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Back-Support Exoskeletons and Rehabilitation Robotic Systems: A Review

Huda Al-Qurnawi *[1], Alaa Al-Ibadi [2]
[1, 2,] Department of Computer Engineering, Engineering College, University of Basrah, Basrah, Iraq
Email: *[1] pgs.huda.ali24@uobasrah.edu.iq, [2] alaa.abdulhassan@uobasrah.edu.iq,
*Corresponding Author

***Abstract*—Employees who perform physical labor and manual material handling duties run the risk of developing bones and muscles problems as well as lumbar discomfort. To support and disperse the load on the spine, spinal exoskeletons are now under development. This article reviews back support exoskeletons in great detail and with the most recent information. It covers the following topics: tasks (lifting, bending, and squatting), weight, power transfer methods, construction (rigid/soft), actuator and motor types, motor coordination, and other crucial aspects. An assessment of exoskeletons for back support capacity to lessen the spine's physical strain is also included in this article. To improve communication and understanding between ergonomics practitioners, developers, customers, and manufacturing workers, the functional and structural aspects will be reviewed. To sum up exoskeletons for the back have the possibility of greatly lower the risk factors connected to musculoskeletal injuries at work. However, the widespread use of exoskeletons in industry is restricted by a number of technical issues and the absence of recognized safety requirements.**

Keywords—Backbone; Exoskeleton; Support; Rehabilitation; Soft robot.

I. Introduction

Although there are growing tendencies toward automation, manual material handling (MMH) jobs are still prevalent in the majority of businesses. These jobs are the primary cause of lower back injuries and occupational health and safety concern. They can significantly strain a worker's lumbar spine, particularly when the person is in static and forward-bending positions [1]. Given the high physical demands of MMH tasks, humans want to use an external mechanical device to surpass physiological limitations and achieve desired physical attributes such as reduced fatigue, rapid movement, or tremendous strength [2]. Musculoskeletal disorder (MSD) is a kind of long-term physical problem brought on by laborers' frequent lifting of heavy goods. It is the reason for an excessive amount of lost productivity, workers' compensation claims, soaring medical expenses, missed workdays, and early retirement. Every year, more than 40% of workers in the European Union suffer from lower back pain as a result of overdoing manual handling duties. Due to awkward body postures, repetitive actions that cause musculoskeletal ailments, and manual handling of materials, the majority of personnel are subjected to physical demands [3] [4] [5].

In many industries nowadays, a significant portion of those work-related diseases are caused by lower back discomfort. According to a study published by the Ministries of Labor and Health, and & Welfare in 2017, 5,051 cases out of 7,844 cases of work-related injuries necessitating a minimum of four days off work (or roughly 65% of the total) involved lower back pain resulting from work-related activities or injuries. Furthermore, within the field of public health and hygiene, which encompasses social welfare institutions, the number of such instances has climbed by 2.7 times in the ten years from 2003. Thus, In order to prevent lower back discomfort, it is still important to put health-promotion techniques into practice. [6][7].

In light of this, wearable robots are emerging technologies designed to improve productivity for workers. These devices offer a promising alternative to reduce musculoskeletal loading and minimize ergonomic risk factors for those who undertake lifting. According to many studies conducted over the past decade, including laboratory simulations, field studies, systematic reviews, and comparative studies, industrial exoskeletons can reduce overall effort, fatigue, and load while boosting productivity and work quality [8].

Commercial exoskeletons have mostly been created for rehabilitation, where the devices are meant to support and help those who are physically weak, injured, or incapacitated by means of prescribed exercises and activities [9]. In order to achieve this, a variety of off-body and on-body lift assist systems have made use of mechanical aids. On-body devices are more common because they are more comfortable and manageable for MMH personnel. Of-body devices, such as trollies or patient lifts, are frequently large and utilized for heavy loads [10]. In the industrial setting, there is a strong need to address back pain issues associated with employment. Extensive research has been conducted on this topic, including studies on muscle fatigue in the trunk during dynamic lifting and lowering, the potential of real-time biofeedback signals to enhance task performance, the development of passive exoskeletons for lower limb support during squat lifting, and the elongation of the backbone's surface while raising and lowering to exoskeleton design. Researchers are also investigating back-support exoskeletons to assist and relieve human operators from awkward postures

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and heavy loads. Ad hoc methods have been considered to optimize design parameters for specific tasks [11][12][13].

Furthermore, in recent decades, there have been various proposals for passive back support exoskeletons. These gadgets can be broadly classified into two groups: rigid exoskeletons and soft coats. Examples of tensile constructions through which the soft jacket transmits force include the personal lift augmentation device (PLAD) and the smart suit light. Rigid structures, bend nondemand return, and wearable torque recovery devices can conduct force using a rigid exoskeleton. It is more comfortable for humans to move around in a flexible exoskeleton, but a rigid exoskeleton has a stronger conduction effect on the load. A key component of the exoskeleton robot is the back device, which lessens the strain on the human spine and reduces the mechanical injury to the back [14].

Professionals in musculoskeletal medicine (MMH) have expressed interest in back-support exoskeletons. According to a 2016 review, using them could lower the activation of the back muscles by as much as 40%, which lowers the chance of injury. The long-term consequences on productivity at work are still unknown, though. The majority of the literature concentrates on lifting actions, ignoring other pertinent ones like carrying, pushing, or tugging. The International Standard ISO 11228 provides ergonomic guidelines for each of these activities, given their linkage to the development of MSDs. Walking is a challenge for passive exoskeletons because of their mechanical components. Active exoskeletons, on the other hand, use controllable actuation elements like electrical motors or pneumatic actuators fueled by external sources. Depending on the task at hand, these actuators can create customized assistance solutions. Exoskeleton controllers, considered multifunctional, use human activity recognition algorithms[15] [16].

