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REVIEW

Application and Progress of Wearable Devices in Orthopaedic Rehabilitation

Wen Lu[1], Xiangyu Chen[2,*]

[1] *Department of Traumatic Orthopaedics, Nanjing Drum Tower Hospital Affiliated to Nanjing University Medical School, Nanjing 210000, Jiangsu Province, China*

[2] *Nanjing University Medical School, Nanjing 210000, Jiangsu Province, China*

Corresponding author: Xiangyu Chen, E-mail: cxy04218@aliyun.com | **DOI:** 10.62311/jha.2026.1.007

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Abstract

Wearable devices are portable, flexible and unobtrusive to wear, and they have accordingly been taken up in orthopaedic rehabilitation medicine. Drawing on a review of the literature, this paper summarises the current state of development of wearable devices in China and abroad, and reviews their application and progress in orthopaedic rehabilitation under four headings: gait monitoring, range of motion, assisted joint support, and spinal cord neurological rehabilitation. The aim is to provide technical support for clinical orthopaedic rehabilitation.

Keywords: wearable device; orthopaedic rehabilitation; telemedicine; literature review

Introduction

Wearable devices are portable devices that embed sensing, information technology and human–machine interaction into something the body can wear[1-3]. Countries around the world have steadily tightened their regulation of digital health technology, which has driven rapid development in mobile health devices, medical device software, wearable devices and the technologies used to study medical products. In recent years wearable devices have also developed swiftly in orthopaedic rehabilitation, and they hold considerable promise[4-5]. This paper reviews the application of wearable devices in orthopaedic rehabilitation medicine, in the hope of providing a reference for clinical practice.

1 Key shared technologies of wearable devices

Wearable devices can be used for the remote monitoring of rehabilitation training in orthopaedic patients, and generally comprise a sensing module, a communication module and a processing module. The sensing module acquires physiological data through highly sensitive sensors — heart rate, range of motion, limb motor function and other health data — and monitors them in real time. The communication module forms a transmission network through an internal microprocessor and connects to medical equipment within the hospital. The processing module transmits the received rehabilitation data wirelessly to a processor, where techniques such as data analysis and data mining are applied, and the results are sent to the clinical rehabilitation centre. This feeds back to the patient whether the daily rehabilitation training is being performed correctly and whether the exercise volume meets the required standard. Wearable devices are mobile, wearable, sustainable, simple to operate and interactive; they perceive the body or the environment through built-in sensors and achieve intelligent exchange of information through wireless transmission, bringing together electronic information, big data transmission, machine algorithms and intelligent human–machine interaction. They are an important vehicle for the delivery of remote rehabilitation and have become a new and revolutionary mode of medical rehabilitation[6]. This paper summarises wearable devices used in orthopaedic rehabilitation in China and abroad along the dimensions of the developing institution, communication technology, wearing site, principal measurements and advantages, as shown in Table 1.

Table 1 Types and functions of wearable devices in orthopaedic rehabilitation in China and abroad

