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Design of a tandem ankle rehabilitation robot

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Abstract

Impaired ankle function resulting from various diseases and sports-related inju-ries is a prevalent clinical concern, significantly affecting patients' mobility and quality of life. In response to the growing demand for effective rehabilita-tion solutions, this paper presents a novel serial-structured ankle rehabilitation robot (ARR) based on emerging robotic technologies and existing rehabilitation products. Taking into account the anatomical movement patterns and physio-logical range of motion of the ankle joint (AJ), a three-dimensional mechanical model was carefully designed to closely mimic natural joint kinematics. A func-tional prototype was developed, and experimental tests were conducted to evaluate key performance metrics, including speed response and positioning accuracy. The results demonstrated that the robot exhibits stable and responsive motion control with high precision. Furthermore, the Anybody simulation soft-ware was employed to assess the activation levels of major muscles involved in ankle movement during robotic-assisted training. The data revealed significant engagement of the targeted musculature, indicating effective muscle stimula-tion. Overall, the proposed ARR shows great potential to fulfill the essential re-quirements of ankle joint rehabilitation training.

Keywords

Ankle rehabilitation; Series structure; Simulation analysis; Prototype experiment; Evaluation of rehabilitation efficacy

1. Introduction

The AJ is a key joint in the human motor system, responsible for a variety of complex motor functions such as walking and running [1]. However, ankle injuries and dysfunctions are very common in clinical practice due to sports injuries, neurological diseases or post-operative rehabilitation [2]. Traditional rehabilitation therapy usually relies on manual assistance by physical therapists, but this method is not only inefficient, but also difficult to ensure the accuracy and individual needs of rehabilitation training[3]. In recent years, with the development of robotics and biomechanics, ARRs have gradually become an important rehabilitation auxiliary tool[4]. Through precise control and multi-degree-of-freedom motion support, rehabilitation robots can provide training programs with strong repeatability and high controllability, which helps to improve the rehabilitation effect and speed of patients. Although the parallel structure has the advantages of small inertia, high stiffness, and compact structure[5], when applied to ARRs, its application in this field is limited due to complex design and control, limited range of motion, unnecessary high precision, and high stiffness. In contrast, the serial structure has the advantages of simple design and control, high flexibility, significant cost-effectiveness, and better ability to meet the needs of ankle rehabilitation[6]. Therefore, this paper chooses the serial structure as the design basis of the ARR.

2. AJ physiological model and structural design

2.1. AJ structure analysis

The basic movements of the AJ include DO, PF, IN, EV, AD and AB. DO refers to the movement of lifting the instep upward and increasing the angle. PF is the opposite movement, with the toes pointing downward and the ankle angle decreasing. IN and EV are the movements of the sole of the foot toward or away from the midline of the body, respectively. IN lifts the outside of the ankle, while EV lifts the inside. AD and AB are mainly the left and right movements of the AJ in the horizontal plane. In AD, the foot moves inward toward the midline of the body, while AB moves away from the midline[7]. The above related movements are shown in Figure 1.

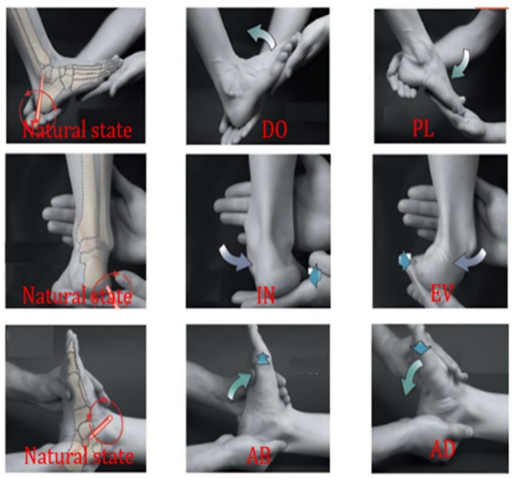


Figure 1. Basic AJ movements

The above movements have different functions and different ranges of motio n. Although everyone's ankle size is different, the range of motion of the rel evant movements is roughly the same,DO/PL,-20~30° ;IN/EV,-30~15° ;AD/AB, -30~30° .

2.2. Structural design of ARR

The designed ARR is shown in Figure 2. The robot has three degrees of freedom, and three joint motors drive the dynamic platform to achieve different movements[8]. The joint motor is an intelligent servo driver that not only meets the various requirements of kinematic control, but also meets the practice of dynamic control[9]. It has built-in encoders, reducers, torque sensors, etc., which can be intelligently programmed to achieve precise control. The robot's motion axes intersect at one point, which is the rotation center of the mechanism. In order to make the rotation center of the patient's ankle coincide with the rotation center of the robot, a dynamic platform height adjustment device is designed.

