Wearable Ankle Rehabilitation Device Based on Novel Series Elastic Actuator

Kai GUO, Sha-sha ZHAO*, Yong-feng LIU, Bin LIU and Hong-bo YANG
Suzhou Institute of Biomedical Engineering and Technology, Chinese Academy of Sciences,
Suzhou 215163, China
*Corresponding author

Keywords: Rehabilitation robotics, Ankle orthosis, Torsion spring, Isokinetic dynamometer.

Abstract. To assist patients with ankle diseases in completing rehabilitation training, a wearable ankle orthosis was presented in this paper. Firstly, the SEA-DTS (the series elastic actuator based on the double-tendon-sheath transmission mechanism and torsion spring), the execution mechanism of the ankle joint and the control system were described. Then, a series of experiments regarding trajectory tracking, moment step response, and position frequency response are carried out to study the mechanical characteristics of the wearable ankle orthosis. Results show that the participation of the SEA-DTS helps the orthosis work smoothly, while causes a maximum deviation of 3.56° in the trajectory tracking, a 10ms-delay and a maximum 16% overshoot in the moment step response performance, the bandwidth of the orthosis is 5.5Hz. Finally, the results obtained from two isokinetic dynamometer experiments prove the effectiveness of the wearable ankle orthosis, which means the proposed orthosis can assist patients with ankle diseases in completing rehabilitation training.

Introduction

Among the joints of the human body, the ankle is the nearest person and ground joints. The ankle bears the weight of almost the entire people, especially when the person at the time of jumping, running and the body weight, ankle under tremendous impact and load, leading to an ankle injury is body joint injury incidence was the highest one, also is a very common clinical disease[1]. The ankle is the most common site of sprain injuries in the human body, with over 23,000 cases estimated to occur per day in the United States[2]. In New Zealand, more than 82,000 new claims and 17,200 ongoing claims related to ankle injuries were made to the Accident Compensation Corporation (ACC) in the 2000/01 year. Costing an estimated 31.8 million New Zealand dollars and making ankle related claims the fourth biggest cost to ACC[3]; Ankle injury accounted for more than 10% of all sports injuries, in which 80% or more were ligamentous sprain injuries[4-8]. Traditionally ankle injuries are rehabilitated via physiotherapy and however, evidence suggests that without sufficient rehabilitation: 44% of people will have future problems [9-11]. Both medical theory and clinical medicine have proved that in addition to early medical treatment and surgical treatment, patients with ankle joint injury need to carry out scientific, accurate, and appropriate rehabilitation training. It plays an important role in the recovery of the ankle joint motor function. In traditional joint rehabilitation training. Physical therapists usually perform one-on-one rehabilitation in a freehand manner. Physiotherapist completes robotic automation device for joint rehabilitation training. The ankle joint rehabilitation device for ankle rehabilitation training has achieved many research results after years of development[12-18].

This paper designs a lightweight, two-degree-of-free wearable ankle rehabilitation device based on a series of elastic actuators. Based on the double lasso transmission mechanism and torsion spring, a new series elastic actuator SEA-DTS is designed, which not only can achieve accurate joint torque control but also can make the wearable ankle joint rehabilitation device have certain joint flexibility. By placing the double lasso drive mechanism outside the ankle joint motion execution assembly, the
mass and inertia of the motion execution component are reduced, power consumption is reduced, and power is transmitted remotely.

The Wearable Ankle Orthosis

Figure 1 shows the overall structure of the two-degree-of-freedom wearable ankle rehabilitation device based on SEA-DTS, which consists of an ankle joint motion execution component, two sets of SEA-DTS, and a control platform. To satisfy the patient's ankle joint multi-degree of freedom rehabilitation training requirements and to minimize the structural complexity, the wearable ankle rehabilitation device has two degrees of freedom in structure, namely dorsiflexion degrees of freedom and valgus degrees of freedom.

![Figure 1. Structure diagram of the wearable ankle orthosis.](image1)

SEA-DTS Series Elastic Driver

Conventional robots, such as industrial robotic arms, often detect the torque value of the joint by adding a rigid torque sensor to the joint to achieve accurate joint torque control. Although this method can accurately and directly measure the torque value of the moving joint, this method makes the joint of the robot lack joint flexibility and is not suitable for the joint rehabilitation device that requires human-computer interaction.

To make the wearable ankle joint rehabilitation device achieve accurate joint torque control and joint flexibility, this paper designs a new type of SEA-DTS series elastic actuator based on double lasso transmission mechanism and torsion spring. The overall structure is shown in Figure 2. The SEA-DTS includes a double lasso drive mechanism, a double lasso drive mechanism, and a torsion spring. The double lasso drive mechanism places the double lasso drive mechanism outside the ankle joint motion actuator for remote transmission of power [19-22]. Torsion springs are used for joint torque control and increase joint flexibility. As shown in Figure 3, the outer ring of the torsion spring is fixedly connected with the execution wheel, the inner ring is connected with the power output disk, and the rotating shaft of the encoder is connected with the execution wheel for detecting the rotation angle of the SEA-DTS execution wheel. To prevent the torsion spring from receiving axial force during operation, the inner ring of the torsion spring is supported on the execution wheel by the torsion spring rotating shaft and the bearing.

