Exoskeleton Technologies, Challenges and Use in Military

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Abstract - *An exoskeleton, sometimes called power armour, exo-frame, or exo-suit, is a wearable mechanical structure powered by motors or actuators, designed to support and enhance motions of the human musculoskeletal system. Exoskeletons are designed to increase the combatant's capabilities during load carriage to allow the combatant to more easily travel through difficult or complex terrain. It can assist firefighters and other rescue personnel in enduring hazardous environments.*

Exoskeletons differ from conventional robotic systems in terms of their operation, as they are a man-in-the-loop system with constant physical contact between the system and the operator. These exoskeletons are designed to either augment the user's performance or provide therapeutic exercises for rehabilitation, or assist impaired individuals in performing activities of daily living, or be used as haptic devices for virtual reality applications. In this paper, a brief about military exoskeletons is presented. The present study also covers technology and its challenges in exoskeletons. This paper is a study paper that presents the overall development of exoskeletons in military uses, with their challenges and future aspects.

Keywords: Exoskeleton, Wearable robots, control, actuator, military

I. INTRODUCTION

Military tasks often require lifting and carrying heavy loads from one place to another, which can cause strain and fatigue on the joints and muscles of soldiers. This can lead to reduced performance and cause chronic musculoskeletal injuries, especially in the lower back and limbs. Apart from this, soldiers need to walk long distances during battle to get to strategic zones, which can cause fatigue in their calf muscles. The use of an exoskeleton to assist soldiers during such tasks can lead to a reduction in the burden felt and in the metabolic cost of their muscles.

The prevalence of Lower Back Pain (LBP) is the most reported pain in field workers handling heavy material manually. The activity of lifting payload significantly strains the lumbar spine and is a major reason for LBP. A study by [1] showed that 45% of reported LBP in West Bengal, India, is due to manual material handling in daily workers. The task of repeated lifting and lowering of payload is more pervasive in the areas of construction, mining, hospital and defence. Back pain, together with related healthcare costs and reduced efficiency, is estimated to cause a socio-economic impact exceeding $100 billion in the United States alone [2]. The Fourth European Working Conditions Survey [3] indicates that nearly 25% of employees in Europe report experiencing back pain. Occupational injuries raise expenses for industries and, more critically, diminish employees' quality of life. Manual payload lifting activity may put workers at physical risk if these activities are performed repeatedly. Also, it may lead to fatigue and injury if repeated over a long period of time. The major risk factor associated with these injuries includes frequent bending, lifting and carrying payload over distance, wrong posture, etc. This category of injuries are known as musculoskeletal disorders, or MSDs.

The U.S. National Institute of Occupational Safety and Health (NIOSH) [4] advises that the maximum safe lifting load for healthy individuals is about 23 kg. for a substantial period of 8 hours. Though in the defence scenario, the situation is quite different, where soldiers are expected to carry heavy loads such as ammunition boxes, guns, etc., over longer periods and distances too. It affects the overall physical and mental fatigue of soldiers in demanding situations. It is often required to lift as much as 30-35 kg of payload for over 50-60 times in a single stretch by a soldier during peacetime.

There are several aids to avoid undesirable spinal loads in industrial set-ups, such as forklifts, trolleys, and overhead cranes. But in the military environment, these tasks of lifting and carrying payload are mostly carried out in fields without these aids. A back-support exoskeleton can aid the user by lowering spinal muscle activity and decreasing lumbar compression. Multiple passive and active variants of such assistive devices have been designed and implemented in practical industrial settings. Though the results of these exoskeletons are promising, for field military situations, the options of these devices are limited to none.

Development of an exoskeleton system is a very challenging field, and researchers are making great progress in this area, not only for civilian purposes but for military scenarios, too. Many countries are already developing field-deployable exoskeletons for use in the military area. It will not be late for countries like India to make significant progress in military exoskeleton and cope up with other countries. In this paper a brief of exoskeleton history, technology, challenges and potential uses of this exoskeleton in the military environment is discussed. The paper is divided in different sections, Section 2 & 3 provides the brief history of exoskeleton and their different types. Different technologies and challenges in exoskeleton design and development is section 4. Section 5 & 6 focuses on exoskeleton development in the field of military and their prospective use in this scenario.