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Device	Country	Communication	Wearing site	Measurements	Population	Advantages	Reference
Soft lower limb exoskeleton wearable rehabilitation device	USA	Microprocessor, sensor	Waist, lower limbs	Step count, gait, walking distance	Postoperative rehabilitation of people with lower limb paralysis	Soft and pliable, close-fitting, comfortable enough for prolonged wear, high accuracy	[7]
Soft wearable rehabilitation glove	Canada	Microprocessor, sensor	Palm	Hand function	Hand function control in patients with upper limb paralysis after spinal cord injury	Accurate and reliable data, low maintenance cost	[8]
Wearable power-assist locomotor	Japan	Microprocessor, sensor	Waist and lower limbs	Distance and duration of independent walking	Powered assistance enabling paraplegic patients to stand upright and to stand, sit and walk independently	Greatly increases the likelihood of restoring walking in paraplegic patients	[9]
Wearable remote monitoring rehabilitation device after knee arthroplasty	New Zealand	Bluetooth, sensor, smartphone	Above the knee and above the ankle	Step count, knee range of motion, knee function	Remote monitoring of exercise rehabilitation after knee arthroplasty	Demonstrates the feasibility of a telerehabilitation software platform for home-based telerehabilitation	[10]
Wearable remote monitoring rehabilitation device after knee arthroplasty	UK	Inertial measurement unit (microprocessor, sensor, Bluetooth)	Above the knee and the ankle	Step count, knee range of motion, knee function	Remote monitoring of exercise rehabilitation after knee arthroplasty; training for people who have lost walking ability; assisting rehabilitation patients with limb movement	Improves the body's capacity for rehabilitation exercise	[11]
Wearable hip-assist rehabilitation exercise system	South Korea	Microprocessor, sensor	Waist and lower limbs	Step count, gait, walking distance	Gait training; improving gait function, muscle strength and cardiopulmonary metabolism in older adults	Incorporates a gait-enhancement and encouragement system	[12]
Wearable robotic device	Japan	Microprocessor, sensor	Waist and lower limbs, spine, elbow	Gait, walking speed, step count	Improving functional mobility in patients with gait disorders	Improves gait parameters and increases walking speed and step count	[13]
Wearable range-of-motion measuring instrument	—	Bluetooth, sensor, smartphone, app	Joints, wrist, hip, knee and ankle, sole of the foot	Range of motion, joint angle, duration of activity	Measurement and recording of range of motion in the rehabilitation of the spine and limb joints	Training module with switchable video demonstrations of rehabilitation programmes; real-time recording of the user's joint angle; reminder function	[14]

2 Current state of wearable devices in orthopaedic rehabilitation abroad

This section describes the current state of wearable devices abroad in three areas: rehabilitation after spinal cord injury, after knee injury surgery and after hip injury surgery.

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2.1 Rehabilitation of patients with spinal cord injury

The wearable device industry abroad is comparatively mature, and the precision of soft wearable electronics, sensors and processors has improved steadily, evolving from simple wearables into more practical soft exoskeleton robots. Harvard University has designed a wearable assistive rehabilitation device to help people with disabilities or those recovering from surgery. The device is light, and patients in a more serious condition can use it as a long-term assistive device. This soft exoskeleton wearable device is made of fabric woven into bands that wrap around the wearer's waist and legs; it is soft yet resilient and fits closely, with a high level of comfort that suits prolonged wear, and its built-in microprocessor and sensors give it high accuracy[7]. Cappello et al.[8] in Canada showed that a fabric-based soft robotic glove can effectively help patients with upper limb paralysis after spinal cord injury to manipulate objects encountered in daily life, confirming that such a glove is an effective device for restoring hand function in these patients. Tanabe et al.[9] in Japan found that wearable robotic exoskeleton gait training is clinically feasible in individuals with incomplete cervical and complete thoracic spinal cord injury; this wearable power-assist locomotor is a medical motorised orthosis intended to give paraplegic patients independent and comfortable walking, and by providing powered assistance it is an effective device for supporting upright walking in paraplegic patients.

2.2 Rehabilitation of patients with knee injury

Innovative wearable devices are also widely used in the functional rehabilitation of patients after joint surgery. Bolam et al.[10] in New Zealand carried out a study of remote monitoring with wearable sensors in patients after knee arthroplasty, demonstrating the feasibility of a reliable, low-maintenance workflow system for remotely monitoring postoperative progress in these patients. Ramkumar et al.[11] in the UK applied remote monitoring to patients after knee arthroplasty and validated the feasibility of a telerehabilitation software platform. Wearable devices can help people who need it to improve their capacity for rehabilitation exercise: they assist rehabilitation patients with limb movement through external force, and provide training for people who have lost walking ability.