II. BACKBONE ANATOMY

The vertebral column, often known as the spine, is a bony structure that runs the length of the back, connecting the head to the pelvis and housing the spinal cord. The spinal cord, which supplies all of the body's nerves and originates in the brain, is the most vital organ that the spine protects. In addition to this primary role, others include maintaining the body's mass, resisting outside forces, permitting flexibility and movement while releasing energy, and preventing collisions [17]. The vertebral body consists of the dorsal portion and the anterior, cylindrical segment. The density of cancellous bone determines its strength and elastic moduli, resulting in highly elastic behavior over a wide range of stress rates. Due to increasing axial loads, the width and depth of vertebral bodies exhibit an inverse relationship. The nucleus pulposus, centrally located in the intervertebral discs, cyclically composes the annulus fibrosus. Helically wound collagen fibers in concentric layers form the annulus fibrosus, providing structural support. Concentric axial forces distribute the load equally throughout the disk, while eccentrically applied forces cause the annulus to bulge and move to the side of the applied stress, with the nucleus pulposus moving in the opposite direction. The varied arrangement of annular fibrosus fibers enhances their ability to withstand shearing and rotational loads[18].Composed of separate bone vertebrae and intervertebral discs, the five unique portions of the spine are the cervical, lumbar, sacral, thoracic, and coccyx see Fig.1 [17].

There are five distinct nerve roots in the lumbar spine and twelve in the thoracic spine. Each of these nerve roots has a name based on the level at which the matching vertebrae exit. The sacrum is composed of five distinct embryonic segments that have fused together to form a single bone structure and five distinct nerve roots that emerge through the sacral foramina[19][20].

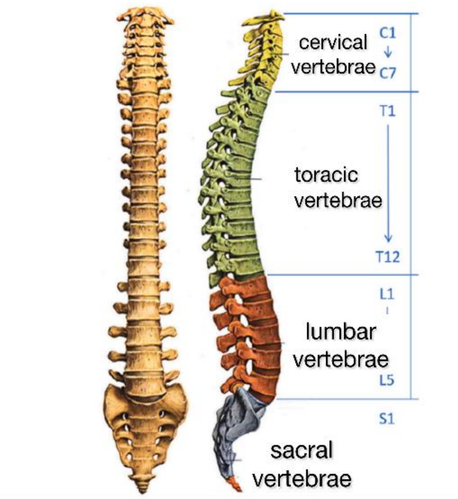

Fig.1 Spine structure for the kinematics analysis [11].

III. BACK- SUPPORT EXOSKELETONS

An exoskeleton is device that helps, facilitates, or improves physical activity and human mobility, while also supporting proper posture. Exoskeletons can either be fully passive and made of mechanical components like elastic beams and springs, or they can be active and powered by electricity. People with neurological or physiological disorders that cause mobility limitation, as well as those recovering from spinal cord injuries and strokes, are benefiting from the creation and utilization of various exoskeletons. Recently, researchers have also developed spinal exoskeletons for use in industrial environments. Researchers are creating these exoskeletons for people whose jobs require them to lift and carry loads, reach above, stand still, and squat [21].

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A) Soft exosuit

Researchers have been increasingly interested in soft wearable robotics during the past 20 years. Often inspired by biological concepts, these types of robots are constructed and assembled without the use of solid components. In addition, these kinds of robots can bend and move without the need for stiff joints [22].Through their inherent high flexibility, strong compliance, exceptional adaptation, and natural and safe interaction, Soft robots have shown enormous promise in wearable technology, medical care, education, service, rescue, exploration, and detection [23] [4] [24] [25].

Because they reduce the risk of collision-related harm to both themselves and their surroundings, soft robots can interact more safely with humans and the environment than traditional rigid robot systems. The flexible bodies of soft robots undergo continuous deformation, leading to high degrees of freedom. One of three methods typically powers soft robots: fluidic actuation, electroactive polymers (EAP), or tendons with varying lengths [26] [25].
Soft robots pose less risk to people, particularly when performing duties that require close physical contact. Therefore, a key study suggests that soft robotics could broaden the scope of human-robot interaction (HRI) in the future and introduce new robot applications [27]. Will review various categories of wearable robots, including their applications, and highlight the unique features and benefits of these innovative technologies.

- The HeroWear Apex

Recently, researchers Maja Gorˇsiˇc and others have created [28]. The HeroWear Apex suit is a biomechanically supportive garment that is simple to wear and lightweight, as well as supporting the lumbar spine [29] . In light of this, their paper provides an assessment of the Apex using 20 adult volunteers across many brief tasks. They completed tasks using an ABA-style methodology. During object lifting and lowering operations, the exosuit reduced the erector spinae electromyogram by approximately 15%.
Fig.2. shows an individual donning the Apex passive back-assist exosuit. With two elastic bands running the length of the back, connecting the upper-body area to the thigh sleeves, the device, which weighs 1.5 kg, consists of an upper-body section resembling a backpack with shoulder and chest straps and thigh sleeves. An engage/disengage switch enables the assistive mechanism to function.
They obtained four measurement types: kinematics, electromyography (EMG), self-report ratings, and heart rate (HR). The outcome variables were trunk ranges of motion (ROM) in flexion-extension, left-right bending, and left-right rotation, as well as thigh ROM in flexion-extension.
It is important to note several study limitations. Firstly, they skipped static learning exercises to shorten the session, despite their relevance to exoskeletons. The Apex engineers researched learning in great detail. They completed tasks with exosuit, but never without it.
Therefore, longer-term research is still required [28][30].