![Figure 2. Structure diagram of the SEA-DTS.](image2)
The principle of the double lasso transmission mechanism is shown in Figure 4, including the drive wheel, the sleeve fixed support block, the rope, the casing, the rope fixing block, and the execution wheel. The double lasso transmission mechanism has a rope, and a lasso fixed on each side of the drive wheel and the execution wheel. When the driving wheel rotates clockwise, the driving wheel pulls the rope b to slide in the groove of the driving wheel and the executing wheel, thereby driving the executing wheel to rotate clockwise around its axis, driving the human joint to rotate clockwise. At this time, the rope b is in a stretched state, and the rope is in a natural state. When the driving wheel rotates counterclockwise, the situation is reversed, the rope a is in a stretched state, the rope b is in a natural state, and the joint is rotated counterclockwise. To avoid the phenomenon of rope slack in the transmission, the rope is always in tension during the transmission process. The pre-tightening block and the pre-tightening screw are added, and the screwing of the pre-tightening screw realizes the manual constant force pre-tightening of the double-lasso transmission mechanism, and the adjustment is performed periodically.

Traditional torque sensors are mostly strained gauge-based, high-stiffness sensors that lack flexibility. In this paper, an encoder-based, flexible torsion spring is used as the joint torque sensor for the wearable ankle rehabilitation device. According to the structural form of the torsion spring in, it consists of inner ring, outer ring, and intermediate deformed body, and the structural design is carried out according to the joint torque and joint shape requirements of the wearable ankle joint rehabilitation device. A group of normal people and a group of stroke patients were subjected to the joint torque required for dorsiflexion and varus/valgus degree of freedom. According to the experimental results, the basic parameters of the torsion spring were: The maximum torque is 8 Nm, the maximum torsion angle is ≤5°, the outer diameter is ≤90mm, and the thickness is ≤5mm. The material used for the torsion spring is 18Ni (300). After aging treatment, the yield strength is 1900 MPa, and the tensile strength is 2060 MPa. In this paper, the ANSYS finite element simulation analysis of the designed torsion spring is carried out. The simulation results under the maximum load of 8.0 N.m are shown in Figure 5. The maximum stress is 1147.3MPa, the maximum torsion angle is 4.481°, and the maximum displacement is 4.39mm.
The torsion spring is used as a torque sensor and an intention detecting sensor in the wearable ankle rehabilitation device. To obtain the corresponding relationship between the moment and the torsion angle, that is, the torsional stiffness of the torsion spring, it is necessary to perform a torque-torsion angle calibration experiment. The experimental calibration data and the effects before and after the deformation are shown in Figures 6 and 7, respectively. It can be seen from Figure 7 that the designed torsion spring has high linearity, the maximum torque can reach 8.0 N.m, and the torsion angle is 3.988° under a maximum torque of 8 N.m.

![Figure 5. Simulation results of the torsion spring.](image)

![Figure 6. Torque versus rotation characteristics of the torsion spring.](image)

![Figure 7. Diagram of the torsion spring before and after the deformation.](image)

### Table 1. Properties of the torsion spring.

| Parameter           | Value  | Parameter   | Value  |
|---------------------|--------|-------------|--------|
| Torsional stiffness | 114.94 | Diameter    | 87mm   |
| Maximum torque      | 8 N.m  | Thickness   | 4mm    |
| Maximum twist angle | 3.988° | Weight      | 87g    |

The actual basic parameters of the torsion spring are shown in Table 1. There is a certain deviation from the ANSYS software simulation results. The main reason for the analysis is that there is a certain error in the wire cutting process so that the wall thickness of the intermediate deformation body is larger than the design value, but the experimental error is relatively small, within an acceptable error range.

**Ankle Joint Exercise Component**

The ankle joint exercise assembly has two degrees of freedom: dorsiflexion freedom and valgus freedom. The structural schematic is shown in Figure 8. The dorsiflexion degrees of freedom include active and passive parts. The active part is included in the SEA-DTS execution section and is connected to it via a degree of freedom connecting plate. The encoder one installed in the dorsiflexion SEA-DTS execution section is used to detect the output angle of the dorsiflexion SEA-DTS. An encoder to is mounted in the passive portion for detecting the angle of motion of the dorsiflexion freedom, that is, the actual angle of motion of the ankle joint dorsiflexion. By multiplying the angular
difference by the stiffness coefficient of the torsion spring, the moment value of the ankle dorsiflexion freedom can be obtained. Valgus freedom also includes active and passive parts. The encoder 3 and the encoder four are respectively mounted in the valgus SEA-DTS execution portion and the passive portion, respectively measuring the output rotation angle of the valgus SEA-DTS and the actual movement angle of the valgus. Similarly, by multiplying the angular difference by the stiffness coefficient of the torsion spring, the moment value of the ankle valgus freedom can be obtained.