II. History of Exoskeletons

The earliest finding on exoskeleton is in the 1960-1970s. The US Armed Forces along with General Electric developed a hydraulically powered exoskeleton called “Hardiman”. The system weight was around 750 Kg and can lift a payload of approximately 680Kg. A haptic feedback mechanism was implemented, allowing the user to perceive forces and interact with manipulated objects. It was run using many hydraulic actuators in a master-slave arrangement. Two overlapping exoskeletons were used in this design. The intention was for the inner exoskeleton to mimic human movement, which could then be utilized to power the outer exoskeleton's hydraulic actuators. The project was not successful overall. The exoskeleton was never activated while a human was inside since any attempt to employ the entire exoskeleton produced a violent, uncontrollable motion.

Figure 1 Hardiman Exoskeleton [5]

Monty Reed, a US Army Ranger, after an accident started working on a LIFESUIT exoskeleton which gave a gift of walking [6]. In 2001, he wore the 12th prototype of an exoskeleton and demonstrated a speed record of 4 kmph in a race of 4.8 km. The prototype was designed to lift 92 kg for the wearer and walk 1.6 km in single charge.

Figure 2 LIFESUIT Exoskeleton by Monty Reed [6]

The Berkeley lower extremity exoskeleton (BLEEX) first of its kind anthropomorphic powered exoskeleton developed for human strength augmentation by University of California, Berkeley, walking at the average speed of 1.3 m/s while carrying a 34 kg payload. The BLEEX exoskeleton includes two 7 DOF lower leg segments of which 4 are active joints along with on-board power supply. It is connected to the human wearer at the torso and the feet such that load is transferred to ground. BLEEX uses a hydraulic actuation system for its actuation. The system incorporates responsiveness enhancement [7] and a combined supportive regulation method [8] that alternates, depending on the walking stage, between responsiveness enhancement and a motion-based strategy governing target torque.

Figure 3 Berkeley Lower Extremity Exoskeleton (BLEEX)[7]

The Hybrid Assistive Limb (HAL) system, created collaboratively by the University of Tsukuba and Cyberdyne, enhances human strength and facilitates rehabilitation gait training. While multiple iterations exist, this discussion highlights the latest HAL-5, specifically the Type-B non-clinical variant. Despite encompassing the entire body, only the hip, knee, and ankle joints receive active actuation within the sagittal plane. The mechanism employs DC actuators combined with harmonic drive units at each joint, with some configurations featuring passive ankle springs [9]. The suit has a total mass of 23 kilograms and incorporates an integrated battery designed to meet peak walking speeds and standing torque demands. This power source enables roughly 2 hours and 40 minutes of uninterrupted operation and permits lifting loads up to 70 kilograms [10].

Figure 4 Hybrid Assistive Limb Exoskeleton (HAL) [10]

The HAL suit is secured to the user at the waist, thighs, and lower legs via specialized straps. Its structural frame does not convey forces directly to the floor; instead, it modulates torque at the hip, knee, and ankle to enhance the wearer's own joint output. The system's perception network incorporates electromyographic detection, angular and acceleration sensors, and balance monitoring units that track center of pressure and center of mass. Ground reaction information is captured through instrumented footwear. Joint positions are measured using rotational sensors. In certain models, electromyography signals are collected from sensors positioned just above and below the thigh region on both anterior and posterior sides. Additionally, a motion-tracking unit located on the backpack estimates torso orientation.

Cable driven Arm Exoskeleton (CAREX) is an upper limb exoskeleton which is developed to support shoulder, elbow and wrist with the help of cables. CAREX has 7 active DOFs, 3 at shoulder, 1 at elbow and 3 at wrist. The cable driven architecture can accommodate possible joint misalignment between the human upper limb and exoskeleton and reduces the chances of injuries to the human subject during movement. Four cuffs make up the mechanical construction of CAREX-7: one on the upper arm, one on the hand, one on the forearm, and one above the centre of the shoulder. To sense their orientations, three tiny IMUs are fastened to the handcuffs, forearm, and upper arm [11]. Steel wires covered with nylon pass through polished openings integrated into the cuffs. Force sensors are positioned at each wire terminus to regulate tension via feedback control. The shoulder attachment on the seating platform can be repositioned laterally and vertically using two adjustable rails, accommodating individual body sizes.

