown that 90% of them died on the way of medical evacuation. It proves the saying that time is life. It is believed that the best first aid time is within 10 minutes after being wounded, and the golden time for emergency treatment is within 1 hour. Currently, stretcher teams are still the main life savers in the battlefield, which are relatively low efficient. Although state-of-the-art rescue equipment has been introduced by developed countries, including specialized rescue vehicles, aircraft and robots. But they are often denied access by harsh battlefield conditions, especially on urban, mountainous and forest terrains. Search and rescue is still a labour intensive work. If individual exoskeletons are available under these circumstances, it is then possible to evacuate and treat the wounded in a timely manner so as to up the odds of their survival. Wearable lightweight individual exoskeletons are flexible and capable of providing assistance to the upper and lower extremities. They are an effective solution to untimely rescue, barring the need for too much manpower at the same time.

Wearable lightweight individual exoskeletons can be used in the following occasions: rapid casualty evacuation, long-time medical operation assistance, fast replenishment of medical supplies, other occasions where heavy loads are to be carried or lifted.

3.5. Integrated Warfare in Modern Battlefield
In future warfare, it can be predicted that wearable exoskeletons will serve as the fundamental platform for controlling and monitoring intelligent unmanned systems to carry out reconnaissance, attack, rescue, evaluation and logistic support tasks, thus forming a smart multi-role system based on man-machine collaboration. Driven by ever-evolving technologies in the areas of sensors, new materials, 5G communications, smart sensing, decision-making and human-machine interactions, exoskeleton systems will make unprecedented progress. Ultimately, the individual exoskeleton will be made the fundamental platform for the "Super Warrior". It will be integrated with functions like joint assistance, load transportation, concealment and protection, life monitoring, medical treatment, body micro-environment. With communication, positioning, reconnaissance, weapons and medical equipment attached, exoskeletons will make soldiers stronger, with improved vision, hearing and situational awareness. They will be better protected, monitored and more adaptive. When highly autonomous systems are capable of completing tactical missions on their own, "Super Warriors" equipped with exoskeletons will mainly play the role of supervision, moral monitoring, decision-
making and supplementation. They will form a smart human-cantered mission assigning and dynamic designating system based on human-machine collaboration. These new modes of operation and tactical applications will launch a new round of revolution in the area of military technologies.

In the final analysis, exoskeletons must make soldiers carrying out combat missions feel that their loads are lightened. They must enable them to march faster, reduce their strain, improve the efficiency of rescue and enhance their combat effectiveness. When used for non-combat missions, exoskeletons must be able to reduce soldiers' labour intensity, increase their work efficiency, lower the risks associated with their work and improve their work performance.

4. Trend of Future Individual Exoskeletons

Soldier-cantered combat platforms will be increasingly important in future information-based warfare. Driven by what is really needed in the battlefield, the exoskeleton evolves as a soldier enabler. Emerging developments in exoskeleton technology offers the potential to augment the dismounted combatant’s capabilities [28]. It will improve soldiers' integrated operational effectiveness, transforming them into "Iron Men". In terms of exoskeleton technology, the key bottlenecks to breakthrough include human-machine integration and modularization, power supply and smart control. As for its development roadmap, it is suggested that the individual exoskeleton follow the path of putting fundamental capabilities in the first place and developing peripheral functions later.

4.1. Technological aspect

4.1.1. High human-machine integration and modularization will make the exoskeleton highly flexible and almost part of the user

Non-interference, safety and reliability are the most valued features of the exoskeleton. It must be capable of following the soldier's body and tactical movements like a piece of garment worn by him. It must be safe to wear and have similar configurations and joints with humans that can move with the same degrees of freedom so as to be highly integrated with the soldier. With progress in new materials and techniques, it is possible to use aeronautical aluminium alloys, carbon fibres, titanium alloys, high strength non-metallic metals, shape memory alloys and nano materials for building individual exoskeletons. These materials can make exoskeletons robust, lightweight and flexible. Meanwhile, techniques such as 3D printing, meld shaping and injection molding can be used to make bionic components for exoskeletons so that they will integrate better with soldiers. Additionally, human-machine bonding systems are also very important for human-machine integration. They serve as a bridge for human-machine interaction. More research efforts should be paid to bonding systems regarding where and how to bond, what materials and configurations should be used so as to optimize human-machine interaction. With modular design, the individual exoskeleton can be made a multi-purpose system taking on or off different modules to meet different mission needs. And it can be better integrated with soldiers in different mission scenarios. The battlefield is an ever-changing place full of uncertainties. Requirements for exoskeletons are more and more challenging. Exoskeletons for one specialized purpose can hardly meet actual needs. To make full use of exoskeletons, soldiers can choose different modules freely to equip their exoskeletons to meet different combat needs. For example, individual exoskeletons can be configured as passive exoskeletons plus joint drive units. A combination of hip, knee and ankle joint power assistance can be used when heavy loads are to be transported. On occasions of light patrol missions, only ankle power assistance is needed while knee and hip joint assisting mechanisms can be removed. For the purpose of material handling, elbow and shoulder joint power assistance can be utilized. The powered parts can be taken off when they are out of power, leaving only the passive exoskeleton in action.