![Figure 8. Structure diagram of the ankle joint execution component.](image)

The ankle joint motion actuator's dorsiflexion motion range is from 0 to 30°, and the plantar flexion freedom range is from 0 to 45°. The valgus degrees of freedom range from 0 to 15°, and the various degrees of freedom range from 0 to 15°. The dorsiflexion/plantarflexion is partially fixed to the tibia connection plate. The valgus degree of freedom is partially connected in series with the dorsiflexion degree of freedom through the degree of freedom connecting plate and is fixedly connected to the footplate through the auxiliary connecting plate. To meet individual adaptability, the ankle joint exercise assembly is designed with a length-adjustable mechanism at the tibia connection plate and the two auxiliary connecting plates. As shown in Figure 9.

![Figure 9. Length adjusting mechanism of the ankle joint execution component.](image)

**Control Platform Hardware Composition**

Figure 10 shows the control platform based on STM32F103, which is mainly composed of the mechanical body of the ankle joint rehabilitation device, the angle sensor, the motor driver, the STM32F103, and the PC. The torsion spring integrated into the mechanical body of the ankle rehabilitation device is used as a torque sensor for detecting the ankle joint torque value. The motor driver is used to drive the motor movement. The PC is used for human-computer interaction and real-time data display of the user interface, as well as the collection and storage of experimental data.
Summary

Aiming at the existing ankle rehabilitation device without joint flexibility, high energy consumption, drive performance requirements higher. Based on double lasso transmission mechanism and torsion spring designed a kind of joint flexibility, two degrees of freedom of wearable ankle rehabilitation device, making the ankle rehabilitation device has a certain flexibility, and reduces the power consumption of the system, and realize remote transmission of power. The trajectory tracking experiment proves that the ankle rehabilitation device has good trajectory tracking performance. The moment step response experiment shows that the ankle rehabilitation device can achieve fast and accurate moment tracking. The trend of the phase-frequency characteristic curve is consistent with that of the amplitude-frequency characteristic curve. The isokinetic muscle force experiment verifies the feasibility of the torsion spring and ankle rehabilitation device designed in this paper. Based on the research in this paper, the future work will conduct the experimental study on the control and performance of the valgus degrees of freedom of the ankle joint. Also, a variety of rehabilitation training modes, such as active and passive training modes, will be studied according to the actual rehabilitation needs of patients.

Acknowledgement

This work was financially supported by “Jiangsu Province Science and Technology Plan Key Project” (No. BE2017007-2), “Changchun Science and Technology Innovation Major Project” (No. CC003247), “Jiangsu Science and Technology Plan Project” (SBE2017740113), “Science and Technology Service Network Initiative of Chinese Academy of Sciences” (KFJ-STS-QYZX-028), and “Suzhou City Science and Technology Plan Key Industry Technology Innovation Prospective Application Research Project” (SYG201824).

References

[1] Bradley D, Croce P, Weinik M M. Ankle Rehabilitation[J]. Journal of Back and Musculoskeletal Rehabilitation, 1992, 2(3):55-62.
[2] Hertel J: Functional anatomy, pathomechanics, and pathophysiology of lateral ankle instability. J Athl Train 2002, 37: 364-375.
[3] ACC898 Managing soft tissue ankle injuries: a summary of recent research. +cost
[4] Fong DTP, Hong Y, Chan LK, Yung PSH, Chan KM. A systematic review on ankle injury and ankle sprains in sports. Sports Med.2007; 37:73-94.
[5] Garrick JG, Requa RK. The epidemiology of foot and ankle injuries in sports. Clin Sports Med 1988; 7:29-36.
[6] Dettori J, Basmania C: Early ankle mobilization, part II: a one-year follow-up of acute, lateral ankle sprains (a randomized clinical trial). Mil Med 1994, 159: 15-20.
[7] Jamwal PK: Design analysis and control of wearable ankle rehabilitation robot. The University of Auckland, Mechanical Engineering Department: PHD thesis; 2011.

[8] Zhang M, T Claire Davies. Effectiveness of robot-assisted therapy on ankle rehabilitation—a systematic review[J]. Journal of Neuro Engineering and Rehabilitation, 2013, 10(1):30.

[9] Stokes M. Neurological physiotherapy[M]. London, UK: Mosby International Limited, 1998.

[10] Trevino S, Davis P, Hecht P: Management of acute and chronic lateral ligament injuries of the ankle. Orthop Clin North Am 1994, 25: 1-16.

[11] Dollar A M, Herr H. Lower Extremity Exoskeletons and Active Orthoses: Challenges and State-of-the-Art[J]. IEEE Transactions on Robotics, 2008, 24(1): 144-158.