https://doi.org/10.47460/athenea.v4i12.57

Advances in exoskeletons for military use

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Received (5/12/2022), Accepted (13/04/2023)

Abstract. - Development and use of exoskeletons worldwide have fostered many applications aimed at occupational health care and safety in multiple areas of industry, including the military. This article presents a systematic review of advances in exoskeletons used for various tasks performed by military personnel. In addition, a systematic review of scientific literature obtained from multidisciplinary bases and the field of occupational health has been carried out. Various technologies and exoskeleton designs assist in specific areas of the body where exertion can cause musculoskeletal disorders. Exoskeletons provide additional torque to multiple joints decreasing physical fatigue and increasing performance in physically demanding tasks. Most exoskeletons used in the military employ electric actuators and have been developed for the hip and knee region.

Keywords: Exoskeleton, assistance, physical performance, military activities, physical demand.

Avances en exoesqueletos para uso en el ámbito militar

Resumen: El desarrollo y uso de exoesqueletos a nivel mundial ha fomentado un sin número de aplicaciones direccionadas al cuidado de la salud y seguridad ocupacional en múltiples ámbitos de la industria incluyendo el ámbito militar. En este artículo se presenta una revisión sistemática de los avances en exoesqueletos que se emplean para múltiples tareas realizadas por el personal militar. Se ha realizado una revisión sistemática de literatura científica obtenida de bases multidisciplinarias y del ámbito de la salud ocupacional. Existe una variedad de tecnologías y diseños de exoesqueletos que brindan asistencia en zonas específicas del cuerpo en donde el esfuerzo puede provocar trastornos musculoesqueléticos. Los exoesqueletos brindan un par adicional a múltiples articulaciones disminuyendo la fatiga física y aumentando el rendimiento en tareas de alta exigencia física. La mayoría de los exoesqueletos usados en el ámbito militar emplean actuadores eléctricos y se han desarrollado para la región de la cadera y rodillas.

Palabras clave: Exoesqueleto, asistencia, rendimiento físico, actividades militares, exigencia física.

I. INTRODUCTION

Exoskeletons are devices that, through electric, pneumatic, hydraulic, or mechanical actuators, provide support to the joints and musculoskeletal systems of the human body by mimicking and driving movements and allowing them to reducing the physical load during the execution of specific repetitive tasks. The primary function of exoskeletons is to help the structure of users hold or manipulate loads and prevent excessive efforts from being concentrated in areas such as the hip, shoulders, knee, back, legs, etc. [1]. Exoskeletons are often required to perform tasks in medicine, industry, military, security, and others that need high physical demand. In addition to this, these devices have been designed to assist people with disabilities or physical mobility limitations. The developments of exoskeletons focus on providing a more natural movement, reducing the devices to more superficial structures, and achieving operation with lower energy consumption to extend their autonomy.

In the military, exoskeletons increase the strength and mobility of active members in campaign and conflict zones. With the advancement of technology in assistance exoskeletons and the development of more efficient actuators, greater importance has been given to implementing these devices in defense and security[2]. Performance improvements have been evidenced in tasks related to the handling of loads and prolonged movements in walks mainly.

In recent years, exoskeletons and exosuits have been used mainly by the medical, industrial, and military industries. Although they have been used for some years to enhance occupational health and safety in workers, there is still insufficient evidence of the physical interaction between the exoskeleton and the human being (pHEI). Assessing pHEI is essential for accepting and using these devices on a large scale. Research into robotic exoskeletons has been very active in the last decade due to advances in hardware, efficiency, and power supply. Since 1960, the study of these devices has sought to combine the human body and a robotic system to provide protection and support, improving the user's athletic ability and muscular endurance [3].

Despite developments in exoskeletons, there are still significant limitations to their practical use, including inefficient actuator power systems and their impact on occupational safety. Nevertheless, the story of exoskeletons has become an essential line of research in robotics.

Table 1 presents in a general way the most frequent types of exoskeletons from the point of view of applicability in the military field, the parts of the body that are assisted by this device, the technologies used, and their frequent applications in which they are used by military personnel [4].

Table 1. Technological aspects addressed by Industry 4.0 in aviation.