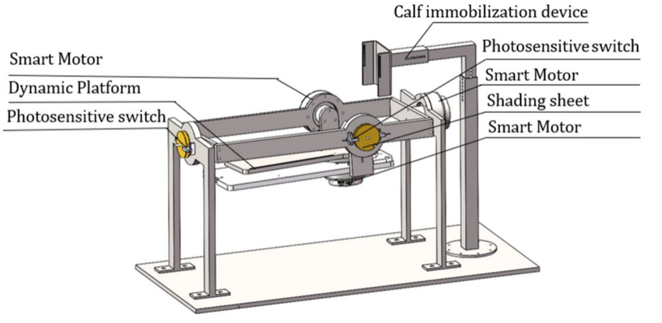


Figure 2. AJ rehabilitation robot structure

For safety reasons, a limit device is set to prevent motor control failure, which may cause the range of motion to exceed the preset angle and cause secondary injury to the patient. The limit devices responsible for IN/EV movement and DO/PF movement have the same principle, as shown in Figure 3. The specific limiting principle is that after the recovery angle is set, the notch on the shading sheet is rotated about 2 degrees larger than the recovery angle and enters the inside of the photosensitive switch. At this time, the photosensitive switch will generate a signal to cut off the power of the system, thereby preventing the motor from continuing to rotate.

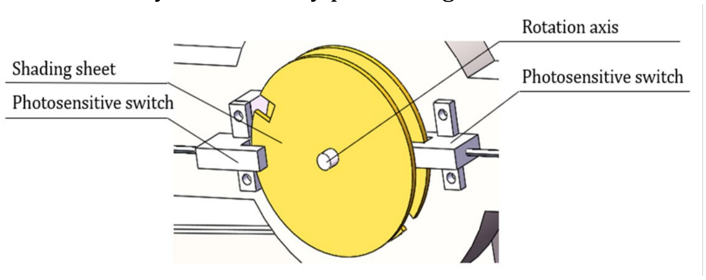


Figure 3. IN/EV and DO/PF Limit Devices

The limit device for the AD/AB action is shown in Figure 4. After setting the rehabilitation angle, place the limit slider at a position greater than 2 degrees than the rehabilitation angle. When the set rehabilitation angle is exceeded, the limit slider will prevent the rotating block from continuing to rotate, thereby preventing the mechanism from continuing to rotate.

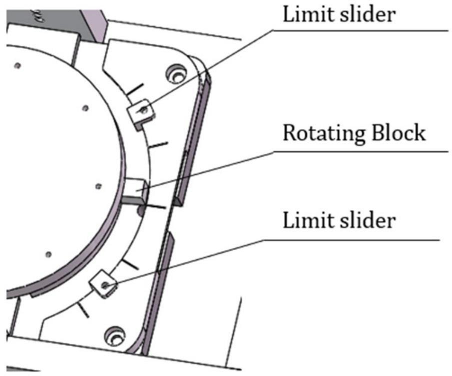


Figure 4. Internal/external rotation Limit Devices

3. Prototype experiment

In rehabilitation training, the AJ rehabilitation robot moves continuously, so the dynamic performance of the control system is the main indicator reflecting the practicality of the robot[10]. The velocity loop is used to control the joints of the robot. The Simulink control model of the AJ rehabilitation robot is shown in Figure 5.

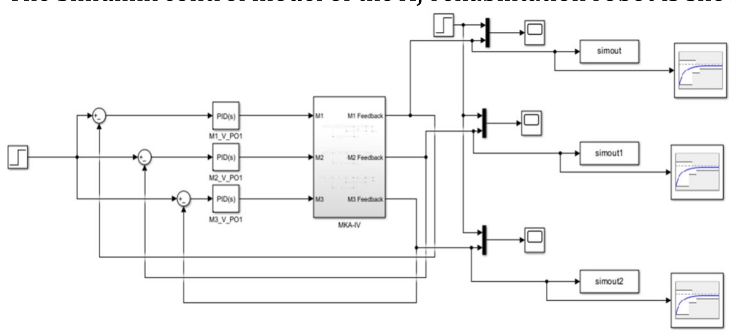


Figure 5. Simulink control model

The experimental prototype was assembled using 3D printing, as shown in Figure 6. Next, the speed response characteristics of the dynamic platform performing three actions are analyzed respectively, moving at speeds of ±2 rpm,
±5 rpm, and±7 rpm, and the system saves data at a frequency of 200Hz. The prototype is allowed to perform DO/PF, IN/EV, and AD/AB movements in sequence, as shown in Figure 7. The dotted line in the figure represents the actual response data, and the solid line represents the simulated data. Analyze two important time domain indicators: rise time and overshoot %. The actual ascent time and overshoot of the robot are shown in Table 2.

