The Research Status of Knee Rehabilitation Robots

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Abstract. Knee injuries have become an increasing challenge to human health in recent years. It not only affects the quality of life but also puts enormous pressure on the healthcare system. Therefore, research on effective knee rehabilitation has become particularly important. This paper reviews the current research status of knee rehabilitation robots, analyses the rehabilitation needs, and reveals the key role of robots in rehabilitation. In addition, the key technologies are analyzed, and the challenges and directions for future development are pointed out, providing useful guidance for further development in the field of knee rehabilitation robotics.

Keywords: knee rehabilitation robot; rehabilitation needs; rehabilitation programme; review.

1. Introduction

With an aging population [1] and modern lifestyles [2], the issue of knee disease and injury [3] has become a global health challenge. As one of the key joints in the human body that bear weight and support movement, the knee joint is susceptible to trauma, inflammation, and degenerative changes, which can lead to pain, functional limitation, and even incapacitation. Over the past few decades, research on knee rehabilitation in the medical field [4] has gradually attracted widespread attention, and the rise of rehabilitation robotics in particular has brought new hopes and opportunities for knee rehabilitation.

Traditional knee rehabilitation methods often require patients to undergo a series of physiotherapy, sports training, and functional exercises under the guidance of a rehabilitation physician. However, these methods are limited by the constraints of manual manipulation and suffer from problems such as difficulty in quantifying the rehabilitation process, high individual variability, and insufficient willingness of the patient to perform.[5] With the rapid advancement of technology, knee rehabilitation robots are emerging as a potential solution to the shortcomings of traditional rehabilitation methods. With the help of advanced sensing technology, mechanical design, and artificial intelligence algorithms, rehabilitation robots are able to monitor the patient's movement status, force exertion and progress in real time, thus providing more accurate guidance and adjustments for individualized rehabilitation programs.

However, despite the remarkable progress made in the field of knee rehabilitation robotics, there are still problems to be solved. The design and control of the robot, patient-robot synergy, and long-term assessment of rehabilitation outcomes still require further research and exploration. The purpose of this paper is to provide an overview of the current research status of knee rehabilitation robotics, with the aim of providing a comprehensive understanding for rehabilitation robotics researchers and healthcare professionals and promoting further innovation and application of knee rehabilitation robotics.

2. Analysis of rehabilitation demands

2.1. Pathological characterization of the patient

The knee joint consists of two joints, the tibiofemoral joint and the patellofemoral joint.[6] The tibiofemoral joint is the connection between the tibia and the femur, while the patellofemoral joint is the connection between the kneecap and the femur. Unlike other joints, in the knee, the individual bones are not in direct contact with each other, but rather with the synovial fluid-filled joint capsule. This ensures that the knee can have greater flexibility, but also increases the risk of wear and tear and inflammation. The main movements of the knee are bending and straightening.[7] The treatment of knee disorders is a long and slow process, and some conditions such as meniscus and soft tissue wear and tear are irreversible processes that continue to lead to knee injuries and illnesses.[8] In order to address this, knee replacement surgery is an option for many patients. Knee replacement surgery is a highly effective procedure that guarantees patients normal low-impact exercise for about 15-20 years after surgery. However, the patient loses the ability to exercise about 3 months after the surgery [6] and requires extensive training and physiotherapy after the surgery to regain the muscle strength and coordination of the knee.

2.2. Basic Knee Injury Recovery Training

The knee is a vulnerable part of the body and one of the more difficult areas to recover from an injury. After regular treatment, it is essential to regain the strength of the muscles around the knee. Through recovery training, the muscles around the knee joint can be made to work properly during exercise, thus avoiding additional impact and injury to the knee joint. The correct gait developed through rehabilitation also reduces the stress on the knee. Rehabilitation is divided into three phases, the first of which is the restoration of joint flexibility and control of pain and inflammation, together with gait training. The second phase is to restore full flexibility, demonstrate a normal gait, and work on flexibility. The final phase is sport/occupation-specific functional training, which results in a full return to pre-injury mobility. Research has shown that all three stages can be accomplished with a rehabilitation robot.[10]

2.3. Post-operative demand analysis for knee replacements

Knee replacement surgery is an option for many patients with severe knee conditions. However, patients maintain hypokinesia, loss of muscle strength, and uncoordinated limb movements long after surgery. For patients in the preoperative period, their knees are still very weak and require training that is predominantly passive. The patient does not actively exert force but only ensures that the knee can move within its normal range of motion, and the use of a sit-to-stand lower extremity rehabilitation robot is more common at this stage. In the mid to late postoperative period, when the patient has initially regained the ability to exercise, the patient needs to perform active force exercises. In order to restore the lower limb muscle strength and coordination exercises, as well as gait correction and other related training. Exoskeleton standing robots and traction robots are good choices.

