Innovative Applications of Wearable Waist Exoskeletons in the Medical Rehabilitation Field

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Abstract. With the rapid development of exoskeleton technology, especially in the research and application of lumbar-support exoskeletons, key technologies have gradually matured, attracting increasing attention. The lumbar-assisted exoskeleton effectively reduces the burden on the lower back by providing balanced assistive torque at the waist and hips, enhancing efficiency in lifting, heavy handling, and daily work. It has been widely applied in various fields and has become a focus of current exoskeleton technology research. However, currently, the application of waist-assisted exoskeletons in medical rehabilitation scenarios still faces some challenges, mainly in terms of limited functionality and complex wearing procedures. For these issues, a wearable lumbar exoskeleton system that integrates assistance, training, and intelligent protection can be used. By using biomechanical analysis to clarify the spinal structure and movement characteristics, a parallel mechanical structure (S/4-SPS) is employed to achieve multi-degree-of-freedom assisted movement, combined with sensors and control systems to achieve precise assistance and rehabilitation training. In addition, it supports various rehabilitation modes such as gait correction and progressive post-operative training, and can achieve remote health management through cloud data connection, possessing high clinical application value and promotion prospects.

Keywords: Wearable exoskeleton, Lumbar support, Medical rehabilitation, Human-computer interaction.

1. Introduction

The lumbar spine, as the mechanical core of human movement, is responsible for maintaining trunk stability and enabling multi-degree-of-freedom coupled movements. Its biomechanical properties directly determine the functional compensation and risk of injury to the spine. The spine is crucial for protecting the spinal cord, maintaining an upright posture and balance, and enabling the body to move and bend. Patients with spinal disorders have weak trunk control, which limits daily activities and reduces quality of life [1]. Clinically, conditions such as lumbar muscle strain, herniated discs, and spinal cord injuries often lead to severe impairment of lumbar function. Traditional rehabilitation therapy heavily relies on the manual operations of physiotherapists, and has inherent limitations such as low efficiency, high intensity, and lack of standardisation, which has driven the development of intelligent and mechanised lumbar rehabilitation assistive technologies.

Back pain is a common occupational disease, with 70% to 85% of workers experiencing at least one episode of acute back pain during their careers [2]. Research shows that lumbar back pain has become the most common occupational musculoskeletal disorder among workers under 45. Lumbar back pain often leads to workers taking sick leave or even disability, placing a heavy burden on both companies and individuals [2]. To meet this challenge, various types of waist-assist exoskeletons have been developed. A waist-assist exoskeleton is a wearable device that can help people lift heavy objects. These types of exoskeletons apply assistive torque to the waist and hips in various ways, evenly distributing the load weight and helping the body bear the forces on the waist when lifting and lowering objects, thereby reducing the burden on the waist and significantly improving handling efficiency [3].

A representative example is the 'muscle suit', which is one of the powered hip exoskeleton robots used for assistance. It uses two McKibben-type artificial muscles for the two hip joints as the driving system and can be applied in various fields such as logistics, healthcare, and agriculture. In addition, the "HAL lumbar support" is a good example of an exoskeleton robot used to enhance assistance. It has sensors attached to the back that detect the bioelectrical signals of muscles to determine when auxiliary torque should be generated by motors located in the two hip joints [4]. However, the vast majority of products are not suitable for the early stages of postoperative recovery, and the complexity of their structure and production costs has not decreased, with the main investment still being in hospitals. The large size and high cost cannot be widely applied to all groups with lower limb dysfunction. Future lower limb rehabilitation products should move towards being smaller and suitable for home use [5].

This article aims to innovatively apply a medical rehabilitation exoskeleton for postoperative or spinal injury patients, with its core design concept shifting from the industrial field to medical assistance and rehabilitation functions. The goal is to apply a simple-structured, easy-to-wear device that helps patients restore normal bodily functions by providing precise assistance and biofeedback, ultimately enabling independent living without assistance.

