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A Preliminary Study on Robot-Assisted Ankle Rehabilitation for the Treatment of Drop Foot

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Abstract This paper involves the use of a compliant ankle rehabilitation robot (CARR) for the treatment of drop foot. The robot has a bio-inspired design by employing four Festo Fluidic muscles (FFMs) that mimic skeletal muscles actuating three rotational degrees of freedom (DOFs). A trajectory tracking controller was developed in joint task space to track the predefined trajectory of the end effector. This controller was achieved by controlling individual FFM length based on inverse kinematics. Three patients with drop foot participated in a preliminary study to evaluate the potential of the CARR for clinical applications. Ankle stretching exercises along ankle dorsiflexion and plantarflexion (DP) were delivered for treating drop foot. All patients gave positive feedback in using this ankle robot for the treatment of drop foot, although some limitations exist. The proposed controller showed satisfactory accuracy in trajectory tracking, with all root mean square deviation (RMSD) values no greater than 0.0335 rad and normalized root mean square deviation (NRMSD) values less than 6.7%. These preliminary findings support the potentials of the CARR for clinical applications. Future work will investigate the effectiveness of the robot for treating drop foot on a large sample of subjects.

Keywords Robot-assisted · Ankle · Rehabilitation · Drop foot · Stretching

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1 Introduction

Drop foot is very common following neurological injuries, such as stroke and spinal cord injury (SCI) [1, 2]. Based on an up-to-date report from the American Heart Association, approximately 795,000 people experience a new or recurrent stroke in the United States each year, of which about 610,000 are the first events and the remainder are recurrent events [3]. An estimated 60,000 stroke survivors live in New Zealand [4] and around 3,000 stroke patients are discharged from hospitals each year with significantly abnormal gait pattern [5]. In New Zealand, every year approximately 80 to 130 people are diagnosed with SCI through injury or medical causes [6]. Many of these neurologically impaired subjects have the symptom of drop foot, which affects their lives and those of many others, especially their families. Neurological impairment such as stroke can lead to reduced or no muscle activity around the ankle and knee causing the inability of an individual to lift their foot. Drop foot prevents them from lifting their feet and toes properly when walking, affecting the balance, general mobility, and self-confidence. Walking for such patients is slow, uncomfortable and tiring,

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taking great effort and concentration, and it also leads to hip, pelvis and back pain.

Treatments of drop foot are variable depending on specific causes. While treatments, such as braces and orthotics [7–9], functional electrical stimulation [10–12] and surgery [13], have been demonstrated to be effective for drop foot, physiotherapy as the primary treatment is commonly prescribed together with other options to maximize the function of the patient [14, 15]. Strengthening exercises of the muscles within the foot and the lower limbs help maintain muscle tone, and improve gait pattern associated with drop foot. For the treatment of drop foot, joint stretching along dorsiflexion is important and requires large driven torque from the robot. A conventional physiotherapy treatment of drop foot usually requires cooperative and intensive efforts from both therapists and patients over prolonged sessions [16].

Robot-assisted ankle rehabilitation solutions, as therapeutic adjuncts to facilitate clinical practice, have been actively researched in the past few decades. The robot could provide a rich stream of data using intelligent sensing units to facilitate patient diagnosis, customization of the therapy, and maintenance of patient records. There are two types of ankle rehabilitation devices. In one group are wearable exoskeletons or powered ankle orthoses developed to control position and motion of the ankle, compensate for weakness, or correct deformities [17–19]. With respect to traditional passive foot orthoses, these actuated devices have additional capabilities to promote appropriate gait dynamics for better rehabilitation The MIT Anklebot developed by Roy et al. [20] was controlled to adjust the impedance of the orthotic joint throughout the walking cycle for the treatment of drop foot. Park et al. [21] developed an active soft ankle orthotic device for use in treating ankle–foot pathologies associated with neuromuscular disorders, including drop foot. Ferris et al. [19] constructed a powered ankle–foot orthosis for human gait rehabilitation with a novel myoelectric controller. These robotic devices usually operate in a mobile way for gait training.

The other group consists of various platform-based robots that are stationary. Each device has a fixed platform and a moving one [22–26]. While Zhang et al. [27] demonstrated the effectiveness of existing rehabilitation robots in reducing ankle impairments caused by neurological injuries, most of them suffer from a variety of limitations when used for the treatment of drop foot. Parallel robots with misaligned rotation centers with the ankle joint are unsuitable for this application [28–30], since that training using these devices usually requires synergic movement of the lower limb of patients Parallel robots whose rotation center coincides with the ankle joint is more suitable for treating drop foot, where the patient can place his/her shank on a leg holder. This kind of robots can have a single range of motion (DOF) or multiple DOFs. Zhang et al. [22] developed a

single-DOF ankle robot for joint stretching and its efficacy has been demonstrated on patients with spasticity or contracture. Two parallel robots developed in The University of Auckland [23, 24] have not been clinically evaluated.