4.1.2. High-efficiency drive and power supply for providing consistent power

The drive unit and power supply unit are two key parts for realizing power assistance. They are closely related with other technical features such as system weight, payload capacity, mobility, power
assisting effectiveness and endurance. In addition, the exoskeleton is worn by the soldier and follows his movements. Theoretically, the smaller its mass and inertia is, the more agile it is. Agility has always been important for individual equipment. Therefore, how to make the drive unit and power supply unit lighter, simpler whereas more efficient is a critical matter. As for the research and development of wearable drives, priorities are high power density motors, electromagnetic actuators, micro-bus servo drives, soft drive control methods and new drive component control methods. When it comes to wearable power supply, future exoskeletons not only need to provide power for themselves, but also for other attached devices, such as individual radios and tactical terminals. Although there are specialized researchers for power supply technologies, exoskeleton research teams will still be responsible for research covering modular configuration and replacement of batteries, dynamic power management and load distribution, protection of lithium batteries, application of lithium batteries in low temperature environments and application of fuel cells.

4.1.3. Intelligent control for in-depth human-machine integration

Traditionally, exoskeleton robot control strategies are based on physical signals, including load feedback [29] and position tracking [30]. These physical signals, after being fused by heterogeneous sensor systems, can be relatively accurate and global. However, they are not as timely as biological signals for reflecting the user's movement intentions. Still, they cannot rapidly send human decisions for the environment to the exoskeleton robot on complex terrains. A solution emerges with the rapid advancement of technologies for picking up brain electrical and myoelectrical signals. This, combined with the advantages that machine vision possesses for environment sensing, sets a new direction for the research of exoskeleton robot control schemes.

To solve the problem of soft motion control, algorithms for the intention perceiving layer should be developed and robust drive control methods for changing environmental rigidity and exoskeleton kinetic models should be established. Next, ways to apply machine learning and deep neural network to robotic motion control should be explored. Efforts should be paid to study online soft control methods based on artificial intelligence. Future individual exoskeletons can be controlled by brain [31]. Through the human machine interface, the exoskeleton can be connected with the soldier's brain and read his brain electrical waves, based on which the movement of the exoskeleton can be controlled. With brain-controlled exoskeletons, soldiers need not to worry about how to operate them. They can march as they normally would. The exoskeleton can be considered part of the soldier's body. This intelligent way of control helps soldiers quickly and precisely adapt to complex battlefield conditions. Besides the above-mentioned critical technologies, further research should be done in gait detection, human machine collaborated walking control measures, evaluation of power-assisting effectiveness.

4.2. Roadmap of development

4.2.1. Phase 1: topical power-assisting individual exoskeleton (before 2025)

Current individual exoskeletons are mainly of the topical power-assisting type, which includes upper extremity exoskeletons, lower extremity exoskeletons and joint exoskeletons. They are designed for some specific cases of application. This phase is a transitional period for exoskeleton development. Limited by current technologies, it will last for some time. With advancing technologies and clearer needs for exoskeletons, light/heavy exoskeletons for walk or work-assisting purposes will be developed and put into use. Their applications will include transporting heavy loads, marching with light loads, handling of specialized equipment (artillery ammunition, medium and small-sized missiles, bombs and ballistic shields) as well as other military supplies. In this phase, exoskeletons are simple in terms of functions and they mainly play role of logistic support. Those demonstrating good performance can be selected for conversion into combat equipment.
4.2.2. Phase 2: Full-body power assisting individual exoskeleton (before 2030)
When the technology of topical exoskeletons matures, a full-body power assisting exoskeleton can be developed by merging the upper and lower extremity exoskeletons. However, this is not simply the sum of them. Its technical difficulty is 1+1>2. New challenges will emerge in this phase. During this phase, full-body exoskeletons are still by and large logistic support equipment with some cooperative engagement capabilities. They can be used in long distance logistic support, close quarter combat, urban operations, special operations, individual antitank operations, individual air defence operations and battlefield first aid. In those occasions, soldiers will be able to carry more military supplies, march faster and farther.

4.2.3. Phase 3: Smart individual exoskeleton (before 2035)
In order to adapt to the ever-changing battlefield in the future, individual exoskeletons will be versatile and smart by 2035. They will become part of the next-generation integrated individual combat system. In addition to power assistance, more capabilities can be developed for exoskeletons to answer soldiers' needs in the battlefield. Soldiers equipped with the augmented exoskeletons will be able to jump farther and higher, climb faster or even perform short-range glide. Exoskeletons can be designed to include body armour and helmets, improving soldiers' survivability in the battlefield. The enhanced exoskeletons will not only be water and fire resistant, but also offer protection against small arms fire, fragments, biological and chemical contamination. Life support systems can also be added to the exoskeleton. These systems will be made from special fibre textiles with life monitors and medication administering kits attached to them. Exoskeletons equipped with these systems will be capable of monitoring soldiers' heartbeat, blood pressure and body temperature, based on which the soldiers' physical and health status can be known. Measures can then be taken to reduce their fatigue and prevent them from getting injured. The exoskeleton can also treat critical wounds so as to improve their survivability.