2. Theoretical Basis

2.1. Biomechanical Analysis

The spine is located in the middle of the posterior wall of the trunk, consisting of 33 vertebrae [6]. The function of the spine is to support body weight, enable movement, and protect internal organs. The vertebrae are usually divided into cervical, thoracic, lumbar, sacral, and coccygeal bones. The cervical spine consists of seven vertebrae, representing C1-C7. The thoracic spine has twelve vertebrae, T1-T12, and the lumbar spine consists of five vertebrae, L1-L5, as shown in Fig. 1. The sacrum is composed of five vertebrae, S1-S5. From the front view, the vertebral bodies gradually widen from top to bottom, with the second sacral vertebra being the widest. From the side view, the spine appears S-shaped, indicating cervical lordosis, thoracic kyphosis, lumbar lordosis, and sacral kyphosis. The upper limbs are connected to the spine through the humerus, clavicle, and sternum, while the lower limbs are connected to the spine through the pelvis. Various activities of the upper and lower limbs are regulated through the spine to maintain body balance. In addition to providing support and protection, the spine also has the function of flexible movement. Although the range of motion between two adjacent vertebrae is relatively small, when the movements of multiple vertebrae accumulate, extensive activities such as flexion, extension, lateral bending, and rotation can be performed. However, lumbar flexion and extension often involve compression of the intervertebral discs, which can lead to varying degrees of lower back pain [6].

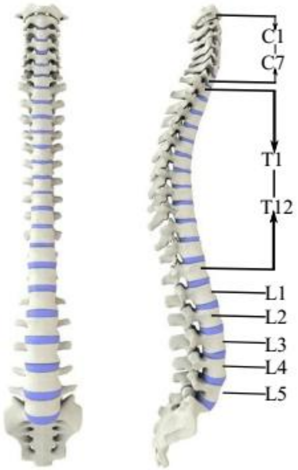

Fig. 1 The structure of the autoencoder [6].

The upper limbs are connected to the spine through the humerus, clavicle, and sternum, while the lower limbs are connected to the spine through the pelvis. Various movements of the upper and lower limbs rely on the coordination of the spine to maintain body balance. In addition to providing support and protection, the spine also has the ability to move flexibly. Although the range of motion between two adjacent vertebrae is small, the cumulative movement of multiple vertebrae can achieve a wide range of activities, such as flexion and extension, lateral bending, and rotation. However, flexion and extension of the lumbar spine are often accompanied by an increase in intervertebral disc pressure, which may lead to varying degrees of lower back pain, thereby affecting the ability to carry out daily activities.

For individuals with spinal structural damage, the spine, as the core structure connecting the upper and lower limbs, needs to bear loads in multiple directions while maintaining body stability. The most severe spinal cord injuries can result in partial or complete paralysis, seriously affecting the ability to care for oneself. Even if the spinal cord is not involved, spinal injuries may lead to long-term pain issues, such as herniated discs or spinal arthritis, which can cause pain, neck pain, or radiating pain. Severe spinal injuries can lead to restricted function of the chest and abdominal muscles, affecting respiratory function and blood circulation, and increasing the risk of lung infections and thrombosis. The aforementioned spinal damage can cause significant psychological stress and inconvenience in daily life for patients.

2.2. Lumbar Assist Exoskeleton Modelling

To visually demonstrate the structural design of the waist-assist exoskeleton, this paper introduces a 3D view of the waist-assist exoskeleton based on SolidWorks modelling (see Fig. 2). The model presents the mechanical structure layout of the exoskeleton waist clearly from the front, side, and back perspectives, including the metal support frame, red flexible linkage components, and the connection and adaptation design of each part, providing a visual reference for subsequent analysis of its structural mechanics, motion adaptability, and assistive principles.