- Laevo

Tessy Luger and others. Presented Laevo® V2.56 Laevo B.V. passive exoskeleton, which had two semi-rigid bars placed laterally (torso structures) and two connecting springs (smart joints; see Fig. 3). It is designed to allow the hip and trunk to move forward and backward. It is weighting the 2.8 kg. Can swap out the torso structures, which join a chest pad and a hip belt, to fit different body forms. Standing up straight eliminates pressure from the angle support in the smart joints, which is monitored by a force sensor built into the chest pad.

They recorded the electrical activity of six muscles unilaterally using surface electromyography (EMG). Using the exoskeleton affected a certain amount of posture; knee flexion increased by 3.0° (>100%), 4.9° (22.9%), and 2.2° (4.6%), respectively, at the minimal, median, and maximal levels.

Fig. 2. Front and back images of a participant wearing the Apex (HeroWear, Nashville, USA). The exosuit is made up of two thigh sleeves, an upperbody portion that resembles a backpack, and two elastic bands that attach the upperbody portion to the thigh sleeves on the back. The study's sensors, such as the heart rate bracelet, optical tracking markers on the shoulders, and wireless electromyography sensors worn beneath the shirt, are also being worn by the participant.[28].

It is important to acknowledge that the present study has certain limitations. Firstly, the study sample was small, consisting mainly of males and with ages ranging from 19 to 38; therefore, it did not represent the whole working-age population. Secondly, the highly controlled laboratory circumstances used to imitate repetitive lifting with different styles and orientations may not accurately represent the real work environment [31].

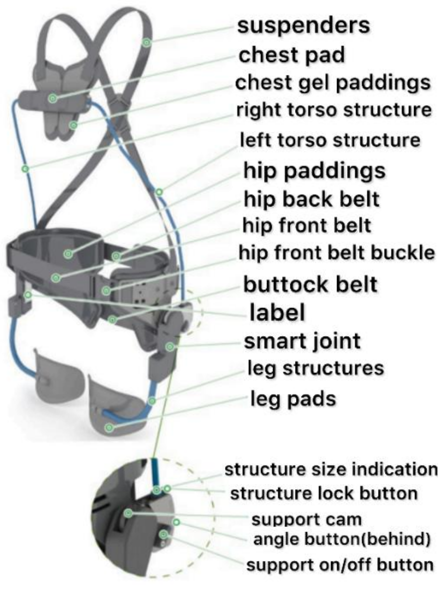


Fig.3. The Laevo® V2.56 passive exoskeleton [31].

- The Auxivo LiftSuit

Rachel M. van Sluijs et al. Presented lightweight (about 1 kg) exoskeleton that supports the back with two textile springs positioned parallel to the back muscles. The exoskeleton is not meant to move the person; rather, it is meant to support the back muscles. The textile contact allows the force to be transmitted to the body.
When wearing the exoskeleton, the primary back and hip muscles saw reductions in muscular activity of up to 25.59% during forward leaning. Additionally, the exoskeleton greatly decreased the peak muscle activity of the lower back muscles during lifting. The decrease varied between 10.74 and 20.52% for the QL (pexo < 0.05) and 6.83 to 14.23% for the ESL (pexo < 0.01).
They recorded surface electromyography (EMG) at 2048 Hz with Trigon sensors.
An exoskeleton familiarization strategy that requires only one session of brief exoskeleton use is one study constraint [32], (shown in Fig 4).

Fig.4. The Auxivo LiftSuit v2.0 passive lift-support exoskeleton is employed [33].

- The spine-inspired back exoskeleton

Fig.5. shows that the back exoskeleton consists of a wearable framework (waist and shoulder braces), a tethered actuation platform, and a cable-driven continuity mechanism each of the twenty segments comprising the robot's spinal system rotates on a ball and socket joint, forming a disc.

The exoskeleton modeled after the spine that keeps natural movement unhindered while lowering spine loadings. It can lessen a variety of forces along the human spine, including the compression, shear, and spinae muscle forces of the lumbar vertebrae, because of its hyper-redundant elastic wearable structure that continually bends, an elastic belt attaches the waist brace and shoulder brace.

According to their design, the base, located beneath the L5/S1 joint, receives the compression force applied to the human back, which is balanced by all of the discs.

The tests confirm that when activated by a single cable, the back exoskeleton can assist with stoop lifting with less than 3.3% tracking error and without obstructing natural movements ,Xiaolong Yang and the others designed this research [8].

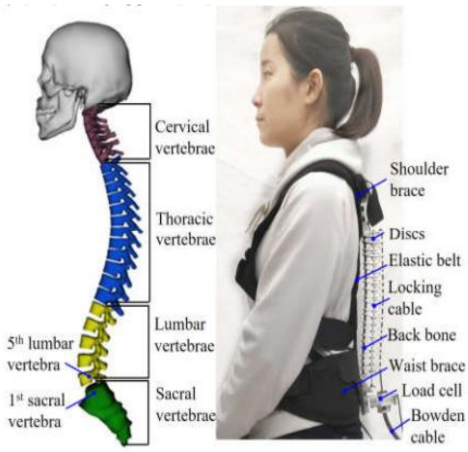


Fig.5. A tethered activation platform, wearable structure (shoulder and waist bracing), and a continuum mechanism make up the spine-inspired back exoskeleton. The spine-inspired soft exoskeleton is a unique design. This is a hyper-redundant, constantly bending continuum mechanism. The under-actuation robot provides assistance while adhering to the human spine's anatomical structure. The structure of the human spine does not impose any constraints on the natural move [8].

