Mechanism Design and Analysis of a Multi-DOF Flexible Ankle Rehabilitation Robot

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Abstract. According to the needs of global social development, this paper briefly describes the design and modelling of an ankle rehabilitation robot. A multi degree-of-freedom (DOF) ankle rehabilitation robot mechanism is constructed by using flexible pneumatic muscle actuators. The relevant mainstream control methods are analyzed. On this basis, we integrate the ankle rehabilitation robot with virtual reality technology and functional electrical stimulation technology, to further improve the participation of patients and improve the efficiency of ankle rehabilitation.

1. Background, Purpose & Significance
The United Nations pointed out in the Report of the Second World Assembly on Ageing that by 2050, the number of people over 60 in the world will increase to nearly 2 billion, accounting for 21%[1] of the total population. Nowadays, many countries around the world are facing the problem of the aging population. With the increase of age, people's physical performance declines, and the risk of suffering from cerebrovascular and nervous system diseases increases significantly, all of which can cause movement disorders in the lower limbs. For the recovery of patients' motor function, it is important to strengthen the recovery of ankle joint function. The ankle joint is a very important weight-bearing joint of the lower limbs, and the body's balance ability is mainly maintained by the ankle joint also. As a hub connecting the human body and the ground, once damaged, will have a great impact on the human body's movement function[2], if the rehabilitation treatment is neglected, there will be sequelae of dysfunction. Besides, traditional one-to-one rehabilitation therapy is difficult to achieve high-precision, high-intensity, and diversified rehabilitation training. With the development of the global economy, the technology and quality of products for treatment, rehabilitation, and services for ankle patients have also improved accordingly.

Traditional ankle rehabilitation robots mostly use a rigid structure with a moving platform at the upper part and a driver at the lower part. At present, the most typical ankle joint rehabilitation robot mainly adopts the 6-UPS Stewart platform structure. This type of ankle rehabilitation robot has 6-degrees of freedom(6-DOF) and is driven by an electric cylinder, which can assist patients with ankle joint injuries to complete three-direction rotation, which brings good news to the rehabilitation training of ankle patients.

On this basis, more and more research institutions will try to use flexible drives instead of cylinder drives to realize the flexible structure of rehabilitation robots and further improve the flexibility and
safety of rehabilitation robots. Now the main flexible drive is Pneumatic Muscle Actuator (PMA). PMA is composed of a rubber tube and a woven mesh, which generates output force by controlling internal air pressure and contraction. It’s movement mode and force/length characteristics are similar to biological muscles [3]. Figure 1 shows the internal structure of PMA produced by FESTO in Germany.

![Figure 1. The internal structure of PMA produced by FESTO](image)

PMA also has the advantages of (1) large output force-weight ratio and high energy conversion rate; (2) simple structure and lightweight; (3) smooth movement and no relative friction parts; (4) low price and convenient maintenance. etc, as a driver design assisted rehabilitation equipment has unique advantages.

Rehabilitation physiotherapy through artificial or simple medical equipment is far from being able to meet the rehabilitation needs of society. Therefore, rehabilitation robotics technology has emerged and has become a research hotspot in the field of robotics. The application of robotics to the field of rehabilitation medicine can not only free the rehabilitation physicians from arduous training tasks but also help patients to carry out more scientific and effective rehabilitation training so that the patient's motor function can be better restored. As a new type of pneumatic component, PMA is used on flexible rehabilitation robots, which can greatly improve the rehabilitation effect of patients and can also further enhance the flexibility and safety of robot control. It plays a very important role in the development of medical equipment.

2. Related Works

With the continuous deepening of research in various countries, modern rehabilitation technology provides a process transition from labor-intensive operations to technically assisted operations. More and more rehabilitation robots have been developed one after another. According to the different drivers, they are mainly divided into strong driving rigid Ankle rehabilitation robots and flexible ankle rehabilitation robots with good flexibility & high safety.

2.1. Rigid ankle rehabilitation robot mechanism

The structure of rigid ankle rehabilitation robots is divided into platform-based ankle rehabilitation robots and Ankle Foot Orthosis (AFO) type ankle rehabilitation robots. Among them, platform-based ankle rehabilitation robots are fixed robots that have multiple actuators to move the patient's ankle to achieve the goal of rehabilitation exercise. They are usually bulky and cannot be used for gait training. The AFO ankle rehabilitation robot is mainly used for gait training and has the advantages of being light and easy to wear.