5. Conclusion
The next generation integrated individual combat system is a future smart human machine collaborating combat system integrated with capabilities such as new soldier weapons, situational awareness, command, control, communications and navigation, wearable power assistance, body armour and protection, life monitoring and regulation. Because of its superb performance, the individual exoskeleton is now part and parcel of the next generation integrated individual system. It is a fundamental element of the overall system and an important indicator showing the sophistication level of equipment. Future soldier systems such as the US Land Warrior, Russian Ratnik-3, French FELIN and Australian Future Soldier will all include exoskeleton systems. With the rapid advancement of military frontier technologies and the ever-evolving modes of warfare, individual exoskeletons look set to follow the development path of "handling and lifting→loaded march→light patrol→special operations". They will become lighter and more agile. Their role will shift from logistic support equipment to combat equipment. Ultimately, they will evolve into "Iron Man" type anthropomorphic suits.

6. References
[1] Yang X X, Zhao G R, Liang Y and Zhao H W 2017 The Control Theory and Application of Intelligent Carrying Lower Extreme Exoskeleton System (Bei Jing: National Defence Industry Press)
[2] Bush N E, Fullerton N and Crumpton R 2012 Telemed. e-Health 18 253-263
[3] Yu S, Han C and Cho I 2014 Appl. Bionics miomech 11 119-134
[4] Agarwal P, Deshpande A D 2019 2 234-259
[5] Panizzolo F A, Galiana I and Asbeck A T 2016 J. Neuroeng. Rehabi 13 43
[6] Mooney L M and Herr H M 2016 J. Neuroeng. Rehabi 2016 13 4
[7] Collins S H, Bruce W M and Sawicki GS 2015 Nature 52 212–215
[8] Cherry M S, Kota S, and Young A 2015 J. Appl. Biomech 32 269-277
[9] Zhou J Y, Wang J, Meng X J 2017 J. Ordna. Equ. Eng. 8 36-40
[10] Cao W 2017 Foreign Tank 9 6
[11] Zhou J Y, Mo X M and Zhang A 2016 Ordna. Equ. Eng.37 104-110
[12] Young A J and Ferris D P 2017 IEEE Trans. Neural Syst. Rehabil. Eng 25 171-182
[13] Collins S H, Wiggan M B and Sawicki G S 2015 Nature 522 212-15
[14] Stadler K S, Elspass W J and Venn H W V D 2014 ROBO–MATE: EXOSKELETON TO ENHANCE INDUSTRIAL PRODUCTION (Mobile Service Robotics: Special Session: Exoskeletons for Emerging Applications)
[15] Gregorczyk K N, Hasselquist L, Schiffman J M, Bensel C K, Obusek J P, and Gutekunst D J, 2010 Ergonomics 53 1263-1275
[16] Karlin and Susan 2011 IEEE Spectr. 48 25
[17] Geng Y 2019 Small Arms 2 15
[18] Fan Y X and Liu W 2017 Small Arms 15 14-16
[19] Strickland E 2019 IEEE Spectr. 56 27-29
[20] Mengü Y, Park Y L and Pei H 2014 Int. J. Robot. Res. 33 1748-1764
[21] Fontana M, Marcheschi S Vertechy R, Salsedo F and Bergamasco M 2014 IEEE Robot. Autom. Mag 21 34-44
[22] Xiao K 2017 Small Arms 14 54
[23] Cao W 2016 Foreign Tank 9 7
[24] Suzuki K, Mito G and Kawamoto H 2007 Adv. Robot 21 1441-1469
[25] Li H, Wang H and Zhang P 2012 J Mach Des Manuf 3 275–276
[26] Li H 2010 J Arms Equip 1 67-69
[27] Rupal B S, Rafique S, Singla A, Singla E, Isaksson M and Virk G S 2017 Int. J. Adv. Robot. Syst. 14 1729881417743554
[28] Mudie K L, Boynton A C, Karakolis T, O’Donovan M P, Kanagaki G B, Crowell H P, Begg R K, LaFiandra M E, Billing D C 2018 J SCI MED SPORT 21 1154-1161
[29] Jung S, Hsia T C A and Bonitz R G 2001 Int. J. Robotics Research 20 765-774
[30] Low K H, Liu X and Goh C H 2006 J. Vib. Control 12 1311-1336
[31] Liu D, Chen W, Pei Z, Zhong C P and Wang J H 2017 Rev. Sci. Instrum 88 104302