2.3 Rehabilitation of patients with hip injury

With population ageing worldwide, an increasing number of wearable assistive devices will be brought into use, and they will play an important role among older adults after hip surgery. Lee et al.[12] in South Korea developed a wearable hip-assist robot that uses an active assistance algorithm to improve gait function, muscle strength and cardiopulmonary metabolic efficiency in older adults. In gait training with the wearable hip-assist robot, the experimental group had the gait-enhancement and encouragement system active while the control group trained without it. The results showed that gait training with this system effectively improved motor function during walking and cardiopulmonary metabolic efficiency in the experimental group. Buesing et al.[13] compared the effects of a wearable robotic device developed by Honda with functional task-specific training on gait parameters. After training, gait parameters improved significantly in both groups, with clear increases in walking speed and step count; the device can improve gait parameters and help restore functional mobility, and is a useful therapeutic tool. This indicates that robot-assisted motor training can be used in the rehabilitation of older patients with gait disorders.

2.4 Prevention of muscle atrophy

Wearable devices are worn directly on the skin and exploit the principle of functional electrical stimulation, for example transcutaneous electrical stimulation; the rehabilitation modes they carry can be adjusted to different parameters according to the patient's needs until a suitable setting is reached, and can effectively improve the symptoms of muscle atrophy. Through wearable devices, electromyography from residual nerve activation in individuals with nerve damage can be used to derive muscle nerve stimulation, which is applicable to people with paralytic and spastic muscle activity. A study of a functional electrical stimulation treatment system for lower limb motor function found that after four weeks of treatment, hip flexor strength on the affected side, quadriceps muscle tone, and the Fugl-Meyer score and Barthel index of the lower limbs all improved significantly[14].

3 Application of wearable devices in orthopaedic rehabilitation in China

Wearable devices have developed rapidly in orthopaedic rehabilitation in China. As population ageing and the burden of chronic disease increase, the supply of medical resources has gradually improved, and the spread of 5G mobile networks in China has provided favourable conditions for the development of mobile medicine. In orthopaedic rehabilitation, wearable devices are used mainly in four areas: safety monitoring during rehabilitation training, assessment of rehabilitation outcomes, assisted limb rehabilitation, and the delivery of home-based rehabilitation[15].

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3.1 Safety monitoring during rehabilitation training

As population ageing in China becomes more acute, a growing number of older adults have orthopaedic conditions such as osteoporosis and osteoarthritis, and they need rehabilitation after surgery. Wearable devices are portable, comfortable, traceable, capable of real-time monitoring, effective and information-based, so they can be used to monitor the physiological parameters of orthopaedic patients during rehabilitation exercise; they are accepted by most orthopaedic patients and fulfil their monitoring role. Remote real-time monitoring of rehabilitation training and daily activity in older orthopaedic patients by wearable devices is of great significance for ensuring their safety. Meng et al.[16] designed a wearable remote rehabilitation device based on micro-sensors that is small, inexpensive and easy to wear, and can be used to track the motion of a single joint. Highly sensitive sensors embedded in wearable devices can capture the rehabilitation posture of older patients, and by matching against a database and relevant data models the posture is analysed; if an abnormality appears, feedback is given to the wearer quickly, preventing falls[17-18].

3.2 Assessment of rehabilitation outcomes

Using the sensors, magnetometers, pressure sensors and transmission systems inside wearable devices, the device simulates the way the central nervous system controls the target nerves and muscles during walking, and helps orthopaedic patients to complete movements such as knee flexion, foot lift, arm raising, stepping and foot strike. Wearable devices track and analyse the patient's gait and give feedback, assessing gait, stride length and step count; through a series of algorithms, the patient's rehabilitation status can then be observed and monitored remotely. The result is a continuous, dynamic data plot that reflects the patient's motor function and rehabilitation outcome, so that the rehabilitation programme can be adjusted individually. Wearable devices can collect patients' symptoms accurately and objectively, and by observing those symptoms they shorten rehabilitation time, improve outcomes, avoid complications and improve patients' quality of life[18].