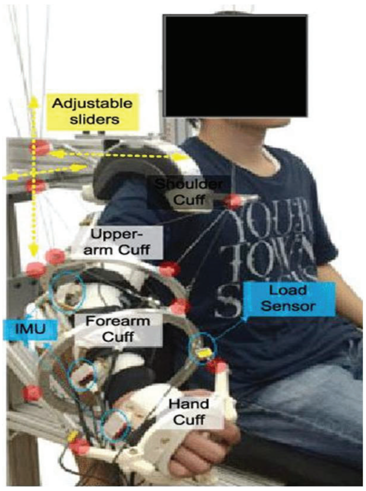

Figure 5 CAREX Exoskeleton [11]

An electricity-powered lower-limb exoskeleton called ''Human Universal Mobility Assistance (HUMA)'' was developed by Japan to research the assistance provided by it for human strength [12]. It has 12 degrees of freedom including active and passive type assistance. The hip actuator provides torque to hip flexion/extension only. A four-bar polycentric mechanism was designed to mimic actual human knee joints. The knee joint is powered through an actuator which is located at the thigh segment. HAL was tested and demonstrated for dynamic gait by using the assistive torque method. It was demonstrated that HAL can walk at 5 kmph or run at 10 kmph with or without 20 kg payload.

Figure 6 Human Universal Mobility Assistant (HUMA) [12]

The Full-Body Exoskeleton (FB-AXO) [13] is a medium-capacity wearable device developed to assist individuals during routine tasks such as ambulation, squatting, standing, bending, and handling objects up to 5 kg in each hand. The architecture is split into Lower-Body (LB-AXO) and Upper-Body (UB-AXO) segments for corresponding extremities. The system features a total of 27 degrees of freedom, with 10 powered and 17 passive. The overall mass of the suit is 25 kg, distributed as 12 kg for the upper section and 13 kg for the lower section. Energy is supplied by a lithium-ion battery, enabling continuous operation for roughly 60 minutes. Brushless DC actuators drive the active joints. The upper segment incorporates a spinal module with three passive degrees of freedom supported by flexible elements, designed to transfer upper-limb loads to the lower segment.

Figure 7 FB AXO exoskeleton [13]

III. Classification of Exoskeletons

Exoskeletons can be classified in several categories depending upon its body area focused, structure types, uses, powering technique etc. The typical exoskeletons are divided into active and passive exoskeletons. The passive exoskeletons are devices which do not use any external power to actuate, though they have in-built elastic devices which store energy during a gait phase and release the same during other gait phases. In contrast, active exoskeletons are power driven devices which provide assistance based on sensing and control. A typical classification of exoskeletons is as shown in fig 6.

Exoskeletons, whether powered or unpowered, can target the upper limbs, lower limbs, or the entire body. Designs vary according to their intended support. Full-body devices assist most or all regions of the user, whereas lower-limb systems concentrate on hips, waist, thighs, and legs. Their main function is to redirect weight toward the floor or reduce stress on specific anatomical areas. Upper-limb exoskeletons provide support for the head, shoulders, arms, and hands.

There are different ways to actuate exoskeletons either through electrical, hydraulic or pneumatic systems, which are the basis for active exoskeletons. The passive exoskeletons use a spring/damper system to provide assistance using stored energy. Also, there are hybrid systems which utilize a combination of mechanical and electrical energy to assist the wearer.

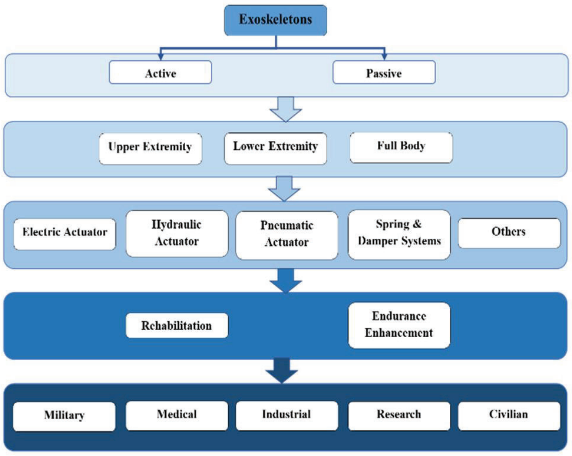

Figure 8 Classification of Exoskeleton

Exoskeletons can also be divided in terms of their utilisation for rehabilitation purposes or endurance enhancement. The wearer is driven in rehabilitative type of exoskeletons where the exoskeleton uses its power to provide suitable gait to users. While in endurance enhancement type of exoskeletons, the wearer is the driver of a system where the system responds to user intended motion through various sensors and control algorithms.