Exoskeleton Type	Assisted body parts	Technology	Frequent applications
Loading exoskeleton	Back, shoulders, and legs	Hydraulic, pneumatic, or electrical systems	Transport of heavy loads
Limb support exoskeleton	Legs, arms, and hands	Sensors, motors, and control systems	Improved movement and precision, reduced muscle fatigue
Protective exoskeleton	Whole body or specific parts	Ballistic materials and shock absorption systems	Protection against injury from explosions, bullet impacts, and debris
Rehabilitation exoskeleton	Legs and arms	Sensors, motors, and control systems	Injury and Disability Rehabilitation

An increasing variety of societal needs justifies the expanding development of exoskeletons. The growing population of people with movement disabilities due to stroke, spinal cord injury, or other related diseases has driven the demand for devices that can improve their quality of life, helping them regain the ability to walk independently [4]. On the other hand, devices that can increase the physical capabilities of people without disabilities are also required to improve their performance in the military field. In the last decade, exoskeletons and robotic assistive devices have made significant progress in making commercially available products. The exoskeletons applied in the military field have five categories that depend on their application. These are Full body Military Exoskeletons, Lower Body Powered Military Exoskeletons, Passive Military Exoskeletons, Energy Scavenging, and Stationary Military Exoskeletons.

Entire body Military Exoskeletons are a category of exoskeletons that cover the soldier's whole body, from head to toe. These exoskeletons provide complete protection against injury and explosions and are often combined with communication and life support systems to increase the soldier's survivability on the battlefield. Lower Body Powered Military Exoskeletons are designed to assist and improve the mobility of a soldier's legs and pelvis[5]. These exoskeletons use electric or hydraulic motors to support the legs, increasing muscular strength and endurance and reducing fatigue. Passive military exoskeletons are military exoskeletons that do not require any external power source; instead, they use passive technologies, such as springs and shock-absorbing materials, to reduce the load on the soldier's body and improve mobility and endurance. Finally, stationary military exoskeletons are used for static and specific tasks, such as handling heavy loads in a stagnant environment. These exoskeletons are anchored to a fixed platform or structure, such as a vehicle, work platform, or military installation, and provide support to reduce fatigue and increase the soldier's endurance.

The movements generated by the actuators of the exoskeletons, in the case of active exoskeletons, must be entirely controlled by electronic systems that are responsible for activating or deactivating them depending on the intention of movement of the limbs or positions adopted by the user of the device. In terms of application, exoskeleton controllers are equipped with task controllers that can be adapted in different ways to meet other goals. Maintaining good safety and health conditions for military members is a crucial aspect. In their routine activities, soldiers must often carry heavy equipment during their missions, prone to musculoskeletal affectations in the back region despite their continuous physical preparation. Therefore, the interest of the military field is in searching for, developing, and implementing new technologies such as exoskeletons [5].

The increase in physical activity of wars and conflicts today has resulted in a more significant load and demand for soldiers, which has promoted solutions such as exoskeletons to ensure better performance and chances of injury during field operations relieving overload and improving the physical capacity of soldiers,, reducing your oxygen consumption and increasing your energy to perform tasks such as walking, running, and jumping. Among the best-known exoskeletons are the Berkeley Lower Extremity Exoskeleton (BLEEX), Raytheon XOS, Human Universal Load Carrier (HULC), and Hybrid Assisted Limb (HAL). The U.S. Defense Advanced Research Projects Agency (DARPA) uses the first three as individual combat exoskeletons, while the HAL is also used outside the military [6].

In the development section, this document explains the technologies used in the models of exoskeletons used in the military field. The Methodologies section describes how the information was obtained from the scientific literature. The results section comments on the findings and new technologies, addressing multiple viewpoints and finally presenting the conclusions.

II. DEVELOPMENT

Exoskeletons in recent decades and within the military have been implemented in applications such as personal protection, cargo assistance, mobility improvement, and rehabilitation. Advances in exoskeleton technology have led to the creation of more advanced and practical models, and it is expected that their use will continue to expand in the future as well as that the academy will strengthen these lines of research by enhancing unexplored areas to improve human interaction with these devices [3].