3.3 Assisted limb rehabilitation

Wearable devices used for assisted limb rehabilitation can monitor, assess, guide and correct faulty posture, and they are of considerable importance for the rehabilitation of patients with limb dysfunction, including those recovering from orthopaedic surgery. Wearable devices can provide joint flexion and extension training to prevent loss of joint function caused by joint adhesion. Zhai et al.[19] designed a soft wearable upper limb rehabilitation device that can control the angle of joint motion and assist patients with joint movement. Ma et al.[20] designed a lightweight dual-hip-driven lower limb exoskeleton rehabilitation device to assist patients with hip rehabilitation. Wearable devices designed around gyroscopes and linear accelerometers for gait analysis monitor the angular velocity and linear acceleration of the limb during walking; gait speed, cadence, step length and the maximum knee angle during movement together indicate range of motion and allow the probability of postoperative falls and other adverse events to be predicted. This supports knee rehabilitation training in patients after total knee arthroplasty, encourages patients to keep exercising, and through human–machine interaction deepens their understanding of sustained exercise therapy and raises their motivation, thereby promoting osteoarticular rehabilitation. As an important branch of wearable devices, skeletal robots can provide joint support for patients after orthopaedic surgery, assist them in exercise and walking, improve their capacity for rehabilitation exercise and shorten the rehabilitation period. Liu et al.[21] designed a wearable upper limb exoskeleton rehabilitation robot based on multi-sensor information that addresses the poor portability, low patient engagement and inadequate adaptability of training modes of earlier wearable devices, with good results. It not only protects the joint and supports the patient's rehabilitation exercise but also increases the load-bearing capacity of the limb and improves the patient's endurance and speed in rehabilitation. The design of wearable exoskeleton equipment proceeds by analysing the physiological structure of the human limb together with the mechanics of human movement and gait, and by carrying out a kinematic analysis of the load-bearing exoskeleton to obtain the trajectory of joint motion and the joint angle; a mechanical analysis of the exoskeleton during the stance phase of the affected limb then allows it to support the joint and complete rehabilitation training.

3.4 Delivery of home-based rehabilitation

Wearable devices can support home-based rehabilitation training. A sensing unit made up of a sensor, an angular velocity sensor and a magnetometer is worn on the outside of the body, and physiological data are transmitted in real time to a processor over Bluetooth, after which software is used to store, synchronise and process the data. Wearable devices play an effective role in the home-based rehabilitation of patients with spinal cord injury. Spinal cord injury is a destructive condition, and most patients are left with disability. Wearable exoskeleton robotic assistance systems can help patients with functional disability to restore or compensate for lost limb motor function. The wearable exoskeleton robot developed by Yang et al.[22] is a lower limb rehabilitation device whose main function is to assist lower limb functional rehabilitation, and it can serve as a mobility aid for paraplegic patients. Wearable robots combine classical robotic principles with soft

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materials and can provide a new class of active assistive device. Soft exosuit wearable devices can promote human–machine interaction. Wearable devices can also draw on interactive gaming platforms and virtual reality environments to help patients complete home-based rehabilitation training, exercising at home through video and simulated scenarios. Compared with conventional rehabilitation, telerehabilitation delivered through wearable devices can provide safe and effective rehabilitation training for patients at home by simulating the real environment.

4 Problems and implications

4.1 The core technologies of wearable devices in China need improvement

Hardware. The sensitivity of wearable device sensors, the sophistication of three-dimensional accelerometers, and the performance and accuracy of components such as magnetometers all need improvement. Because wearable devices must be worn for long periods, questions of material comfort, battery life, device radiation and electronic chip integration also remain to be resolved[23].

Software. The compatibility of data acquisition frequencies across the sensors carried by a wearable device, the efficiency of data collection and processing, data analysis techniques, error, the credibility of transmitted data, the design of intelligent medical rehabilitation software and the friendliness of human–machine interaction all need further improvement[24-25].