A compliant ankle rehabilitation robot (CARR) has been recently developed in our group [31]. This robot has been significantly improved with respect to previous prototypes [23, 24], and its advantages include the use of compliant actuators, three DOFs for three-dimensional ankle training, and high actuation torque when used for joint stretching and muscle strengthening. These features make its applications more extensive with respect to other ankle rehabilitation robots. While this robot can be used for the treatment of drop foot due to large capacity of joint actuation torque, its use and efficacy have not evaluated yet. This paper will investigate and evaluate the use of this ankle robot on neurologically impaired subjects for treating drop foot. This paper is organized as follows. Section 2 introduces the ankle rehabilitation robot with detailed kinematic and functional description, the joint-space controller design, and the training protocol. Preliminary clinical trials on three patients were conducted in Section 3, followed by discussion and conclusion in Section 4.

2 Methods

2.1 Compliant Ankle Rehabilitation Robot (CARR)

The ankle rehabilitation robot has a bio-inspired design by mimicking the configuration and actuation of the ankle joint by natural muscles, as shown in Fig. 1. This device, as a parallel mechanism, consists of a fixed platform and a moving platform, of which the moving one is actually a three-link serial manipulator. The third link of the moving platform is also denoted as the end effector that is rigidly connected with the foot plate through a six-axis load cell. It has three rotational DOFs that are actuated by four Festo Fluidic muscles (FFMs) (FESTO DMSP-20-400N). The reason why the proposed ankle robot is redundantly actuated is that the FFM can only pull and cannot push, which means that n+1 actuators are required to achieve n-DOF motion [32] These three DOFs are for ankle dorsiflexion/plantarflexion (DP), inversion/eversion (IE), and adduction/abduction (AA), respectively. Four proportional pressure regulators (FESTO VPPM-6L-L-1-G18-0L6H) are used for direct pressure control of individual actuator.

To allow trajectory control of this ankle robot, the posture measurement of the end effector should be conducted. Various assessment techniques have been reviewed by Zhang et al. [33] in the field of robot-assisted ankle rehabilitation. On this device, three magnetic rotary encoders (AMS AS5048A) are installed along each axis (red, blue

Fig. 1 The prototype of the CARR. (FFM: Festo fluidic muscle; PPR: proportional pressure regulator; these three DOFs are presented in red, blue, and pink dotted lines, respectively; the fixed platform consists of an upper platform and a lower one; and the lower fixed platform is connected with the first link of the moving platform by a revolute joint)
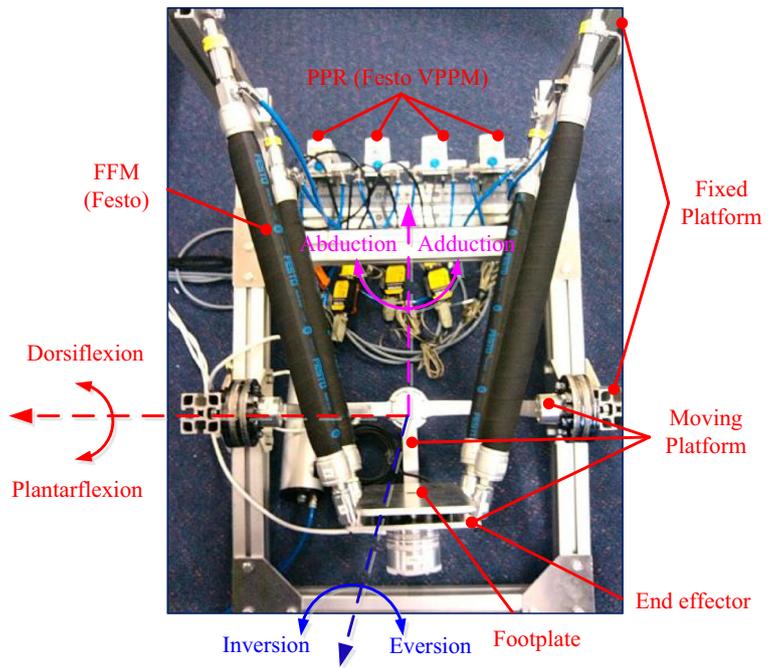
and pink dotted lines in Figs. 1 and 2) for measuring three-dimensional angular positions of the end effector and the foot plate. It is assumed here that there is no relative motion between the foot plate and the human foot during the training, thus the measured position of the foot plate equals that of the involved foot. These electronic components including the actuation system and the sensing unit, communicate with an embedded controller (NI Compact RIO-9022) through three independent modules (NI 9401, NI 9205 and NI 9263) for digital input/output, analog input and analog output, respectively.