Table 2 presents the aspects identified in scientific literature according to the characteristics or lines of research related to developing exoskeletons for the military field, whose criteria are also used in the industry in general [7].

Table 2. Areas of research related to developing projects in exoskeletons for the military field.

Research aspects in military exoskeletons	Description
Design and development of exoskeletons	Research into the design and development of safe, reliable, comfortable, and effective military exoskeletons that reduce physical load and improve soldier performance.
Clinical and ergonomic evaluation	Conducting clinical and ergonomic studies to evaluate the efficacy and safety of exoskeletons in alleviating physical load and preventing injury to the soldier. Identify best practices regarding the adaptation, training, and use of exoskeletons.
Development of control algorithms	Research into developing control algorithms and human-machine interface software that can improve the accuracy and efficiency of exoskeletons and enable better interaction between the user and the exoskeleton.
Integration of exoskeletons with other systems	Research into integrating exoskeletons with other military systems, such as weapons, communication systems, and vehicles. Identification of interoperability requirements and assessment of the impact of exoskeleton integration on operational effectiveness and efficiency.

Of the four areas in Table 2, most studies show a frequent site that connects skeletons with the study of humans, which is robotics (Fig. 1). The participation of multiple disciplines is evidenced, such as mechanical design, human engineering, control and electronics, physiology, human-computer interaction, etc. In addition, the United States' significant contribution to these investigations and developments is highlighted. Most studies consider robotic wireless technology systems for lower extremity support. Artificial intelligence has been incorporated into these developments to improve motion control, user interaction, and experiences [8].

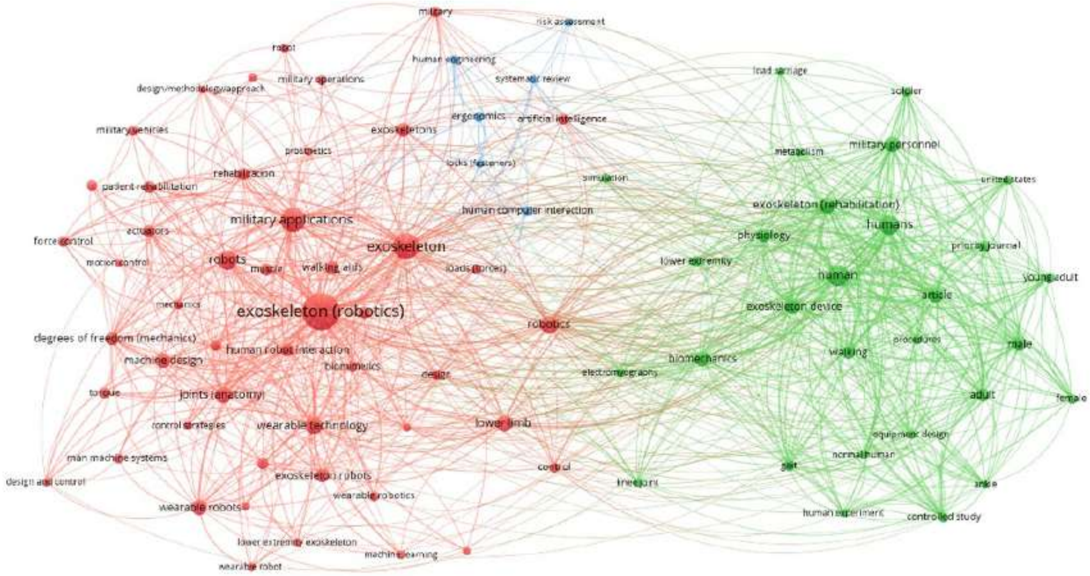

Fig. 1. Bibliometric graph of occurrence of keywords in 200 studies of exoskeletons that mention military applications
Considering the base of SCOPUS (last ten years), graphics made with VOSviewer®

Military exoskeletons have focused on assisting certain limbs and specific body areas compromised by the realization of great physical exertion and muscle fatigue due to repetitive movements.

Exoskeletons for the military focus on assisting the following parts of the human body: elbow-shoulder, shoulder, hip, ankle-knee-hip, knee, and spine [9]. Figure 2 presents illustrations of exoskeletons with structures similar to those used with current technologies in military personnel.