The exoskeletons can be used for military, civilian or industrial purposes. There are exoskeletons which are being used for research or clinical purposes also.

Figure 9 (a) HULC in combat operation, (b) HULC in payload lifting activity, (c) Industrial Exoskeleton for payload lifting, (d) Chairless chair exoskeleton supporting worker in industry

IV. Technologies in Exoskeleton

The development of exoskeleton in the past decade made significant progress with advances in actuators, computation power and sensing devices. However, the success of an exoskeleton depends on several key technologies such as availability of more compact, efficient, and powerful actuators; more reliable and accurate position and force (or torque) sensors; and more lightweight, strong, and durable materials. Another important aspect that significantly limits the performance of these devices is a lack of an intuitive and flexible user interface to control these devices. In this section, we discuss the design, actuation, and control aspects of typical exoskeletons.

a. Design

Since, most of the exoskeletons are going to be used in an unstructured environment along with unpredictable body parameters and movement intentions, therefore conventional design philosophy cannot be utilised. Furthermore, the actuators are dead loads on soldiers therefore they should be as lightweight as possible. In order to have an effective control of exoskeletons, it is required to control interaction forces between the device and human limb. An effective force control system requires a rigid exoskeleton consisting of stiffer structural members for ease of load transfer to ground without significantly loading human joints. However, stiffer structural members can be bulky and have high inertia, which could alter the natural motion of the wearer.

Recently, there are developments in soft exoskeleton made up of compliant materials, Bowden cables or air muscles as flexible power transmission. Though these exoskeletons are much smaller and light weight, providing required assistance using flexible elements is challenging. Also, due to their complaint nature and lack of accurate control over position or assistance, control becomes difficult.

In view of above, neither a rigid nor a soft exoskeleton can be fully utilised to provide adequate assistance during movement. Therefore, the challenge in designing an optimised solution having rigidity of stiff members and flexibility of compliant materials is much more essential for ease of control and assistance.

b. Actuation

Actuators are one of the most critical components of an exoskeleton. The joint assembled with the help of the actuator is the most weighted part of any active exoskeleton. However, with improvements in technology and optimised designs, portable and highly functional devices are being built. For an exoskeleton, it is required to have a high torque to weight actuator at joints but it is also required to have lesser back-drivability torque for users to do free motion. Motor units with gearing exhibit significant reflected mass, making reverse motion challenging. Likewise, fluid-based actuators, including pneumatic and hydraulic types, experience considerable resistance, limiting back drivability. Despite this, electric actuators dominate modern exoskeleton designs because they offer accurate modulation, low acoustic output, and strong operational dependability. Though, with current technology it is not possible to have force control without using additional sensors. A direct drive system at exoskeleton joint operating at low speed and high torque regions is the efficient solution of the problem. Using a gearbox significantly increases nonlinearity of the system due to inherent friction which makes it difficult to measure torque using motor current. More recently, series elastic actuators (SEA) have been developed that introduce an elastic element into transmission. SEA reduces output impedance, allows for low back drivability with stable force control and the capability of energy storage that can reduce overall power requirements [14].

c. Sensing

Sensors are the most important element of any system for control. Exoskeleton system uses many sensors for measuring various physical quantities such as position of joint, force/torque at joint, intent of motion of wearer etc. There are various sensors used by researchers for estimation of joint position tracking along with gait phase estimation. Some exoskeletons use ground reaction force sensors for finding gait phases. IMU has been used for estimation of user trunk position in payload lifting exoskeletons. Several research exoskeletons have been developed that measure electro-myographic signals from human muscles to detect human intent and then control the exoskeleton based on this sensed intention using sophisticated control algorithms. A few exoskeletons have used Brain Computer Interface (BCI) to capture the intent of human limb motion before actuation. However, due to the complexity of brain signals and the invasive nature of the sensors needed for reliable sensing, the use of such signals for controlling exoskeletons is very limited [15].

d. Materials

Advancement in metal processing and machining brought lightweight material such as aluminium alloy as a load bearing structural member. Titanium is being used in some exoskeleton which is more expensive but best suitable in terms of its better strength and lower weight. Use of Carbon fibre or glass fibre is also evident in lightweight exoskeleton. These materials not only provide better strength but also add aesthetics to the exoskeleton. Though modification in fibre composite structures is a tedious process, they can be used for final prototypes as light weight solutions. 3D printing and additive manufacturing brings fabrication of complex three-dimensional shapes for rapid prototyping and testing.