3. The current status of research on knee rehabilitation robots

With the continuous progress of medical technology, rehabilitation robotics [11], as an important innovation in the field of modern rehabilitation, is gradually attracting widespread attention. In the field of knee rehabilitation, rehabilitation robotics [12] can be categorized into seated and horizontal patient rehabilitation robots, exoskeleton standing rehabilitation robots and traction standing rehabilitation robots. These different types of rehabilitation robots are unique in their design, principles, and application modalities, providing diverse solutions for knee rehabilitation.

3.1. Rehabilitation Robot for Sitting and Horizontal Patients

A sit-stand rehabilitation robot is a patient rehabilitation training in sitting or recumbent form. Zhang et al [13] designed a sit-stand mobile rehabilitation robot (MMRR) as shown in Figure 1. The robot combines the functions of lower limb rehabilitation, sit-to-stand transfer training, and a six-to-stand wheelchair and simulation was used to demonstrate the effectiveness of its design. Mohanya et al. [14] designed a modular lower limb rehabilitation robot and analyzed its kinematics and dynamics. It was shown that the robot could record hip, knee and ankle movements while supporting the patient's limbs, and its effectiveness has been verified by clinical gait patterns. Luo et al. [15] proposed a simple, reliable, and universally applicable lower limb rehabilitation robot, which can achieve passive training, active training, and joint training of the patient's lower limbs, and has the characteristics of high flexibility, etc. Wang et al. [16] designed a seated horizontal new leg orthosis, as shown in Figure

2, by adjusting the size of the connecting device to make the mechanism of the hip, knee and ankle joints fit the corresponding joints of the patient, and using a particle swarm optimization algorithm is used to obtain the optimal solutions. Eiammanussakul et al [17] designed a seated lower limb rehabilitation robot to solve the rehabilitation problem of patients with muscle weakness, which can perform various types of therapeutic exercises on the hip, knee and ankle joints. Meanwhile, Eiammanussakul et al [18] designed a robot for seated/recumbent training which contains multiple joints for synergistic training such as knee, ankle and hip joints. It was shown that this robot can perform a variety of exercises such as leg press, cycling, gait trajectory tracking, or customized exercises. Feng et al. [19] designed a seated/recumbent lower limb rehabilitation robot with mechanical limit protection, electrical limit protection, and software protection, which prevents secondary injuries to the patient.

Feng et al. designed a new applicable seated horizontal lower limb rehabilitation robot.[20] A new trajectory planning method based on fourth-degree polynomial interpolation was proposed based on doctors' clinical recommendations to plan the maximum speed of each joint according to the patient's condition, thus reducing the impact load on the damaged leg. Sagila et al. [21] designed and produced a therapeutic robot (hunova) that incorporates training of trunk and pelvic muscles while rehabilitating the knee to enable the patient to improve body stability and movement posture. Wang et al. [22] designed a passive lower limb rehabilitation robot (Huang et al. [23]) to aid lower limb recovery. body stability and movement posture can be improved, thus helping the recovery of the lower limbs. Wang et al. [22] designed a passive lower limb rehabilitation robot (HE-LRR), as shown in Figure 3, which solves the problems of the traditional rehabilitation robots, such as large size and high mass. Experimental studies show that this robot can help patients achieve rehabilitation movements such as continuous passive motion (CPM) and straight leg raise (SLR).