- AireLevate

Amit Nirmal Cuttilan and others they designed the AireLevate to overcome the present drawbacks of pneumatic exoskeletons. Fabric makes up the 1.5-kilogram AireLevate exosuit, which takes the shape of an apron. Mostly worn on the body's front side, it consists of a single cloth plate on the chest that splits into two sections on the thighs. Pneumatics power the AireLevate exosuit, which functions as a hybrid active-passive wearable exosuit see Fig.6.They tested the AireLevate's capacity to provide lower back support on a group of healthy participants. The range of motion (ROM) of the lumbar spine is supported by the AireLevate and ranges from about 90 degrees of forward flexion to full extension. It may adapt geometrically to the linked object thanks to its soft robotic qualities.

They utilized motion capture cameras to evaluate subject movement and Surface Electromyography sensors (SEMG) to measure muscle activation in order to guarantee consistent manual handling activities even in the absence of the AireLevate.
During the test, participants did not report significantly different levels of overall or localized discomfort or difficulty donning the suit, regardless of whether they used AireLevate support or not [34].

A B C

Fig.6. The desined of AireLevate exsoloton (A) AireLevate. (B) The user's front view of the AireLevate device. (C) An image of the user's AireLevate's back [34].

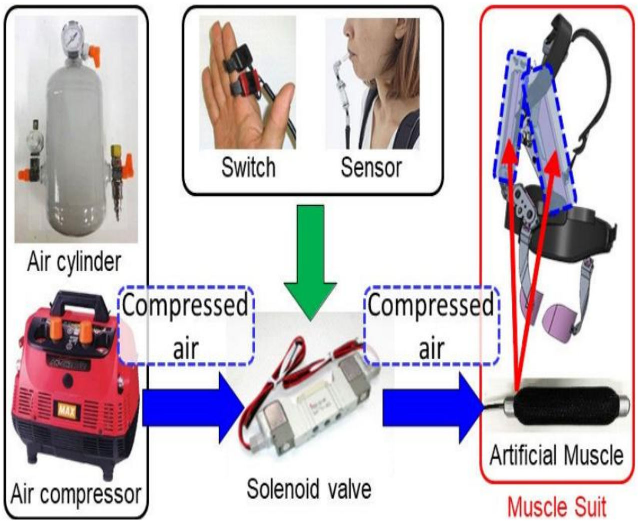
- Power-assist suit

In Fig.7 The help suit is constructed using a balloon actuator and pneumatic artificial muscles.
This assist suit is lightweight, flexible, and high output, all desirable qualities.
Attached to the rear portion are two artificial muscles. The balloon actuator's amplification mechanism secures it in the pelvic position. The air pressure in these actuators allows them to move. As the balloon actuator is pressurized, the moment arm of the artificial muscle increases, causing the amplification mechanism to extend outside.
Therefore, the amplification mechanism efficiently transmits the helpful force to the human body. Belts hold the amplification mechanism in place. Since the belts pass between the femurs, the user can walk normally. The gadget is 2.5 [kg] in weight.
This research did not take into account the lifting motions speed. These factors contribute to a reduction in the assistive force [35].

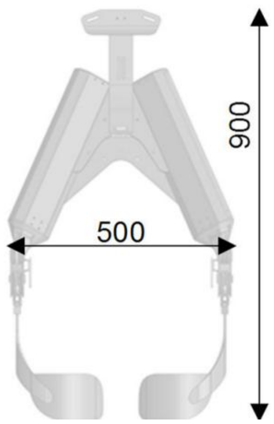
Fig.7. Suit for power assistance [35].

- muscle suit

The lightweight "muscle suit" utilizes soft pneumatic actuators, also known as McKibben artificial muscles. Researchers concentrate on the supporting roles of There are two varieties of muscle suits: the solo model and the standard model. In contrast, the latter outfits a device to passively provide assistance force in the absence of an actuator, the former uses the actuator to generate assistive force actively.
Fig.8(a) shows the Muscle Suit standard model's system configuration for lower back assistance. A solenoid valve, which feeds and releases compressed air, an air compressor, and a sensor or switch to operate the solenoid valve are all necessary for an artificial muscle. In the product's commercial version, two types of switches are available: a breath-activated switch and a touch sensor switch located on the chest that may the moment the chin comes into contact with the valve, regulate it.
switch, which the user can operate by breathing in or out of the mouthpiece.
The regular version of the lower back muscle suit assistance weighs 5.5 kg and has dimensions of 900 x 500 x 220 mm. It produces constrictive force by compressing air, which is then transferred to the pulley and converted into rotating pressure to raise the upper body. also applies the response force to the leg frame show in Fig.8(b) [6].



(a)



(b)

Fig.8. (a) Hardware components used to operate the muscle suit (b) The Muscle Suit CAD model's dimensions [6].

- KirigoBrace

Created and described a CT/MRI-compatible spring with kirigami-inspired properties that could be used to change their previously designed exoskeleton hinge vertebrae. It was also comfortable to wear, corrected instantly in the brace, and didn't limit motion, and is used in rehabilitation.
Fig.9 depicts the general architecture of the exoskeleton vertebrae. The entire system joins the hinge vertebrae to wearers through flexible bracing and springs. The proposed flexible brace is a form-fitting, one-piece compression garment with high-modulus elastic straps and semi-rigid silicone pads for correction. The brace also incorporates a pelvis belt, short pants, vest, and an exoskeleton hinge vertebrae system. The corrective bands, fitted with silicone convex-shaped padding, apply corrective forces to the convex portion of the spine at the peak of the spinal curve. The subject's spine curve aligns with the placement of the padding on her radiograph.
Applying the Kirigami-inspired structure reduced the subject's internal stress during bending, made returning to an upright posture easier, and improved the brace's posture correction. A clinical experiment assessed the immediate corrective effects [36].