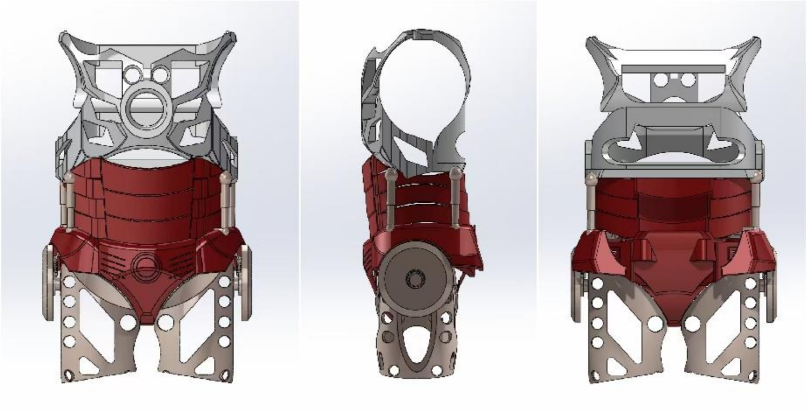

Fig. 2. The structure of the autoencoder (Photo/Picture credit: Original).

2.3. Waist Mechanical Structure

The lumbar exoskeleton mechanism described in this section is a spatial closed-loop structure that conforms to the physiological structure and motion characteristics of the human waist. Among them, the human pelvis and thoracic segments are respectively equivalent to the upper and lower platforms of the mechanism, and the movement of the spine between the pelvis and thoracic vertebrae can be simplified as a spherical pair; the mechanical mechanism adopts a parallel structure design, connected to the upper and lower platforms of the human mechanism by four SPS series mechanisms. At this time, the human-machine closed-loop system can be described as S/4-SPS, with the human body structure being serial, its two ends connected to the mechanical mechanism, and movements such as lumbar flexion and extension around the sagittal axis, lateral bending around the coronal axis, and rotation around the vertical axis are all driven by the parallel mechanical structure, with the training angles of the lumbar region determined by the output pose of the parallel mechanical structure [7].

2.3.1 Coordinate system definition

There are three types of measurements when using a robotic system: kinematic measurements, dynamic measurements, and neuromechanical measurements. Inertial measurement units and motion capture systems are used to measure the range of motion (ROM) of the torso. Trunk flexor and extensor strength is assessed using an isokinetic dynamometer, such as Biodex, through isokinetic or isometric testing. A handheld force gauge is a portable device[8]. First, the following two right-hand coordinate systems are defined: Fixed coordinate system P-xyz: This coordinate system is fixed to the exoskeleton's fixed platform (usually corresponding to the human pelvis segment). Take the geometric centre P of the platform as the coordinate origin. The positive direction of the x-axis points from the origin P to the hinge point A_1. The y-axis lies in the plane of the fixed platform and is perpendicular to the x-axis. The Z-axis is perpendicular to the fixed platform plane, and its positive direction is determined by the right-hand rule. Moving coordinate system K-xyz: This coordinate system is fixed to the moving platform of the exoskeleton (usually corresponding to the human thoracic vertebra segment), with the geometric centre of the moving platform K as the coordinate origin. The positive direction of the x-axis is from the origin K towards the hinge point B_1. The y-axis lies in the plane of the moving platform and is perpendicular to the x-axis. The z-axis is perpendicular to the plane of the moving platform, with its positive direction determined by the right-hand rule [9]. (As shown in Fig. 3)

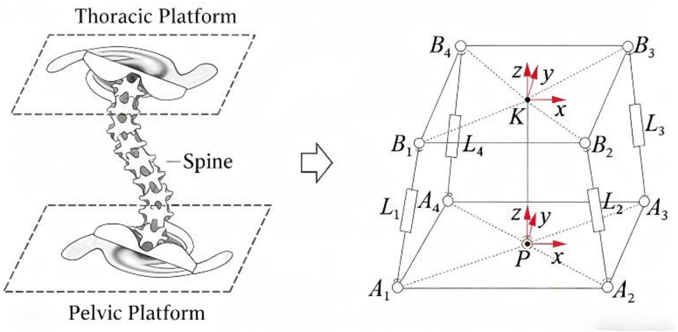

Fig. 3 The structure of the autoencoder [7].