(a) (b)

Figure 1. The MMRR. a Prototype with the indicated components: (1) leg module, (2) cushion, (3) movable platform, and (4) backrest. b the schematic diagram.[13]

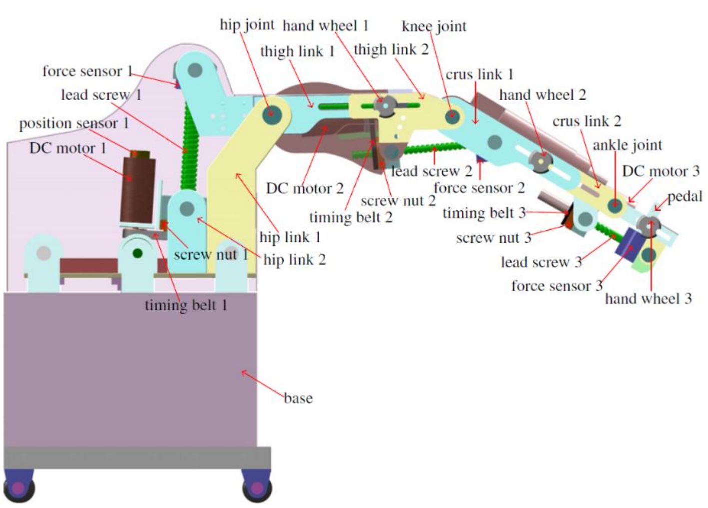


Figure 2. The virtual prototype of the leg orthosis.