4.2 The safety of wearable devices in China needs strengthening

Only by improving industry standards for wearable devices and completing the relevant legislation can the wearable device market develop in a healthy and orderly way. In 2015 China issued the China Wearable Alliance Standard, establishing a standardisation system for the smart wearable device industry that assesses product quality along three dimensions — safety, intelligence and wearability — and certifies the safety of the device itself, its battery, its power adapter and its wireless connection. For wearable products that intervene in human health, the relevant government departments exercise strict control, establishing rigorous and explicit industry standards to regulate the sector and to standardise the medical wearable device industry, so as to avoid problems such as uneven product quality arising from an incomplete standardisation system[26-28].

4.3 The data privacy of wearable devices in China needs strengthening

Wearable devices collect large amounts of patients' private data, but at the same time there is a risk of leakage of patients' private health data, and legislation to protect personal health data is essential[29-30]. Between 2018 and 2020 China successively introduced health and medical safety protection law and personal information protection law; a personal health data protection law would comprehensively raise the security of citizens' health data and information[31-32].

4.4 Rehabilitation health insurance policy for wearable devices in China needs improvement

One study projects that by 2030 the proportion of China's total population aged 65 and over will rise to 18.2%. A large number of older orthopaedic patients urgently need home-based rehabilitation services[33-34]. At present, however, wearable devices are expensive, which directly affects patients' use of them. Against the background of Healthy China 2030, China must continue to strengthen the relevant rehabilitation health insurance policy for wearable devices, promote the development and delivery of telemedicine, break down regional constraints, allow more patients to enjoy the benefits of telemedicine, and extend medical resources to people in more remote areas[35].

5 Summary and outlook

Given their lightness, portability and capacity for remote monitoring, wearable devices will in future develop towards low power consumption, intelligent human–machine interaction, micro-integrated electronic chips, high-speed big data transmission and machine algorithm processing. Against the background of Healthy China 2030, the quality of orthopaedic rehabilitation bears directly on the safety and quality of the medical service patients receive for orthopaedic surgery. Because they are multifunctional, reliable and miniaturised, and because they can acquire big data and deliver precision medicine and telemedicine, wearable devices represent the future direction of orthopaedic rehabilitation; they will change the conventional model of orthopaedic rehabilitation and follow-up, meeting the requirements of modern precision rehabilitation, better satisfying patients' physiological and psychological needs and improving their quality of life. The outlook for wearable devices in orthopaedic rehabilitation is as follows.

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5.1 Delivering precision and remote rehabilitation

Telerehabilitation is an innovative treatment approach; demand for home-based telerehabilitation is growing and increasingly hard to meet, and wearable devices will play an important part in telemedicine, with demand rising sharply for contactless tracking and remote monitoring devices and products. The core function of a wearable device is real-time physiological monitoring and remote transmission. It acquires precise rehabilitation big data and continuously monitors dynamic changes in functional recovery in orthopaedic patients in real time, and is suitable for older patients, people with disability, people with functional impairment and patients with special needs. It can likewise play an important part in preventing falls during rehabilitation training, assisting rehabilitation exercise, health monitoring and chronic disease management.

5.2 Connecting in-hospital and out-of-hospital rehabilitation

Patients discharged from hospital still have problems such as pain, swelling and limited joint function, and how to carry out effective home-based rehabilitation exercise is an urgent question. Wearable devices can transmit and dynamically display home-based rehabilitation data for orthopaedic patients in real time and intuitively, and form a feedback mechanism; an intelligent terminal app allows rehabilitation physicians to obtain accurate rehabilitation data remotely, adjust the rehabilitation programme in good time and provide individualised intervention, joining in-hospital rehabilitation to out-of-hospital rehabilitation and thereby improving the effectiveness of remote orthopaedic rehabilitation.

5.3 Improving public adherence to and satisfaction with rehabilitation

By continuously monitoring rehabilitation training in orthopaedic patients remotely, wearable devices urge patients to complete their rehabilitation programme and increase remote interaction between patient and physician; patients can rehabilitate at home, saving time and cost, and adherence to and satisfaction with rehabilitation improve. Wearable devices help to create a new model of orthopaedic rehabilitation service, raise the professional standard of orthopaedic rehabilitation and promote its scientific development.

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