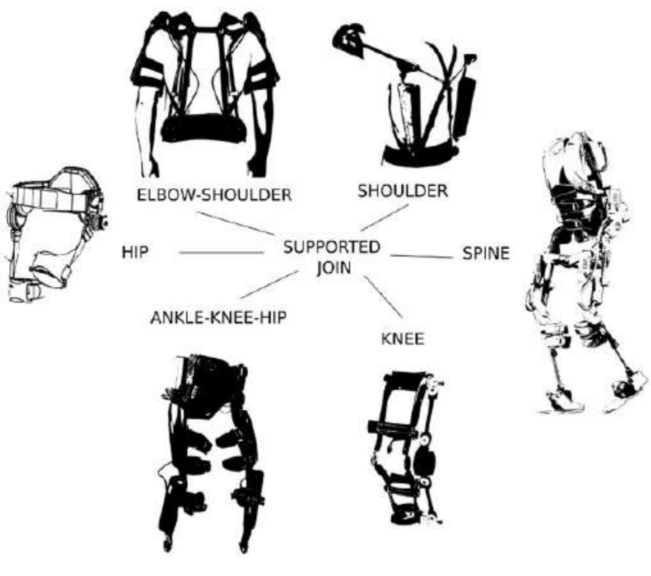

Fig. 2. Bibliometric graph of occurrence of keywords in 200 studies of exoskeletons that mention military applications
Considering the base of SCOPUS (last ten years), graphics made with VOSviewer®

Technologies employed in exoskeletons have been linked to the actuators that provide additional torque when the user requires it for their movement. Motion transmissions include actuators: cable driven, hypoid gear, variable stiffness actuator, springs BoC, pneumatic, hydraulic, passive, and electric [2].

The United States, Russia, Israel, China, and South Korea lead the most significant investment in exoskeleton research and development projects. The United States has invested significantly in the research and development of military exoskeletons to reduce the physical burden on its soldiers and improve their battlefield performance. It has also established collaborative programs with universities and companies to accelerate the development of advanced exoskeletons. Russia: Russian industry has been working on the development of military exoskeletons for several years now. Russian exoskeletons have been used in military exercises and are expected to be used in real missions [10]. Israel has invested in developing military exoskeletons to improve its soldiers' mobility and carrying capacity. Israel has developed lightweight and portable exoskeletons that can be adapted to different tasks on the battlefield. China has invested in research and development of military exoskeletons to improve the performance of its soldiers. Chinese exoskeletons have been used in military exercises and are expected to be used in real missions. South Korea has been developing military exoskeletons to improve its soldiers' carrying capacity and mobility. Korean exoskeletons have been used in military exercises and are expected to be used in actual missions [11]. It should be noted that other countries in Europe and Asia are working on the research and development of military exoskeletons, although to a lesser extent than those mentioned above.