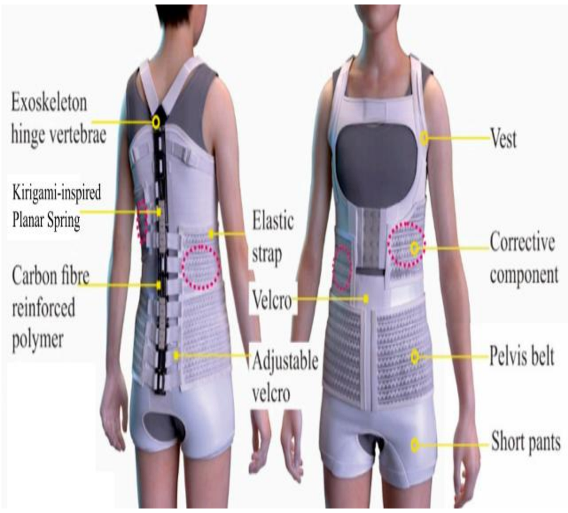


Fig.9. The exoskeleton hinge vertebrae's general design [36].

- The soft active brace

On a finite element (FE) model of a scoliotic spine, Athar Ali et al. offer finite element analysis of an active soft brace fit. In order to investigate the brace action, the authors conducted an in vitro experiment to generate and validate a FE model of the spine. They selected the fabric's material attributes based on research on several types of soft braces. The active soft brace applies forces using elastic resistance. They can control these forces with a lightweight, low-power twisted string actuation (TSAs) device [37] [38] [39] (see Fig 10).
By altering the tension in the elastic bands, the brace's pressure on the spine can be adjusted.
They assessed the scoliosis correction for varied tensions in the elastic bands of the active soft brace using the FE model's capacity to forecast the contact pressure between the brace and trunk.
Presented modeling the Scoliotic Spine with Finite Elements Making a geometry that resembles the human trunk as closely as feasible is the main goal of the finite element analysis. They validated the trunk model by comparing the range of mobility of various spinal segments with in vitro research.
They have demonstrated in-brace correction in terms of thoracic rotation, shoulder rotation, and lateral bending using differences in the forces applied by the TSAs. [40].

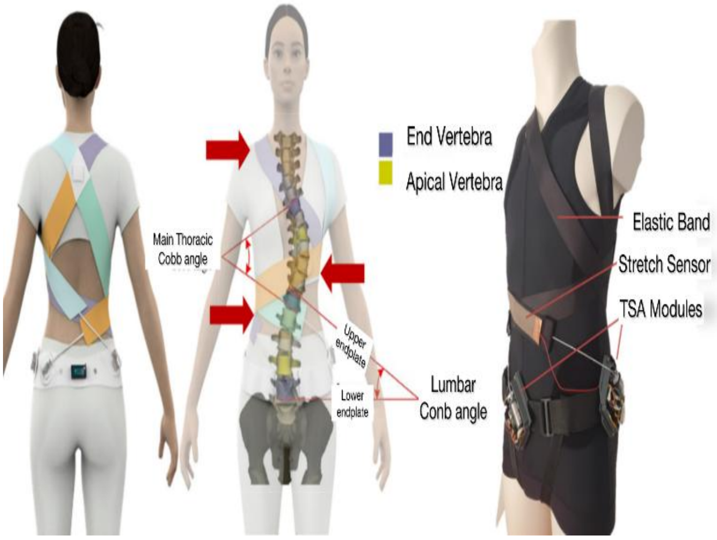


Fig.10. Conceptual design and prototype of a soft active brace [40].

B) Rigid exosuit

The construction of rigid exoskeletons uses rigid articulated structures to connect actuators to the user's clothing. These articulated stiff structures exert forces perpendicular to body segments while running parallel to them [41].
Because of misalignment problems, rigid exoskeletons are heavier and more complex, but they allow the creation of precise and regulated assistive torques [42].
Even though the classic rigid robot can achieve complex and accurate motion, multi-redundant motion control often requires a large number of rigid link joints. We typically refer to robots with such rigid connections as redundant or hyper-redundant robots. To prevent breaking fragile objects or harming people while performing the work, the robot must have some degree of flexibility. In order to increase the security of rigid robots, the industry typically requires many relevant sensors or technologies, such as posture, force feedback, and machine vision, to execute compliant control of the output power. This is because traditional robots typically employ stiff motors and rigid joints [23].

Their capabilities are limited due to complex systems, weight, expense, safety concerns, high power consumption, and slow response [43]. will go over a number of wearable rigid robot categories, their applications, and the special features and benefits of this cutting-edge technology.

- XoTrunk

Tommaso Poliero et al. Present an active Back-Support Exoskeleton (BSE), aiming to minimize injuries associated with musculoskeletal disorders in complex working settings, The Italian Workers' Compensation Authority (INAIL) and the Istituto Italiano di Tecnologia (IIT) collaborated to develop XoTrunk, an exoskeleton designed specifically for use on railroads. It is powered by two torque-controlled electrical motors, which transfer forces to the wearer in the sagittal plane see Fig.11. The generated torque creates two forces that disperse throughout the mechanical system, pulling the torso and thighs backward. The frame-fastened lumbar cushion absorbs the exoskeleton's reaction force. its weight total 8.0 kg [44].