e. Controls

Exoskeleton control requires in-built flexibility to address the variability in the physical characteristics of the human neuromuscular system which varies significantly from person to person. This variation in impaired population is more varied than the healthy population. Delay in actuation is also most critical which leads to loading of human limbs intermittently. Several control strategies such as cascade control, model-based control, impedance, admittance control etc. are demonstrated in different exoskeletons. Some of these controllers are adaptive in nature and learn subject specific assistance requirements. It provides assistance according to the needs of the subject. For control systems to work efficiently the sensing and actuation should be properly tuned to handle environmental variability and uncertainty in which they are typically used. Control systems are always a challenge among exoskeleton developers. The advancement in sensing and actuation brings down the gap between human control and robotic control. A typical control system for an exoskeleton has the following structure.

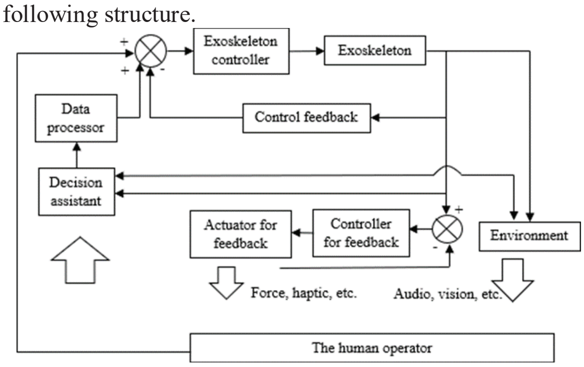

Figure 10 Typical control scheme of an exoskeleton

The CAREX-7 control scheme is organized in two tiers: the upper layer calculates reference cable forces to produce the desired wrench, while the lower layer drives the actuators to track these force trajectories through a high-gain PID feedback loop.

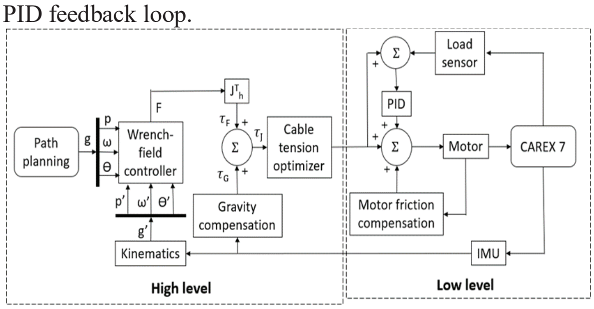

Figure 11 Two level control architecture in CAREX 7[11]

Within the upper controller, the nominal trajectory is generated offline, while the target pose in task space is updated online. The present position of the hand is obtained using forward kinematics. A wrench field computes suitable assistive forces that guide movement along the planned trajectory. To realize these forces and counterbalance gravity, a cable-tension optimizer determines the necessary values, which act as feedforward inputs for motor drives.

In the lower controller, motor excitation includes three elements: reference signal, friction compensation, and PID correction. Friction characteristics are identified through a velocity–friction calibration procedure. Load sensors attached to each cable provide feedback, enabling the PID scheme to regulate actuators so that reference tensions from the upper layer are accurately tracked, minimizing adverse effects of cable compliance and resistance.

The BLEEX control framework [17] enhances closed-loop responsiveness to applied forces and torques, operating independently of pilot commands or human–machine interfaces such as force sensors. Based solely on exoskeleton structure data, the controller makes an educated guess as to how to manoeuvre in a way that minimizes the pilot's sense of force. When the position of touch between the pilot and the exoskeleton is unpredictable and unknown, this control technique can effectively generate locomotion. This control method differs from compliance control methods employed for upper extremity exoskeletons, and haptic systems because it requires no force sensor between the wearer and the exoskeleton.