Four sub-chains with SPS configuration are used between the upper and lower platforms, where the connection points of the sub-chains to the upper and lower platforms are ball bearings (S), and the sub-chains themselves are movable joints (P). The constraint chain SP represents the movement of the human spine. Each branch between the upper and lower platforms is equipped with an electric push rod, connected to a small DC motor driver to control the length or force of the actuator. Each actuator contains an integrated linear potentiometer, which is connected in series with a pressure sensor [10]. (See Fig. 4.)

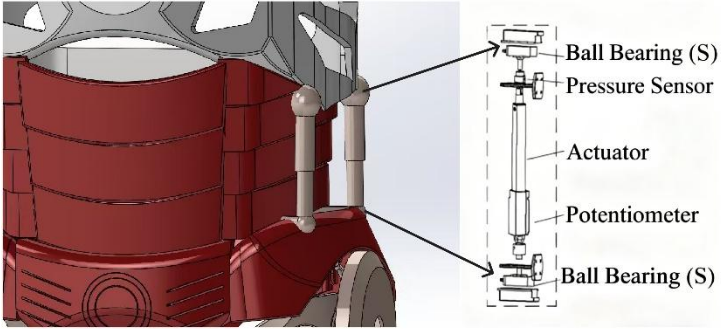

Fig. 4 The structure of the autoencoder [10].

2.3.2 Rotation matrix representation

By using Z-Y-X Euler angles, the rotation matrix of the moving coordinate system relative to the fixed coordinate system is obtained as

$$ {}_{K}^{P}R = R_z(\alpha) \times R_y(\beta) \times R_x(\gamma) = $$

$$\begin{bmatrix} \cos\alpha\cos\beta & \cos\alpha\sin\beta\sin\gamma-\sin\alpha\cos\gamma & \cos\alpha\sin\beta\cos\gamma+\sin\alpha\sin\gamma \\ \sin\alpha\cos\beta & \sin\alpha\sin\beta\sin\gamma+\cos\alpha\cos\gamma & \sin\alpha\sin\beta\cos\gamma-\cos\alpha\sin\gamma \\ -\sin\beta & \cos\beta\sin\gamma & \cos\beta\cos\gamma \end{bmatrix} \tag{1}$$

Among them: ${}_{K}^{P}R$ is represents the rotation matrix α of the moving coordinate K-xyz relative to the fixed coordinate P-xyz, β and γ represent the angles by which the moving coordinate system K-xyz rotates around the z-axis, y-axis, and x-axis of the fixed coordinate system P-xyz, respectively [7].

2.3.3 Velocity jacobian matrix

This means that we can precisely control the force and torque applied to the patient's waist by controlling the output of four motors, enabling compliant training and assisted training.

2.4. Hip Joint Assembly Structure

The rotation of the human knee joint is complex because the centre of rotation (CoR) changes in a regular pattern, and rigid exoskeletons adapt to this change through specific mechanisms, resulting in increased weight and inertia. For these exoskeletons, the external downward force on the thigh cuff is mainly due to gravity [11]. The hip joint structure of the lumbar support exoskeleton is shown in the view of Fig. 5. A frameless bilateral exoskeleton is used, which can simultaneously provide assistive torque to the wearer's hip joints and transmit external loads to the ground through handle-parallel linear actuators. The exoskeleton system is anchored to the body only via the posterior waist belt and thigh cuffs, while the exoskeleton's calf section is not coupled with the biological calf. This design combines the advantages of exoskeletons, providing joint torque and transferring load to the ground [12]. This component mainly consists of a casing, connecting rod, motor, bearing, and coupling. It uses a joint directly driven by the coupling to provide high-torque active assistance, suitable for scenarios such as bending and lifting; at the same time, drawing on the concept of passive assistance, a torsional elastic element is integrated into the coupling to store and release energy, providing assistance when the motor is not operating, thereby reducing overall power consumption. Achieving intelligent switching between support and follow modes through an electronically controlled clutch: In support mode, the motor works in coordination with the elastic element to assist; in follow mode, the clutch disengages, allowing the joint to rotate freely, ensuring flexible movement for the wearer and saving energy.