Typical ankle rehabilitation robots based on the Stewart platform structure are like Rutgers Ankle[4], vi-RABT[5] & Ankle rehabilitation robots[6], etc.. Compared with platform-based ankle rehabilitation robots, AFO ankle rehabilitation robots can be used for gait training and have advantages such as lightweight. The ankle-foot orthosis is a single-joint orthosis, used to assist and support ankle joint movement, and can assist humans in walking. The first ankle and foot orthosis was made in the late 1960s[7]. Subsequently, related researchers developed a variety of ankle and foot orthoses, such as
AAFO[8] designed by Mazumder et al., PAAFO[9] designed by Shorter et al., and BLEEX[10][11] designed by Kazerooni et al.. The specific analysis is shown in TABLE 1 below.

**Table 1. Partly rigid ankle rehabilitation robots**

| Types of robots | robot name | institution | details | Characteristics |
|-----------------|------------|-------------|---------|-----------------|
| Platform-based  | Rutgers Ankle[4] | Rutgers University | Based on the Stewart platform, with 6-DOF, combined with virtual reality to provide assistance and resistance. | 2-DOF Can exercise in two directions: dorsiflexion/plantarflexion, varus/valgus, and can play virtual reality ankle games. |
|                 | vi-RABT[5] | Northeastern University | | 2-DOF, Fuzzy logic control has been designed for ankle rehabilitation robot. Besides, error based performance indices are used to compare the performance of the controllers. |
|                 | Ankle rehabilitation robots[6] | Karadeniz Technical University | | |
| Ankle & foot orthosis | AAFO[8] | Mazumder O, Kundu A, Lenka P, et al. | The proposed device consists of a linear actuator mechanism with the supportive brace and is controlled by measuring the user's interaction force. Provides both plantar flexor and dorsiflexor torque assistance by way of a bidirectional pneumatic rotary actuator. Using a portable pneumatic power source & embedded electronics to control the actuation of the foot. | Is a pair of wearable robot exoskeleton legs, can improve the walking ability of patients & assist the patient to assume greater weight. |
|                 | PAAFO [9] | The University of Illinois at Urbana-Champaign | | |
|                 | BLEEX [10] [11] | University of California, Berkeley | | |

2.2. Flexible ankle rehabilitation robot mechanism

The flexible ankle rehabilitation robot driven by PMA has the advantages of simple structure and good flexibility. Major research institutions have also turned their research focus to flexible ankle rehabilitation robots. Like rigid ankle rehabilitation robots, the structure of flexible ankle rehabilitation robots is also divided into platform-based ankle rehabilitation robots and AFO ankle rehabilitation robots.

Aiming at the needs of ankle rehabilitation and the flexibility of pneumatic muscles, Meng Wei[12] of Wuhan University of Technology and others designed a parallel rehabilitation robot for lower limbs and ankles and proposed a control method in the long-term repetitive trajectory control for passive training. A multi-degree-of-freedom control system structure is realized on the parallel robot, and the safety and controllability of the flexible parallel robot are verified through models and experiments.

Xie[13] of the University of Auckland in New Zealand and others designed a flexible ankle rehabilitation robot CARR with three rotational degrees of freedom. The rehabilitation robot is driven by four PMAs, which can simultaneously assist patients with ankle injuries to complete rehabilitation exercises in the three directions of X, Y & Z axes. At the same time, the robot platform is equipped with an angle sensor, a six-axis force/torque sensor, and a single-axis tension sensor, which can realize a variety of different training methods.

From the above analysis, it can be known that the rigid ankle rehabilitation robot has led researchers into a brand new field. However, with the continuous deepening of research, various research institutions are also to solve the problem that rigid ankle robots are likely to cause secondary injuries to patients, and they have begun to research flexible ankle rehabilitation robots with high safety and flexibility. However, most of them gradually developed platform-based flexible robots constructed with PMA can only assist patients to complete rehabilitation training with two degrees of freedom. The few robots that can complete rehabilitation training with three degrees of freedom cannot meet the rehabilitation needs.
of patients in the adduction/abduction direction. Therefore, there is still a lot of room for the development of current ankle rehabilitation robots.

3. Mechanism design of a Multi-DOF Flexible ankle rehabilitation robot

3.1. Ankle motion model
The ankle is one of the most complex structures of the human body and one of the most vulnerable joints of the human body. To realize the rehabilitation of the ankle, the ankle rehabilitation robot structure that meets the rehabilitation needs is designed. It is also necessary to analyze the ankle structure and rehabilitation needs. The structure of the human ankle is shown in Figure 2. It is mainly composed of Fibula, Tibia, Calcaneus & Talus, etc.

There are three main forms of ankle movement, as shown in Figure 3 below. They are dorsiflexion/plantarflexion movement around the X-axis, eversion/inversion movement around the Y-axis, and abduction/adduction movement around the Z-axis.