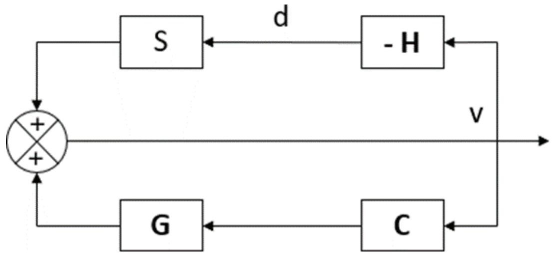

Figure 12 Closed loop system used in BLEEX [17]

Figure 12 illustrates closed-loop behaviour with pilot dynamics included, showing the updated exoskeleton sensitivity transfer function from d to v, which remains unaffected by the feedback path containing H. It also demonstrates a crucial property of human exoskeleton control. The system possesses two different feedback loops. The top feedback loop is internal to the human, and shows that torques were exerted on the exoskeleton in response to applied pressures by the pilot. The bottom loop shows how this tightly regulated feedback system interacts with the exoskeleton. While the lower feedback loop is positive (potentially destabilizing), the upper human feedback loop stabilizes the overall system of pilot and exoskeleton taken as a whole.

The control system of HAL is primarily designed to enhance mobility, as its intended applications include outdoor activities such as walking through corridors and climbing stairs. The control scheme demands instantaneous computation and networked communication. The exoskeleton system is designed as a master–slave architecture, where the master is integrated into the slave system. In this configuration, the exoskeleton functions as the master device, enabling the operator to control HAL (the slave) and generate amplified power. For real-time monitoring of sensor data via the remote controller, radio communication is established between the HAL controller and the remote controller using the User Datagram Protocol (UDP). Phase Sequence Control produces a chain of assistive movements by shifting between elementary actions, known as phases. A feedback controller is employed to regulate the assist torque, ensuring that the myoelectric signals generated during power-assisted walking are properly maintained.

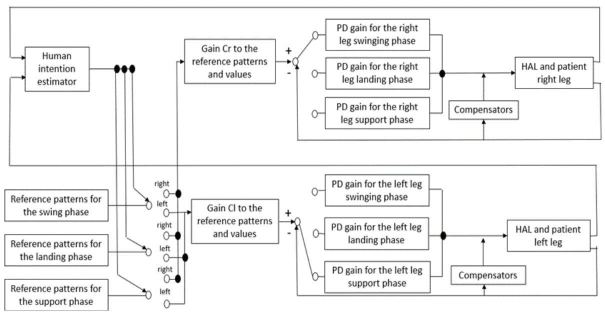

Figure 13 Phase synchronisation Control in HAL [18]

Beneath the intention estimator block, three blocks are defined: a library of reference patterns for the three walking phases, and reference values for the landing and support phases. During walking, these references are allocated to the two legs by the intention estimator. The standard PD control blocks are positioned to the right of the tension estimator and the reference library.

The LB-AXO subsystem adopts a distributed control scheme [13]. Four CAN-based motor power drives linked to corresponding slave controllers locally operate the motorized revolute knee and hip joints in each leg. A master CAN controller serves as the hub connecting the four slave CAN controllers. Each of the four slave controllers manages the motor command output and sensor input locally. They also use the CAN bus to share data with the master program. In addition to connecting and processing data from slave controllers, the master controller also acts as a GUI for human-to-LB-AXO communication. The master controller establishes connections, maintains synchronization, and offers centralized system control.

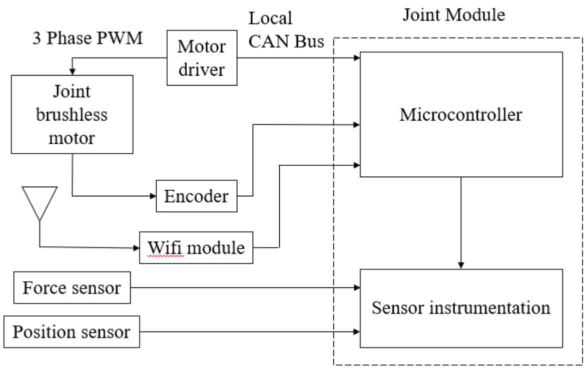

Figure 14 FB-AXOs joint level control [13]

f. Power

Most of the exoskeletons used battery supplied power for their operation. Introduction of lithium ion technology makes the exoskeleton system more portable than before. Lithium ion batteries are high power density batteries which reduce the overall size and weight of the exoskeleton. At present, exoskeletons are utilising these batteries for power requirement however, technology updation in the field of high-power density batteries shall further bring down exoskeleton weight and furthermore increase the endurance of the system.