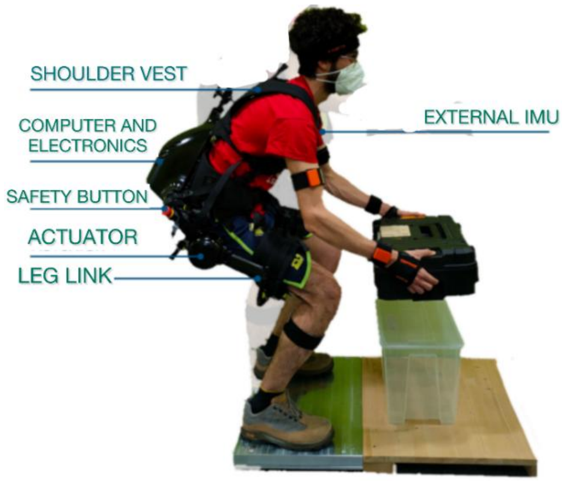


Fig.11.The experimental configuration involves a participant using the XoTrunk exoskeleton to perform tasks such as lifting and lowering a box. The shoulder vest front is where the IMU for acquiring linear acceleration is attached (at the sternum) [45].

- BackBoost

Several researchers, including Ung Heo and Sangjoon J. Kim[46], have examined the development of pneumatic back support exoskeletons. Their focus has been on creating a fully portable exoskeleton by integrating all the system's pneumatic components. The goal is to enhance the exoskeleton's capabilities, allowing it to lift six loads per minute (6 l/m) with a maximum extension torque of 80 Nm.
Fig.12 displays the system configuration. A commercial trunk/thigh brace and shoulder strap come into contact with the human body and exoskeleton. Straps and braces distribute the weight and contact force applied to the skin, ensuring the user's comfort and safety, each of the upper and lower links features a single degree of freedom (1 DoF) rotary joint with a pneumatic cylinder attached on both sides. They chose two cylinders (CM2D32-75FZ, SMC, Japan) with a 32 mm diameter and a 75 mm stroke as the actuator,

An integrated Li-ion battery provided power to the entire system.
A DC motor-gearbox powers a microcompressor with a double-piston crank mechanism, enabling it to generate a maximum pressure of 1100 kPa.
The produced prototype weighs 9.2 kg in total (not including the battery), which is less than the 10.5 kg weight requirement for portability, The 750 g battery is sufficient to operate the system for 1.6 hours[46].

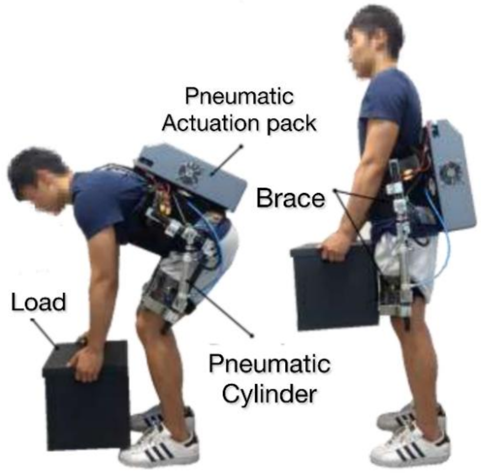


Fig.12. An overview is given by the pneumatic back support system for a portable exoskeleton. The microcompressor that is part of a pneumatic actuation pack allows the system to run on a pneumatic cylinder and makes it completely portable [46].

- Robo-Mate

The function of the active back-support exoskeleton, known as Robo-Mate, is to assist laborers in moving heavy goods. The novel technique, which makes use of the user's trunk's angular acceleration, aims to reduce lumbar overload and, consequently, the danger of acquiring MSDs.

Eleven individuals in good health participated in the Robo-Mate exoskeleton efficacy assessment. They instructed each participant on how to perform a lifting and lowering task in two distinct scenarios: one with and one without the exoskeleton.

In Fig.13 the prototype is displayed. The physical attachments include shoulder straps, a waistband. Additionally, there are specific Velcro bands that secure the connections of the leg exoskeleton to the thighs. The hip joints have two actuators controlled via electrical torque.

The leg links incorporate five passive degrees of freedom and a spherical joint between Both the sturdy frame and the shoulder straps provide stability., ensuring the user's freedom of movement. Maria Lazzaroni et al carried out this project [47].

Fig. 13. The prototype exoskeleton called Robo-Mate [47].

- MK2

Stefano Toxiri et al. They introduce a torque-controlled back-support exoskeleton to assist people with manual handling, thereby reducing the risk of injury and compressive pressures on the lumbar spine. They propose a parallel-elastic actuator (PEA) design rationale to meet the asymmetrical torque needs related to the goal task [48].
Fig.14. displays the second iteration of the prototype exoskeleton that their group created (Mk2). The commercial backpack's shoulder and waist straps, chosen for their comfort, serve as its attachment points on the torso. Furthermore, Velcro straps attach the leg links to customized thigh bands. One actuator on each side produces torque between the torso and the matching thigh link [49].
They designed their exoskeleton to perform the physical task of repetitively handling objects up to 15 kg in industrial settings. Based on human motion data and a biomechanical model, inverse dynamics estimates that the human body generates over 200 Nm to extend the hips and lower back at joint speeds of up to 2 rad/s [48].

Fig. 14. The Mk2 prototype exoskeleton, as it is now worn by a user. This close-up of the customized thigh attachment, which consists of a stiff, bent metal plate attached to the thigh with a specially designed velcro strap, is shown on the bottom right. [48].

- LAD

The Lifting Assistance Device (LAD) system architecture is described in detail.