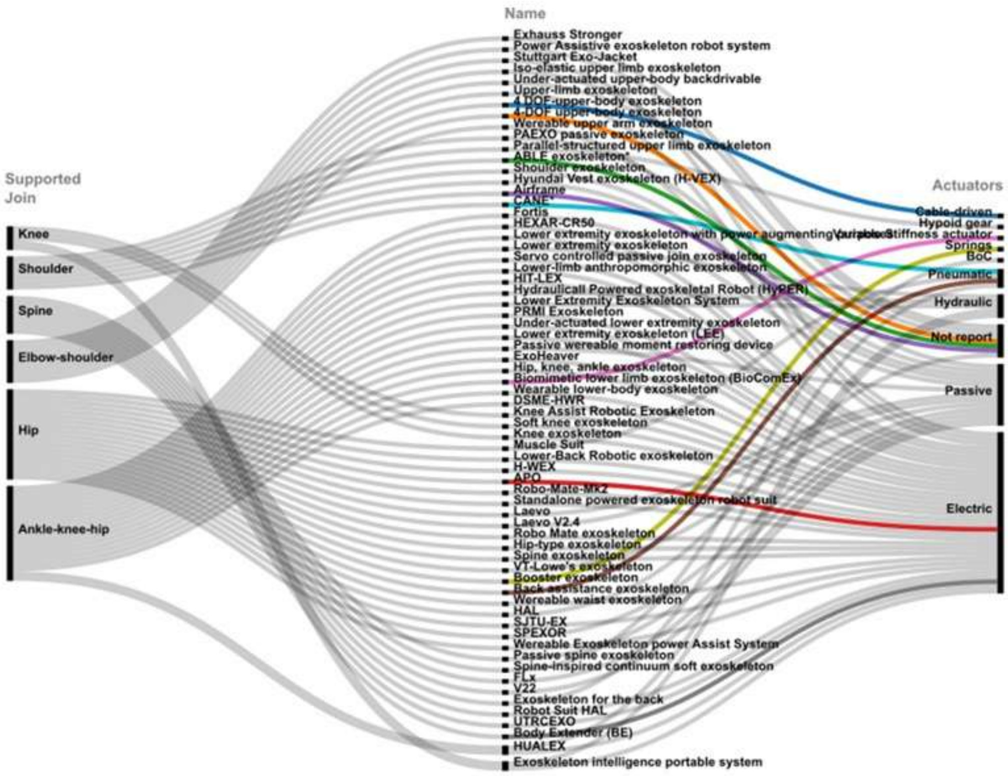

Fig. 3. Types of actuators and exoskeletons developed for assistance according to the parts of the human body.

Figure 3 presents multiple developments of exoskeletons driven by the countries that most research and produce them. Although the devices in Figure 3 are commercial and used in the military field, the type of assisted joint, the name or model of the device, and the type of actuator used are specified in the graph.

The adoption of exoskeletons and their military use raises ethical and social concerns that need to be addressed by ethicists, industry, and society at large. These concerns include the personal and psychological impact on disabled people and their families, access to expensive technology, and the dependency it can generate [12]. One of the concerns is that the extensive use of exoskeletons on soldiers could promote an increased workload of personnel and dehumanize activities during wars and conflicts. These problems have no easy solutions and may require regulatory solutions or cost reduction as technology becomes more accessible. But in general, exoskeletons and other human enhancement technologies raise complex questions that force us to redefine our perception of humanity and ourselves.

Evidence shows that wearing custom exoskeletons during a military obstacle course resulted in better overall performance than a condition without an exoskeleton. However, some obstacles, such as going up and down stairs, hatches, and tunnels, were performed more slowly with the exoskeleton. In addition, while weight acceptability and torso stiffness were similar in both conditions, overall performance acceptability was better without the exoskeleton.

Table 3 presents the most advanced exoskeletons that use state-of-the-art technology and are used by the armies of the most developed countries to support their military personnel. The name of the devices, the country of origin, and the most frequent applications in the military field are described [13].

Table. 3. Most technologically advanced exoskeletons used by the world's armies.

Country	Areas of AI application	Examples of applications/project names
United States	Air traffic management, the workload of pilots and air traffic controllers	NASA Airspace Technology Demonstration 3, Federal Aviation Administration's Route Automation Modernization, Boeing Airpower Teaming System
China	Navigation and maintenance of commercial aircraft, autonomous drones	China's Commercial Aircraft Corporation C919, Autonomous Aerial Refueling
United Kingdom	Predictive aircraft maintenance, pilot training simulation, air traffic management	Rolls-Royce IntelligentEngine, NATS-iTEC Programme, Mixed Reality Training for Aircrew
Singapore	Management of aircraft maintenance and repair operations, design and production of more efficient and safer aircraft	Singapore Airlines Maintenance, Repair and Overhaul (MRO) Hub, Development of High-Performance Electric Propulsion System for Small Aircraft, Development of Supersonic UAV
France	Flight data analysis, air traffic planning optimization	SESAR Joint Undertaking, Thales Flight Management System, Data-driven Control and Surveillance of Air Traffic
Russia	Threat detection and security at airports, optimization of flight route planning	Sputnik, GLONASS, Integrated Security System for Airports
Australia	Aircraft maintenance, identification of faults and component problems	Qantas Group's Integrated Operations Centre, GE Aviation's Digital Collaboration Centre
Germany	Optimization of air traffic controllers' workload, air traffic planning	German Aerospace Centre's Digital Tower Solution, Electronic Flight Strips
Japan	Flight information management, flight route planning	Air Traffic Control by Augmented Reality, Route Control with the Support of AI and Big Data
United Arab Emirates	Airport security, threat detection, aircraft maintenance, component problem identification	Abu Dhabi Airports' Autonomous Wheelchair, Predictive Maintenance for Aircraft Systems, Enhanced Safety and Security Features in Dubai Airports