V. Use of Exoskeleton in Military Scenario

With increasing information-based war games, soldiers have to carry more and more equipment out in the field. This increase in loads can be fatal for soldiers in harsh and hostile environments. Exoskeletons can enhance soldiers' speed, strength, and endurance, making them a key area of research for defence applications. Wearable robotics are very important subclass of military robots in upcoming war games. Military exoskeletons are being tested by the U.S., China, Taiwan, South Korea, Russia and Australia. Most of these projects remain classified and are not available in the public domain. Though, there is still enough information available in the public domain related to military exoskeleton which give insight to development in this field over last few years.

A passive exoskeleton named as Soldier Assistive Bionic Exosuit for Resupply (SABER) designed and evaluated at US Army field testing in 2022. SABER is an unpowered passive exoskeleton without any actuator. SABER uses elastic element to relieve some of the load from soldier's back and spine. The SABER is meant to assist with lifting and reduce back strain during logistics operations.

Figure 15 Soldier Assistive Bionic Exosuit for Resupply (SABER) [19]

The Chinese PLA is advancing a novel exoskeleton called the portable ammunition support assist system for individual troops. Reports indicate that it offers up to 20 kg of load assistance, alleviates more than half of the carried weight, and significantly lowers the likelihood of waist injuries. Chinese developers are developing many core technologies related to exoskeleton and have made different suits for different exoskeleton activities.

Figure 16 Passive Exoskeleton by China in user trial [20]

Lockheed Martin is creating a hydraulic-driven load-bearing exoskeleton for dismounted troops, designated the Human Universal Load Carrier (HULC). This system allows personnel to transport weights of up to 91 kg, with the mass redirected to the ground via the mechanical structure. The HULC underwent controlled lab environment testing in 2010. The HULC is battery-powered, flexible and microelectronics-based exoskeleton which enables users for squatting, crawling and lifting. It weighs around 24kg without batteries and provides an endurance of 20km with an average speed of 4kmph. It can also reach upto speed of 16kmph for short duration. Lockheed Martin has tested the system for elevated environmental conditions such as sand, wind, rain and high temperature. It was reported that metabolic cost of the user decreases while using HULC on a treadmill testing.

Figure 17 HULC developed by Lockheed Martin [21]

The Russian exoskeleton ‘Ratnik’, a combat suit, is built by the Central Research Institute for Precision Machine Building. Ratnik is a passive exoskeleton that offloads burden from soldiers, enabling extended marches and assaults while supporting loads exceeding a hundred pounds. It relies on springs to capture and release energy, thereby reducing strain on the wearer. Limited deployment has begun in the automotive sector, where it is reported to lessen shoulder and back injuries among workers. Also, being a passive exoskeleton the construction is simple and not using any motorised mechanism for the suit.

Figure 18 Ratnik passive exoskeleton in field [22]

In absence of advanced power technology, the focus of development shifted from full body to limited body exoskeletons, where lower extremity exoskeletons provide assistance to legs and transfer load to ground so that soldiers experience less fatigue during repeated tasks of marching etc. Since, a military exoskeleton always has to be flexible and compliant to support human body shape and size, the amount of load that it can carry is limited. Exoskeleton can be made of hard material to support extra load or be made of soft and flexible materials. A powered exoskeleton can be only use for providing mobility assistance and reducing the metabolic cost due to weight of gear carrying by soldier.

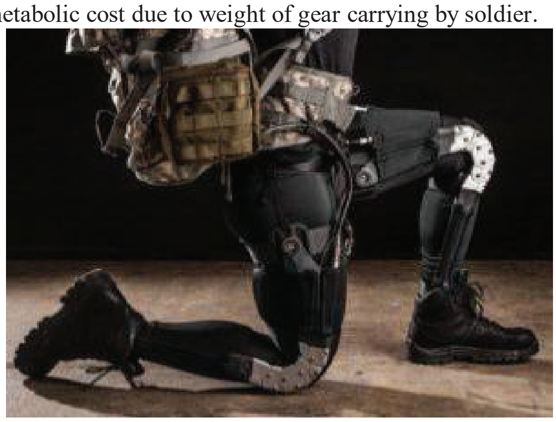

Figure 19 DARPA Warrior Web Exosuit [23]

There are also passive exoskeletons developed for military purpose with a primary aim to reduce the fatigue of soldier during an activity or transfer the load to ground which shall increase soldier’s endurance during long marching. The Marine Mojo by 20KTS+ is designed to absorb shock and vibrations through boot of a soldier on boats during patrolling in coastal lines. The Marine Mojo exoskeleton, developed for Australian Defense, is a system of Bowden cables to transfer a percentage of the weight of a soldier’s backpack into the ground [24].