A quick-release, fitting harness encircles the wearer's waist, thighs, and shoulders for easy wear.

and taking off. In order to accommodate the natural lumbar and hip joint motions that occur when walking and lifting, the LAD has four degrees of freedom. These movements are called flexion/extension and abduction/adduction.

A brushless DC (BLDC) motor, ball-screw transmission, and series spring comprise the three mechanical components that make up the SEA module on the rear of the LAD shown in figure 15. The series elastic actuator (SEA) can regulate the output force by adjusting the degree of compression applied to the series spring. Two Bowden cables transfer the force from the SEA to the wearer's body.

Flexible sheaths guide the inner cables, fastened to the pulley at the flexion and extension (FE) joints, as they move from the pulley to the SEA.

The sensor system uses an inertial measurement unit (EBIMU-9DOF3, E2BOX) to monitor the trunk tilt with respect to gravity and three linear potentiometers to measure the spring displacements of the SEA.

This implies that the LAD may lessen the risk of industrial athletes experiencing lower back pain (LBP) by reducing the compression highlights on the lumbar spine during lifting tasks [50].

Fig.15. System architecture of our lifting assist device (LAD) prototype. (Color fgure online) [50].

- The SPEXOR

Axel S. Koopman et al. have developed a novel design for an exoskeleton within the SPEXOR cooperation. This innovative design has moment support up to 50 Nm, enhanced fitting by the use of misalignment compensating mechanisms, and separation of hip and lumbar flexion. The current study's objective was to assess this exoskeleton's biomechanical performance during static bending and lifting. as Fig.16 The exoskeleton weighs 6.7 kilograms. Two hip/thigh modules, a pelvis, and a spine make up this structure. The spine module's three circular carbon fiber beams run along the back. These beams attach at the top to a back plate, which has a translational and rotational degree of freedom relative to the beams, to account for axial rotation and elongation of the back during bending.
By manually adjusting the overlap's length, the beams at the pelvis are connected to a base that is attached to two overlapping rigid carbon frames. This connection allows for the hip/thigh module to fit a wide range of pelvic widths. The hip/thigh modules feature spring-loaded joints (MACCEPA 2.0). Enhanced with devices for misalignment adjustment to take user and exoskeleton movements into account. One

drawback is that, in contrast to some previous research, lumbar flexion differed less between lifting approaches.

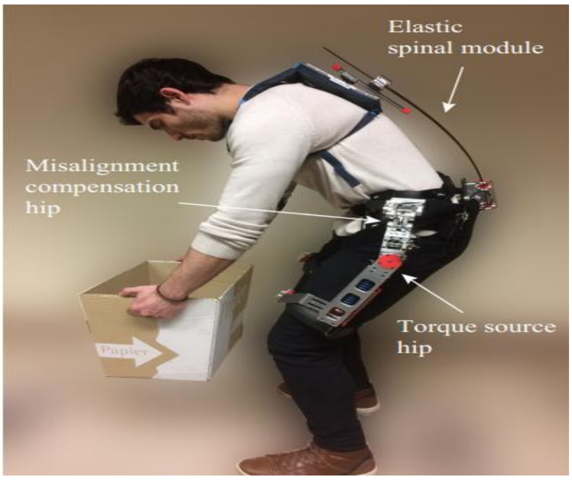


Fig.16. To relieve the lower back's burden, the SPEXOR passive back support exoskeleton combines torque generators with elastic beams (MACCEPA). In order to minimize discomfort and relative movement, misalignment compensation mechanisms are engaged at the hip and the back. This text has been taken from "Passive Back Support Exoskeleton Enhances Range of Motion with Flexible Beams." [51].

- HAL

Kousei Miura et al. recently designed the hybrid assistive limb (HAL), a wearable robotic suit that assists with joint motion interactively based on the wearer's voluntary drive. HAL effectively decreased the amount of lumbar strain during repeated lifting motions.
The lumbar and thigh molds, power units, and exoskeletal frame make up the HAL.
Bilateral power units are located on the wearer's greater trochanters Show in Fig.17. Potentiometers monitor relative angles, while angular sensors measure the angle of the hip joint.
HAL for Care Support facilitates hip joint extension through a hybrid control system that consists of a cybernic autonomous control (CAC) system and a cybernic voluntary control (CVC) system.
One of the study's limitations is that it only assessed lifting action in the vertical plane. In order to perform actual lifting work, lumbar rotation is also required.
The Japanese Ministry of Health, Labor, and Welfare provided an Industrial Disease Clinical Research Grant to support this work [52].

Fig. 17 HAL product picture (right) and the HAL use in a Japanese mining company (left) [53].

- The VT-Lowe's

Simon Athulya A. and others designed the VT-Lowe's exoskeleton to provide lower back support when lifting objects. Carbon fiber beams running along the user's legs and back provide a restorative force when they bend down and attempt to straighten again, they use soft items like thigh pads, shoulder straps, and waist belts to secure the beams to the user.
They also established the correlations between the shoulder-hip-knee (SHK) angle and the torso angle. They positioned four markers on the upper corners of the lifted box and 37 retro-reflective markers on the specific landmarks shown in Fig. 18.
They encountered several limitations in their research. Particularly for those without an iliac crest marker, their movement of the hip markers might have introduced a tiny amount of error into the true hip position; this would have affected the SHK and knee angles.
The findings showed that wearing the exoskeleton increased the ankle dorsiflexion angle and decreased the knee and waist flexion angles [54].