Analyzing the above table of military exoskeletons, some interesting trends and patterns can be observed regarding the technology and its application in the military field. First, most exoskeletons are designed to improve soldiers' mobility and strength and help lift and carry heavy loads. This suggests that one of the main goals of military exoskeleton technology is to increase soldiers' physical capacity and endurance in combat situations.

Various countries are developing advanced military exoskeletons, with the United States leading the way in the number of exoskeletons produced. This suggests a significant investment and resources devoted to researching and developing military exoskeleton technology.

A variety of specific applications are evident for different military exoskeletons. For example, some are designed specifically for protection, while others are designed to improve soldiers' mobility and strength. This suggests that there are a host of different approaches to the design and implementation of military exoskeleton technology and that exoskeletons may have a variety of specific applications in different military contexts. Furthermore, modern technology also empowers using artificial intelligence (AI) in exoskeletons to improve the efficiency, accuracy, and responsiveness of exoskeleton control and feedback systems and detect and fix potential problems before they become significant problems [8].

Some studies show the impact of using exoskeletons in the military field. For example, an improvement in strength and endurance has been determined according to a 2017 study published in the Journal of Biomechanics, which determined that using exoskeletons increased soldiers' strength and endurance by 27% and 23%, respectively [14]. Furthermore, a 2020 study published in the Journal of Military Medicine has reduced the risk of injury. It was found that using exoskeletons reduced pain in the back and legs by 41% and 39%, respectively. In addition, participants reported less fatigue after wearing the exoskeletons, suggesting they can help prevent injuries in combat situations [14].

There was an increase in efficiency, according to a 2019 article published in the Journal of Human Performance in Extreme Environments which determined that using exoskeletons reduced the time needed to complete cargo transport tasks by 19%. In addition, participants reported reduced perceived exertion and greater task efficiency when wearing exoskeletons [15]. Furthermore, the improvement in precision and stability has been evidenced according to the article in the Journal of Neuroengineering and Rehabilitation, in which it was found that the use of exoskeletons improved the precision and stability of the user's movements by 29% and 23%, respectively. Additionally, participants reported greater accuracy and control in delicate hand and finger movements when wearing exoskeletons.

III. METHODOLOGY

The information from scientific literature has been obtained from articles of previous reviews published in scientific repositories and databases such as SCOPUS, IEEE, and Science Direct. In addition, articles were screened that will not describe military applications of exoskeletons and that were not related to tasks common to this field, considering routine field activities and requiring considerable physical demand. A total of 14 reference works were carried out to develop this article. The documents reviewed corresponded to the period of the last five years.

Figure 4 describes the workflow in selecting the articles considered for this study that provide input in the identification of military exoskeletons on developments of the last five years in several countries of the world and for multiple parts of the body that are assisted with these technologies. Open access documents were considered based on "military AND exoskeleton." To obtain information, open-access documents, reviews, overviews, and original research were considered, and conference papers were excluded.