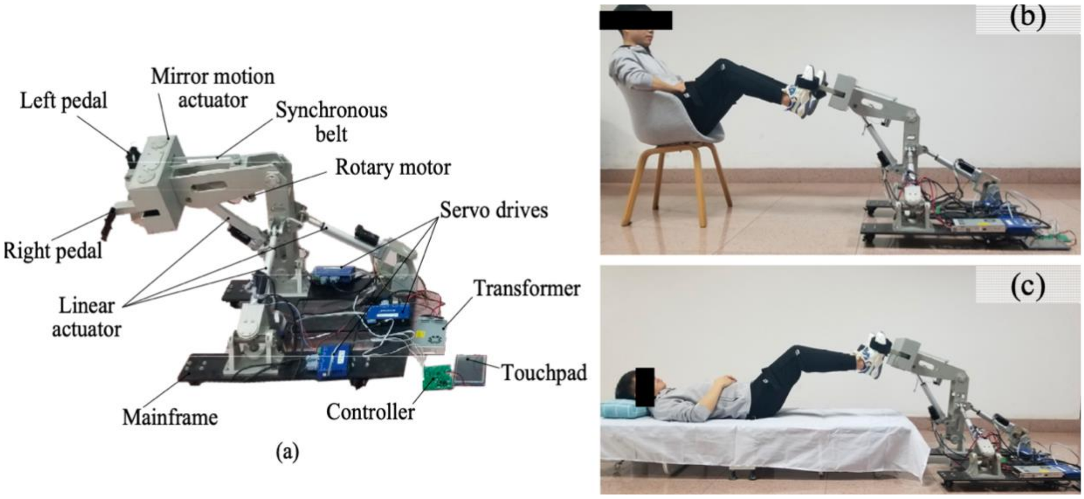


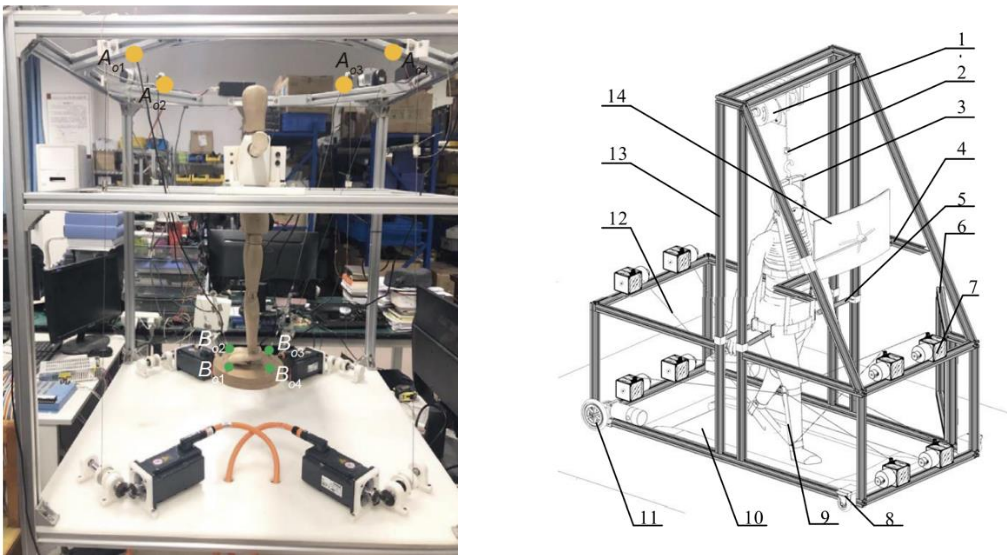
Figure 3. HE-LRR

3.2. Exoskeleton Standing Rehabilitation Robot

Exoskeletal standing rehabilitation robots are devices that are used to assist in the rehabilitation of patients in a standing position. Chen et al. [23] designed a standing-controlled knee physiotherapy robot (KADO) to assist patients with knee injuries in regaining their natural gait. The robot uses an anthropomorphic design that locks the knee joint while allowing the patient to move normally and provides the wearer with a controlled assistive torque via actuators and multiple sensors. Kirby Ann Witte et al. [24] designed a lightweight exoskeletal knee-assisting robot, which has been shown in benchtop tests to support patients during walking. The frame straps etc. of the robot ensure the patient experience. Deng et al. [25] designed an active power-assisted exoskeleton robot with a unique human-machine motion mapping to give the patient a higher degree of freedom. The effectiveness of this robot was confirmed in a single-leg swing experiment and reduced the foot effort by about 25 %. Kim et al. [26] designed a portable knee-assisted exoskeleton device that weighs only 3.5 kg and is widely applicable and can be used via controller area network (CAN) on a PC or an embedded microprocessor. etc. Bouhabba et al. [27] designed a lower limb rehabilitation robot. The robot also consists of three crank-rocker mechanisms, thus ensuring higher flexibility. Hu et al. [28] designed a recumbent lower limb rehabilitation robot, which has the features of universality, high flexibility, and flexible human-robot interaction. Granados et al. [29] designed a passive exoskeleton rehabilitation robot, which is designed to help patients to complete sit-to-stand and stand-to-stand (STS) posture transitions. sit (STS) posture transitions. experimental studies have demonstrated that patients can transfer the force from their own upper body to the lower body, resulting in a passive system with voluntary control of the natural movement of the upper body. Gao et al. [30] proposed a humanoid-designed electrically-driven lower limb exoskeleton rehabilitation robot, which can help patients recover standing and walking abilities through wearable walking assistance training. and walking ability to restore and improve limb dysfunction.

3.3. Traction Standing Rehabilitation Robot

In addition to the robots mentioned above, there are also traction rehabilitation robots, and the traction standing rehabilitation robot is also a device that assists the patient in rehabilitation training in a standing position, unlike the exoskeleton robot, which performs rehabilitation training by means of a traction rope. Li et al. [31] designed a cable-driven rehabilitation robotic system (ALLTD) with a unique double-linkage structure, which is shown in Fig. 4(a). shown in 4(a), can accomplish a variety of application scenarios. It was computationally demonstrated that this robotic system could perform rehabilitation tasks for patients with different lengths of lower limbs. Chen et al. [32] proposed a rope-type standing lower limb and lumbar rehabilitation robot with a mechanical structure including a cable-driven parallel locomotion platform, a wearable and fixed exosuit for the upper limbs, and an adjustable mechanism for the lower limbs. The validity of this model has been demonstrated anthropomorphically. Oh et al. [33] designed a self-paced standing gait rehabilitation robot, which can reduce the gait asymmetry of patients and also stimulate the recovery of damaged nerves by detecting their leg swing speeds through a series of sensors and changing the walking speeds in real time. Zou et al. [34] designed a movable cable-driven lower limb rehabilitation robot (MCLR)). As shown in Figure 4(b), it can achieve walking training in active, passive, and assisted modes, and its speed servo system can provide better tracking ability to help patients complete the active training and rehabilitation needs. Zi et al. [35] designed an active lasso-driven lower limb rehabilitation robot powered by cables and pneumatic artificial muscles (PAMs), which is divided into two independent parallel robots: a lumbar twisting device and a lower extremity traction device. Simulations showed that this robot has the characteristics of high flexibility and good adaptability. Wang et al. [36] investigated a rope cable-driven lower limb rehabilitation robot (CDLR). According to the experiment, after the optimization of the algorithm, this robot has a more uniform tension distribution of the tension of the pulling rope, faster real-time response, and is able to fit all stages of the patient's rehabilitation. Wang et al. [37] designed a cyclic interference compensation control method for the control of the traction standing rehabilitation robot, which avoids cyclic interference by automatically learning the interference pattern and thus compensating for it in advance, thus improving the accuracy of the control.