Fig. 18. Motion capture marker positioning. On the acromion process is where the shoulder marker is positioned. The lateral epicondyle of the humerus is where the elbow marker is positioned. The anterior and posterior superior iliac spines are referred to as ASIS and PSIS, respectively. Every marker is positioned on the subject's left and right sides. [54].

- WPAD

Created a wearable power assist device (WPAD) using pneumatic muscles to lessen the strain on the lower back.
The mechanical frame, sensing and control unit, and power unit make up the WPAD (Fig.19a). In the power unit assembly, pneumatic muscles are used as actuators; aviation aluminum alloy is used for the mechanical frame; and displacement sensors, an embedded system based on proportional-integral-derivative, are part of the sensor and control unit.

When operated in accordance with its rated working parameters, the WPAD may generate a maximum torque of 75 Nm. The equipment weighs 2.5 kg in total. The human lumbosacral joint's biomechanical model is displayed in (Fig. 19b).

A digital heart rate monitor that was fastened to the sternum was used to record the subjects' heart rates, and the results showed that wearing the WPAD lowers their heart rates.

The limitations of current research First, the testing procedure was standardized, and the study is limited to a laboratory setting, which is not the same as a real industrial one. Second, Some WPAD users reported severe strain on their thighs during the Borg scale testing, and their leg pain worsened with continued use [55].

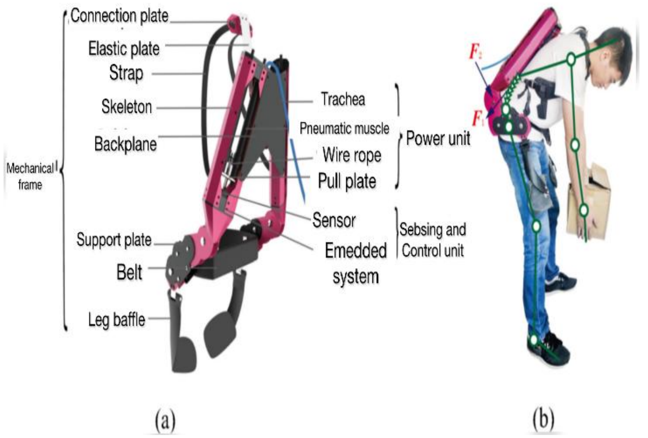
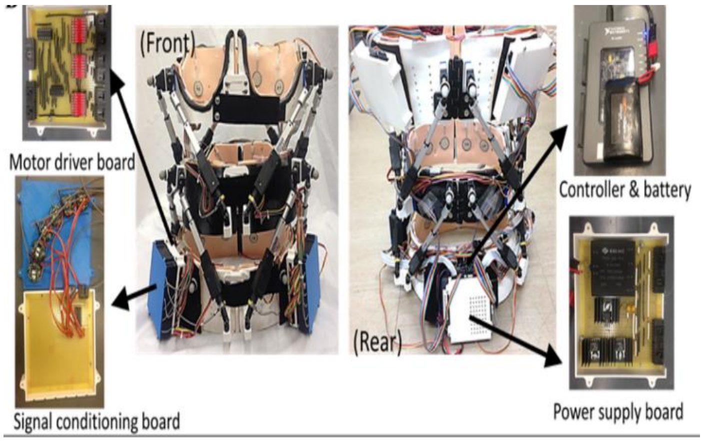


Fig.19. A power unit in the backpack, a sensing and control unit to regulate the power unit's efficacy, and a mechanical frame that distributes stresses to the shoulders and hips make up the wearable power assist device (a). When a person bends to lift large objects, the mechanical skeleton model uses a wearable power assist device (b) [55].

- RoSE

The Robotic Spine Exoskeleton (RoSE), a tool, measures forces and moments while manipulating the orientation and location of specific human torso cross-sections. The Robotic Spine Exoskeleton (RoSE) consists of three rings that encircle the pelvic, thoracolumbar, and thoracic regions. A parallel-actuated module with six degrees of freedom links them together see Fig.20. The study used two-level, one-way displacements in each DOF to try to figure out how stiff the human torso is in three dimensions by measuring the forces and moments that go with them. The RoSE consists of two parallel-actuated modules, each with six limbs configured with a UPS and connected in series with twelve active DOFs. Every limb had a linear actuator attached to a tiny motor driver. Three specially designed electronics boards handled the motor control, sensor communications, and voltage supply regulation. The RoSE can dynamically sense and modulate three-dimensional forces applied to the torso, enabling prompt correction changes. To address the generalizability of these findings, bigger and bone maturity-matched sample sizes are required for future research [56].



(A)

(B)

Fig.20. (A) RoSE uses a double parallel-actuated platform construction that incorporates sensors, motors, batteries, microcontrollers, and integrated electronics (B) Illustrative image of wearing the exoskeleton [56].

IV. CONCLUSION

In terms of operation and structure, kinematic compatibility, and muscle activity reduction, this article offers a comprehensive assessment of the many back support devices now on the market that have these unique functional and structural characteristics. The final exoskeletons' comfort, biomechanical efficacy, complexity, and cost-effectiveness are determined by the design decisions made for each of these characteristics. We speculate that soft exoskeletons are lighter, less expensive, and less complicated to operate than rigid exoskeletons. Rigid devices, on the other hand, have more adaptability possibilities and, thus, more uses. Improving control to take advantage of rigid exoskeletons' versatility and increase their potential effect is one of the unresolved technological difficulties facing them. Soft robotic suits reduce biomechanical joint loading less than rigid exoskeletons, but they are lighter and offer less mobility restriction. Soft back support devices are kinematically compatible because they transfer forces in the form of tensions without changing the kinematics of the body. However, the fact that they usually restrict range of motion is one of their disadvantages.

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