In terms of structural composition, the shell is made of lightweight high-strength materials, and the interior integrates the motor, bearings, and coupler, with interfaces connecting to the waist and leg supports. The connecting rod, as a power output component, is made of carbon fibre. One end is connected to the casing via a bearing, and the other end is fixed to the leg support plate. The motor is a flat brushless type, capable of high torque output, and drives joint movement through a flexible coupling with integrated elastic elements. The bearings are selected as high-load deep groove ball types to ensure smooth and stable joint rotation.

The hip joint can automatically switch modes according to posture during operation: when the wearer bends over to work, the system enters support mode, with the motor and elastic elements working together to provide assistance in standing up and reduce lumbar load; when walking or when no assistance is needed, it switches to follow mode, with the motor dormant and the clutch disengaged, allowing free joint rotation. This integrated design combines high performance with low power consumption, featuring a compact structure and flexible mode switching, suitable for various applications such as industrial handling and rehabilitation training, effectively enhancing wearing comfort and operational efficiency [13].

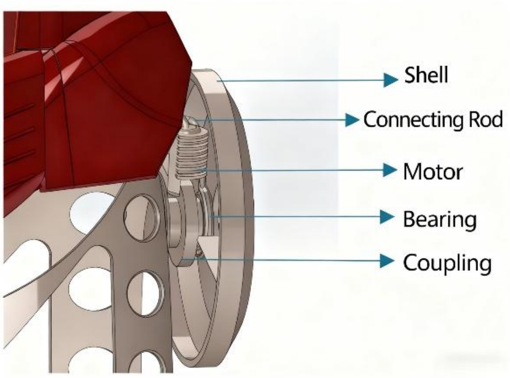

Fig. 5 The structure of the autoencoder (Photo/Picture credit: Original).

3. Control System

Through the mechanical structure and control system of the lumbar exoskeleton, it can provide lumbar support and traction rehabilitation training for patients with lumbar issues. The control system of the lumbar exoskeleton mainly consists of seven modules: human-machine interaction module, communication module, position sensor module, pressure sensor module, information processing module, main control module, and motor drive module. The position sensor module is mainly composed of a gyroscope and a potentiometer inside the electric actuator. The gyroscope is located at the waist of the human body and is used to collect posture signals such as yaw angle, roll angle, pitch angle, and their angular acceleration at the waist, while the potentiometer is used to collect the position signal of the motor. Real-time monitoring of human movement through sensors, dynamically adjusting actuator output. BackX uses torque sensors to detect the contact force between the exoskeleton and the human body, thereby adjusting the motor output torque to achieve adaptive assistance in different task scenarios. This control strategy improves the system's response speed and safety [14]. The pressure sensor module consists of four pressure sensors, used to collect the pressure signals experienced by each electric actuator of the lumbar exoskeleton during interaction with the human body. The motor drive module consists of a position controller and a force controller. The position controller, together with the position signal collected by the potentiometer, forms the inner control loop, which controls the lumbar assistance mode. The force controller, together with the pressure signal collected by the pressure sensor, forms the outer control loop. The hybrid control of the inner and outer loops is used for traction rehabilitation training. The block diagram of the control system is shown in Fig. 6.