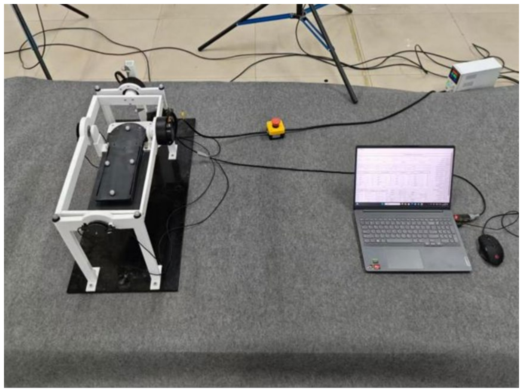
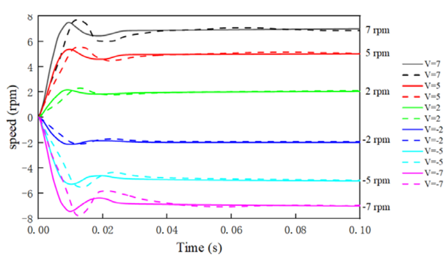


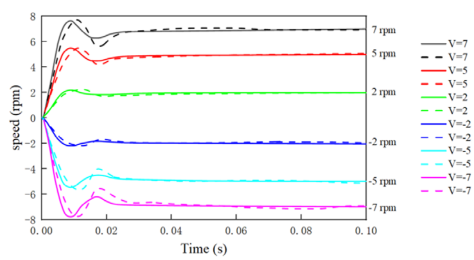
Figure 6. Experimental prototype

Figure 7. Prototype Movement

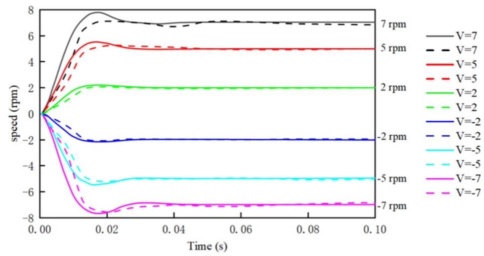
Next, the speed characteristic curve of the prototype motion is sorted out and compared with the speed characteristic curve obtained by simulation, as shown in Figure 8.



(a)



(b)



(c)

Figure 8. Speed response curve. (a) DO/PF speed response curve. (b) IN/EV speed response curve. (c) AD/AB speed response curve

Table 1. The experimental data of speed response

Speed(rpm)		2	-2	5	-5	7	-7
DO/PF	t_r(ms)	7.14	8.23	9.25	9.62	10.59	11.75
	σ(%)	7.45	8.23	11.21	11.26	10.45	10.78
IN/EV	t_r(ms)	8.21	8.42	9.38	8.68	11.25	11.48
	σ(%)	3.12	8.04	3.25	9.23	2.15	8.08
AD/AB	t_r(ms)	11.20	10.68	12.13	10.78	12.74	12.33
	σ(%)	3.18	8.45	3.05	3.65	2.02	8.78

According to Figure 8, the simulation curve of the velocity characteristic curve is roughly consistent with the experimental curve, which verifies the accuracy and reliability of the model and control algorithm, and also shows that the physical parameters of the system and the assumptions in the simulation process are reasonable. According to the data in Table 1, when the robot performs DO/PF, $t_{r\,max}$ =11.75ms, σ_{max} =11.26%. When performing IN/EV movement, $t_{r\,max}$=11.48ms, σ_{max}=9.23%. When performing AD/AB movement, $t_{r\,max}$=12.74ms, σ_{max}=8.78%. The smaller rise time and overshoot indicate that the system has fast and smooth dynamic response characteristics, and the stability and control performance are good.

4. Conclusions

In order to reduce the burden of ankle rehabilitation doctors and provide patients with more timely and effective rehabilitation treatment, this paper proposes an ARR with a serial structure. The movement characteristics of the AJ are analyzed, and the range of motion of the AJ is listed, so as to set a reasonable rehabilitation range in the subsequent rehabilitation process. The structure of the ARR was designed using Solidworks software, the mechanism design principle and dynamic model were introduced, and the safety limit device was designed.The speed response characteristics and position accuracy of the prototype were tested. The results show that the prototype has good speed response characteristics and position accuracy, which meets the design expectations. laying the foundation for further human-machine experiments in the future.

The next step of the research should focus on formulating flexible rehabilitation strategies for different patients and conducting experimental analysis in combination with specific patients.

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