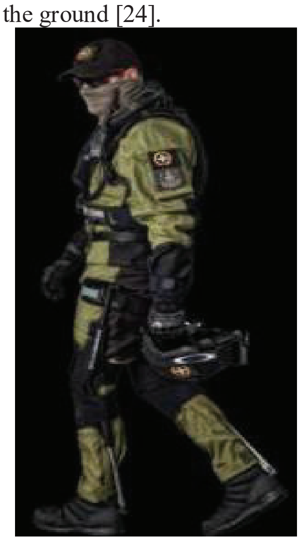

Figure 20 Marine Mojo, 20KTS+ by Australia [24]

VI. Potential Military Use Scenario of Exoskeleton

- **Logistic Support in difficult terrains**

Carrying heavy loads across difficult terrain continues to be a major challenge for soldiers. It is even more essential to carry these loads in complex mountainous terrains where deployment of mechanical transport is a challenge. A best way to carry these loads can be use of load-carrying exoskeleton which not only enhances the endurance of soldier but can be faster and efficient. It is envisaged that an exoskeleton can be used for logistic support on high altitude regions, transporting heavy ammunition through inaccessible terrains etc.

- **Patrolling on complex terrains**

It is often required soldiers to do patrolling in high altitude areas such as mountains. This patrolling is carried-out by soldiers with their gears, which leads to exhaustion and fatigue. The rough terrain in mountainous areas can cause lumbar and spinal injuries as well as demand in terms of oxygen needed at those altitudes. A lightweight exoskeleton for their backpack support can significantly reduce these injuries as well as provide higher endurance to soldiers patrolling schedules. Individual lightweight exoskeletons can be used for long time, long distance border patrols at high altitude, high frequency joint exercises, counter-insurgency and other special operations.

- **Transportation of military supplies and ammunition handling**

Soldiers often carry heavy payloads which may contribute to poor balance, resulting in falls and fatigue while bending, lifting payloads, walking with payload and unloading the payload. An active exoskeleton assisting waist part during bending and lifting offers low fatigue and muscle strain. It is often required to lift as much as 30-35 kg of payload for over 50-60 times in a single stretch by a soldier during peacetime. Individual exoskeletons for lifting and transporting can be used for handling of military material. It can help soldiers lift and carry more and longer. It can be foreseen that exoskeletons of this type can support manual material transport for ammunition handling, large to medium calibre guns, aircraft missile loading etc.

- **Soldier Evacuation in Battlefield**

The well surveyed data showed that 90% of injured soldiers died on the way to medical evacuation. Although state-of-the-art rescue equipment has been introduced by developed countries, including specialised rescue vehicles, aircraft and robots. Many times, battlefield conditions are harsh and difficult for these vehicles to access. A lightweight exoskeleton can be useful solution for evacuation of injured soldiers from the battlefield. It can be a time effective and optimal solution for providing first aid to injured soldier on the battlefield. Exoskeleton can be used for rapid casualty evacuation, replenishment of medical supplies etc.

- **Integrated Warfare in Modern Battlefield**

As stated by war specialists that future war shall be fought by soldiers with more information than gear, exoskeleton can be a vital platform for carrying advanced reconnaissance, communication equipment to the battlefield. It can provide requisite logistic support, higher endurance and payload capacity than ever to provide more information to network centric warfare. It can form a smart multi-role system based on man-machine collaboration.

VII. Conclusion

Exoskeletons represent a transformative frontier for future battlefields, offering unprecedented gains in endurance, strength, and operational resilience for soldiers. While major defense powers such as the US, Russia, China, and Australia have made significant progress, critical challenges still limit large-scale deployment. Future research must prioritize breakthroughs in lightweight high-density power sources, bio-inspired compact actuators, and adaptive multimodal sensing capable of real-time context awareness. Integration of AI-driven control architectures, neural interfacing, soft robotics materials, and energy-harvesting mechanisms will be key to achieving seamless human–machine symbiosis. By addressing these frontiers, researchers can accelerate the transition of exoskeletons from experimental prototypes to reliable, mission-ready assets that redefine soldier performance in future combat environments.

VIII. References

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