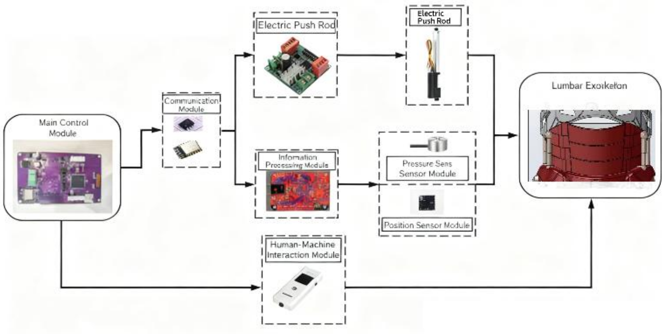

Fig. 6 The structure of the autoencoder [7].

4. Application Cases

Waist-assist exoskeletons have demonstrated significant application value in multiple high-load scenarios. In the field of industrial manufacturing, Mammatus and others proposed an active waist-assist exoskeleton called the "Muscle Suit," designed to assist workers in manually lifting and handling heavy objects. The upper limb part is equipped with six degrees of freedom, allowing workers to wear it with the purpose of assisting workers in manual handling and operating heavy objects. The German Bionic System Company and Fiat collaborated to develop an active lumbar support exoskeleton, "CRAY," for construction and healthcare. CRAY is battery-powered and designed to carry goods and tools, reducing pressure on the lower back when manually lifting heavy objects [13]. In the field of medical rehabilitation, the application of lumbar assistive exoskeletons is expanding from traditional occupational support to modern clinical rehabilitation treatment, showing great potential. Its main value lies in providing precise assistance and training for patients with lower back dysfunction, such as those with weakened lumbar muscles or reduced stability due to stroke, spinal cord injury, or chronic strain. The Canadian company B-Temia has developed the Keeogo lower limb exoskeleton robot, which uses sensors and on-demand assistive algorithms to actively support or stabilise the legs at critical moments of movement, suitable for patients with mild symptoms or in the later stages of rehabilitation [15]. At the same time, repetitive, controllable targeted training helps to reactivate and strengthen the patient's core muscle groups, improving neuromuscular control and breaking the vicious cycle of 'pain-limited activity-muscle weakness'. In 2017, Shihomi and others designed a knee joint exoskeleton rehabilitation robot, Robot-KAFO, suitable for stroke patients. Experiments have shown that Robot-KAFO can effectively improve patients' gait performance and muscle condition [16]. Significantly enhance trunk stability, daily living activities, and overall rehabilitation progress, with the ultimate goal of helping patients gradually reduce their reliance on external assistance and regain independent mobility.

5. Conclusion

This article provides a comprehensive account of a wearable lumbar assistive exoskeleton for the medical rehabilitation field, whose design concept transitions from the industrial sector to the medical sector. Through in-depth biomechanical analysis, a human-machine closed-loop system centred on the S/4-SPS parallel mechanism has been established, capable of effectively accommodating the complex multi-degree-of-freedom movements of the waist. The integrated sensor system and the force/position hybrid control strategy based on the Jacobian matrix provide key technological support for achieving precise and compliant rehabilitation assistance and training. The system combines both assistance and rehabilitation functions, providing not only quantitative and adjustable assistive torque to reduce lumbar load, but also supporting various personalised rehabilitation modes such as gait correction and progressive post-operative training. Through the cloud data platform, the system has established a closed-loop management from patient training to remote guidance by doctors, significantly enhancing the scientific nature and accessibility of the rehabilitation process.

However, there is still room for further optimisation of this idea. For example, by introducing more advanced artificial intelligence algorithms, rehabilitation data can be deeply analysed to achieve adaptive and predictive adjustments to training programmes. Using the metaverse, human-computer interaction, and the powerful data integration and analysis capabilities of artificial intelligence, it is expected to precisely customise personalised rehabilitation plans for each patient and adjust the operating parameters of exoskeleton robots in real time based on the patient's rehabilitation progress and physical feedback. Pursuing further lightweight and intelligent development in materials and drive units will be key to advancing this exoskeleton from the laboratory to widespread clinical and home use.

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