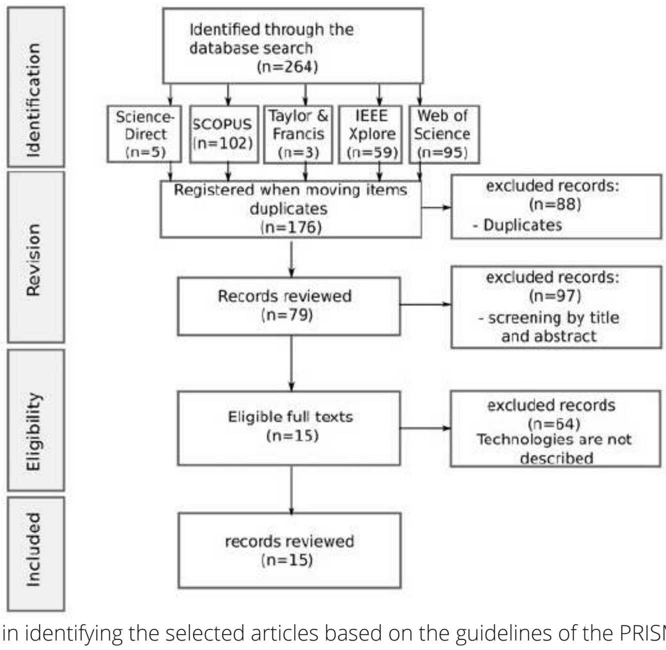

Fig. 4. Workflow in identifying the selected articles based on the guidelines of the PRISMA methodologies.

IV. RESULTADOS

This review article has identified the exoskeletons used in the military field and the type of assistance it provides, especially to soldiers and their operating technologies. It has been described as the contribution to the conditions of safety and occupational health that contribute while performing tasks of high physical demand. The advantages and disadvantages of the use of these technologies are identified. The line of research in exoskeletons has generated interest in recent years. One of the most important aspects is the interaction and comfort of using these devices.

Significant progress has been made in developing exoskeletons for use in the military. One of the most significant advances has been the miniaturization of the systems, creating more portable exoskeletons adaptable to different combat situations. In addition, incorporating sensors and artificial intelligence systems have improved the ability of exoskeletons to adapt to the needs of soldiers and provide personalized support in real-time. Another critical advance that has been identified has been the development of exoskeletons with flight capabilities, which can be helpful for reconnaissance and surveillance missions. Work has also been done on creating exoskeletons that can provide medical support on the battlefield, such as devices that stabilize fractures and prevent further limb damage. Overall, these advances improve soldiers' ability to accomplish their missions and reduce the risk of injuries and illnesses related to physical and mental stress on the battlefield. Table 1 shows the advantages and disadvantages observed in the use of exoskeletons in the military environment.

Table. 4. Workflow in identifying the selected articles based on the guidelines of the PRISMA methodologies.

Advantages of exoskeletons in the military field	Disadvantages of exoskeletons in the military
Increased strength and physical endurance	Development and acquisition cost
Additional protection against injuries and threats	Weight and volume of the device
Improved accuracy and stability	Need for power supply.
Facilitates the transport of heavy loads	Adaptation to different operating environments
Logistic applications in maintenance tasks	Limitations in mobility and agility

The exoskeletons most developed in the last decade are electrical due to the ease of implementing these technologies and microelectronics developments that advance the best use of electrical energy. The actuators of these exoskeletons are characterized by their operation with direct current and have a structure similar to that of Figure 5.

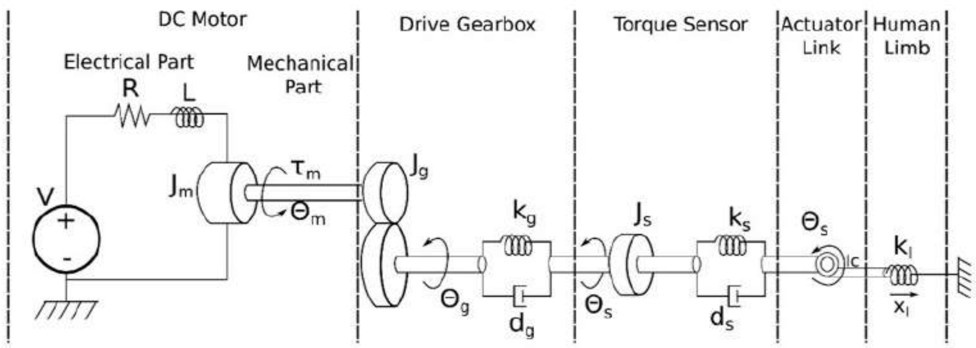

Fig. 5. Schematic representation of the electrical, electronic, and mechanical components that make up the control system of electric actuators in torsion-assisted electric exoskeletons.