To meet the rehabilitation needs of the ankle, it is necessary to realize the rotational movement of the ankle in the three directions of the X, Y, and Z-axis, especially the rotational movement of the X and Y-axis. Because in the ankle rehabilitation process, the X-axis and Y-axis rotation movement play a major role[14]. When designing the robot, the range of motion of the human ankle in three directions is important to consider. Table 2 [15] shows the maximum range of motion of the ankle of most people.

![Figure 2. The structure of the human ankle](image)

![Figure 3. Three main forms of ankle movement](image)

| Table 2. Partly rigid ankle rehabilitation robots |
|-----------------------------------------------|
| Model Coordinate | Movement Direction | Maximum Movement Angle |
| +θ₁ₓ | dorsiflexion | 20.3°-29.8° |
| -θ₁ₓ | plantarflexion | 32.6°-40.8° |
| +θ₂ᵧ | inversion | 14.5°-22.0° |
| +θ₂ᵧ | eversion | 10.0°-17.0° |
| +θ₂ | adduction | 22.0°-36.0° |
| -θ₂ | abduction | 15.4°-25.9° |

3.2. Mechanism design of ankle rehabilitation robot
Pneumatic muscles can only provide pulling force, not thrust, and must have a redundant force to achieve the forced closure of the robot platform. That is, to complete a rotational movement with n degrees of freedom, at least n-1 pneumatic muscle drivers are required[16]. On this basis, it is possible to design a
rehabilitation robot with the upper driving part and the lower moving platform, and ensuring that the rotation center of the robot is consistent with the rotation center of the patient's ankle.

The ankle rehabilitation robot is mainly composed of the main motion module, a power transmission module, and a support module. Helping the patient complete the rotational movement in the three directions of dorsiflexion/plantarflexion, varus/valgus, and adduction and abduction, it can limit its translation in the three directions of X, Y, and Z axes. The power transmission module is mainly driven by 5 FESTO pneumatic muscles, which are connected to the moving platform through a flexible cable and use pulleys to change the direction of the driving force to achieve the rehabilitation needs of the ankle. The leg support brace with bolts. The telescopic rod is used to adjust the height of the thigh support plate to meet the requirements of patients with different leg lengths. The overall structure is shown in Fig. 4.

Figure 4. The overall structure of the designed ankle rehabilitation robot

4. Analysis of related control technology of ankle rehabilitation robot

4.1. Inversion sliding mode control method
The pneumatic muscle driver has the advantages of good flexibility, good output flexibility, and a large output force/weight ratio. However, the pneumatic muscle driver also has shortcomings such as strong nonlinearity and time-varying. Moreover, in the rehabilitation process, due to the disturbance of the patient's limbs, the modeling error of the pneumatic muscle driver, and the friction between the components, this is all for the pneumatic The precise position control of the muscle-driven ankle rehabilitation robot brings difficulties. Zhu Chengxiang of Wuhan University of Technology[17] proposed an adaptive backstepping sliding mode control method based on nonlinear disturbance observer, which effectively solves the problem of uncertain disturbance during robot motion.

4.2. Impedance control method
During the operation of the ankle rehabilitation robot, it is necessary to select different motion modes for the ankle rehabilitation training of patients with different degrees. Therefore, it is necessary to study the position control and force control methods of the robot. Xu Tu[18] of Wuhan University of Technology proposed an impedance control method for pneumatic muscle-driven robots, which can control the robot force by real-time adjusting the relationship between the position of the robot's end-effector and the output force.

5. Conclusion
According to the rehabilitation needs of the human ankle and the movement characteristics of pneumatic muscles, this project design a flexible pneumatic muscle-driven multi-DOF parallel redundant ankle rehabilitation robot. On this basis, the software and hardware control system of the ankle rehabilitation robot in the actual environment is established. Moreover, preliminary experiments are carried out in the
directions of dorsiflexion/plantarflexion, inversion/eversion, and adduction/abduction, combined with related control algorithms, verified the feasibility of the robot.

6. Development and prospect of ankle rehabilitation robot technology

Existing ankle rehabilitation robots mostly rely on robots to drive patients to perform passive training, which cannot improve patient initiative and muscle activity. Although there are researches on the application of functional electrical stimulation technology in medical treatment, long-term electrical stimulation can cause muscle fatigue in patients, fail to produce the desired joint movement, and hinder the progress of treatment. There are also reports on the integration of functional electrical stimulation and ankle joint rehabilitation robots, but the rehabilitation training process is relatively boring, and it is difficult to change the status quo of passive training for patients. In some existing rehabilitation systems, although virtual reality technology is introduced to guide patients in active training, precise control of force and position is difficult to achieve. Therefore, rehabilitation robots can be integrated with virtual reality technology and functional electrical stimulation technology to improve patients’ initiative, muscle activity, and further improve rehabilitation efficiency.

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