(a) (b)

Figure 4. Traction Standing Rehabilitation Robot (a)ALLTD, (b) MCLR.

4. Analysis of key technologies

4.1. Structural and institutional innovations

The active rehabilitation training device is a device that relies on the patient's own muscle strength for rehabilitation training [38], and thus has high requirements for the structural design of the device. Currently, existing rehabilitation robots mainly use mechanisms such as link structures, guide rails [39], wire traction [40] and gantries [41] to achieve the functions of joint limitation and patient support.

The linkage structure [42] is widely used in rehabilitation robots and consists of a plurality of rigid links and joints that mimic the movement trajectory of a human limb. This structure is capable of realizing a wide range of rehabilitation movements through precise motion control and is appropriately adapted to the patient's motor ability. Structures such as guide rails and wire traction [43] are commonly used to achieve joint limitation and motion guidance for robots. The guide rails guide the direction of motion of the robot and ensure smooth and precise movement. Wire traction, on the other hand, can be used to simulate different levels of exercise loads by controlling the traction force, allowing the patient to undergo progressively increasing training according to his or her condition. The gantry (or parallel mechanism) is a parallel mechanism that realizes the movement of the rehabilitation robot through multiple parallel motion links. This structure has a high degree of stability and motion precision and can provide more stable support and motion control for patients.

4.2. Drive unit design

Rehabilitation robots are trained by using mechanical devices to drive the human body for rehabilitation training, and one of the most critical technologies is the drive technology.[44] Currently, the existing drive methods for rehabilitation robots focus on electric [45] and hydraulic.[46] Electric drive[47] is one of the most common drive methods in rehabilitation robots. It passes through an electric motor and transmission devices, such as motors, reducers, and transmission gears. Electric drive has the advantages of precise control, easy programming and adaptation to different rehabilitation maneuvers. By adjusting the speed and torque of the electric motor, different speeds and intensities can be achieved to suit the patient's rehabilitation needs. On the other hand, hydraulic drive[48] is another common drive method for rehabilitation robots. It utilizes the pressure of a liquid to achieve mechanical movement, usually using hydraulic cylinders and valves to control the flow of the liquid. The hydraulic drive offers advantages such as smoothness, reliability and higher load capacity. This type of drive is suitable for rehabilitation exercises that require greater torque and force, such as heavy training and muscle strength recovery.

4.3. Control strategies

The intensity of training is a crucial factor in the rehabilitation process and needs to be precisely controlled and adapted to the patient's recovery process.[49] This individualized adaptation ensures that the rehabilitation training is not unduly burdensome for the patient, but also achieves the desired rehabilitative effect. Resistance training is considered to be an adjustment of great importance. By adjusting the resistance to exercise, impedance training can be freely adapted to the patient's rehabilitation status and level of ability. This flexibility allows impedance training to gradually improve the patient's exercise ability and help them gradually adapt to higher-intensity rehabilitation training, thus achieving better rehabilitation results.

5. Conclusion and Outlook

The research on knee rehabilitation robots has shown diversified development, and different types of robots such as seated-recumbent patient rehabilitation robots, exoskeleton standing rehabilitation robots, and traction standing rehabilitation robots have all played an active role in providing precise rehabilitation programs. Meanwhile, key technologies such as structural and institutional innovations, drive design and control strategies continue to drive the progress of robots, making them more relevant to patient needs and achieving more efficient rehabilitation.

With the continuous advancement of intelligent technology, personalized rehabilitation solutions for robots will be further enhanced. Refined control strategies and motion monitoring will help improve robot adaptability and rehabilitation outcomes. However, the complexity of the technology, cost, and safety issues with human-robot collaboration still need to be addressed. In future research, more interdisciplinary collaboration is needed to integrate knowledge from the fields of engineering, medicine, and biology to continue to drive innovation and development of knee rehabilitation robots.

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