Where V represents the source of direct electrical energy; R is the resistance of the electrical system; L is the inductance of the electrical system; J is the rotational inertia, Θ the angle of rotation; d is the damping K the induction constant used and X is the displacement of the limb or joint that moves with the exoskeleton.

Table. 5. Effort-work relationship in the design of exoskeletons.

Mechanical Effort	Physical Work
Exoskeletons reduce physical exertion.	Exoskeletons perform mechanical work.
Help lift and carry heavy loads.	Perform repetitive tasks in an assisted manner.
Allow movements with less fatigue.	Contribute to carrying out activities more efficiently.
Reduce tension and stress in the body	Help maintain productivity in physically demanding tasks
Improve muscle endurance	Facilitate performing physical tasks for extended periods.

Exoskeletons reduce users' physical effort, helping them perform physical tasks more efficiently and with less fatigue. On the other hand, exoskeletons also serve mechanical work by assisting users in the execution of tasks, such as lifting heavy loads or performing repetitive movements.

Table 6 shows the most important aspects considered in the design of exoskeletons. These are essential considerations in creating military exoskeletons, as they affect functionality and user experience. For example, exoskeletons must be ergonomic, durable, and easy to use while offering mobility, protection, and compatibility with other equipment used by soldiers. In addition, energy autonomy and communication capacity are essential factors to maximize effectiveness on the battlefield.

Table. 6. Factors to consider in the design of exoskeletons.

Aspect	Description
Ergonomics	Design that fits comfortably to the human body, minimizing discomfort and fatigue.
Mobility	Ability to allow natural and broad movements for optimal functionality.
Strength and durability	Rugged construction and durable materials to withstand the demands of military use.
Adjustability	Possibility to adjust the exoskeleton to suit different users and body sizes.
Compatibility with military equipment	Design that allows simultaneous use of other equipment and standard soldiers' armament.
Ease of use	Intuitive and easy to use for soldiers, without requiring prolonged training.
Power supply	Efficient battery systems or alternative energy sources for adequate autonomy.
Threat Protection	Integration of ballistic, thermal, or chemical protection technologies, as needed.
Connectivity and communication	Wireless communication capabilities to interconnect devices and share information.

CONCLUSIONS

The use of exoskeletons in the military is a complex and controversial topic that requires careful evaluation of the potential benefits and risks. Therefore, it is crucial that rigorous research is conducted and that the ethics and legality of using these devices are carefully considered before making decisions about their implementation in the military field.

Exoskeletons can improve the efficiency and capability of soldiers on the battlefield. By providing greater strength, endurance, and protection, exoskeletons can allow soldiers to carry more weight and maintain high performance for extended periods. Exoskeletons can also reduce the risk of injuries and illnesses related to physical and mental stress on the battlefield. This can include back, shoulder, and knee injuries, heat-related illnesses, and fatigue.

Although exoskeletons have great potential to improve soldiers' ability on the battlefield, they also present some challenges. This includes the cost, the need for energy for its operation, and the complexity of the technology. In addition, it is important to consider ethical risks and concerns about reliance on technology on the battlefield.

Exoskeletons have been explored as a promising technology to improve soldiers' strength, endurance, and protection in the military field. They can provide soldiers with greater strength and physical endurance, allowing them to carry and handle heavy loads more efficiently. In addition, these devices can reduce muscle fatigue and help avoid injuries associated with transporting heavy equipment over long distances.

There are developments designed to provide additional protection to soldiers. They may include features such as integrated armor plates or shock absorption systems to protect the user against injury caused by explosions, debris, or projectiles. But they can also help improve soldiers' accuracy and stability by reducing tremors and unwanted movements. This can be especially beneficial for activities that require precise aim, such as using firearms or handling delicate equipment.

Exoskeletons can also have logistical applications in the military field. For example, they can facilitate the loading and unloading of supplies, equipment maintenance and repair, and construction tasks in rugged terrain. However, despite the potential benefits, there are challenges associated with using exoskeletons in military affairs. The challenges include the cost of developing and acquiring the devices, their weight and volume, the need for power supply, and adapting to different operating environments.

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