2.2 Muscle Length Control in Joint Space

The inverse kinematics of the developed CARR system can provide a unique solution of the lengths of the FFMs for a given posture of the end effector. As in Fig. 3, the fixed coordinate frame of the upper fixed platform is denoted as O_f and the moving one of the moving platform as O_m. Connection points of the ith actuator on the fixed and moving platforms are denoted as P_i^f and P_i^m respectively. Their

position vectors P_i^f and P_i^m are defined in Eq. 1 as well as the position vector $\overrightarrow{O_f O_m}$. The position vectors L_i^f of the ith actuator is described in Eq. 2, where the rotation matrix of the end effector with respect to the fixed platform using a fixed axis rotation sequence of its orientation $\theta_x, \theta_y, \theta_z$ is denoted as R_m^f The length l_i^f of the ith actuator is given in Eq. 3.

$$\begin{cases} P_i^f = \begin{bmatrix} x_i^f & y_i^f & 0 \end{bmatrix}^T \\ P_i^m = \begin{bmatrix} x_i^m & y_i^m & 0 \end{bmatrix}^T \\ O = \overrightarrow{O_f O_m} = \begin{bmatrix} 0 & 0 & -H \end{bmatrix}^T \end{cases} \tag{1}$$
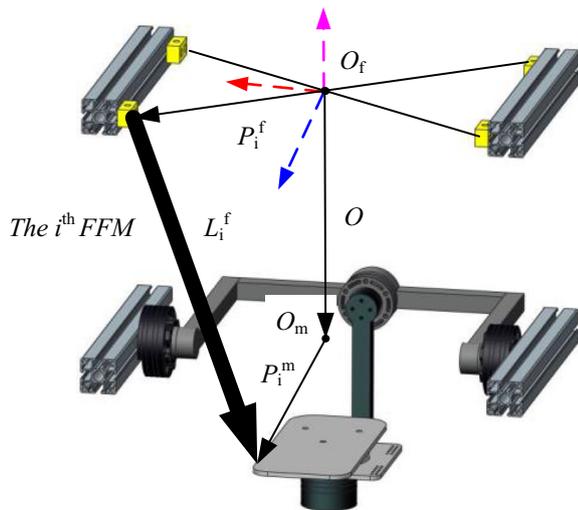
$$L_i^f = O + R_m^f P_i^m - P_i^f \tag{2}$$

$$l_i^f = \sqrt{\left(L_i^f\right)^T L_i^f} \tag{3}$$

Trajectory control of an ankle rehabilitation robot is a basic requirement for both passive and active training. The trajectory control of the CARR can be achieved by controlling

Fig. 2 Installation of the rotary encode on the CARR. (FP: fixed platform, the red, blue and pink dotted lines are the same as those in Fig. 1)
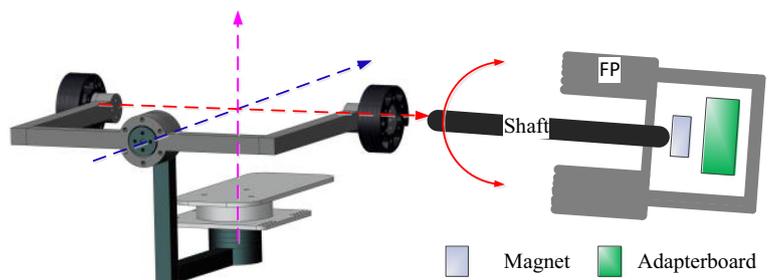
Fig. 3 .The kinematic geometry of the CARR. (The red, blue and pink dotted lines are denoted as axis-X, Y and Z, respectively, representing the rotation axes of ankle DP, IE and AA)

individual FFM length in joint space, as shown in Fig. 4. The desired individual FFM length can be calculated by inverse kinematics based on the desired posture of the end effector, while, as the feedback to the proportional–integral–derivative (PID) controller, the actual individual FFM length is obtained also by inverse kinematics based on the measured posture of the end effector. These four individual controllers output four pressure values that directly go to four proportional pressure regulators to actuate the CARR.

The desired trajectory is generally prescribed by a physiotherapist or a doctor, and denoted as $\theta_d(t)$ in Eq. 4. The measured trajectory is obtained from three magnetic rotary encoders and denoted as $\theta_m(t)$ in Eq. 5. Individual FFM length can then be obtained in Eq. 6 based on inverse kinematics, where $L_{4\times1}^d(t)$ and $L_{4\times1}^m(t)$ represent the desired and measured FFM lengths, respectively. The parameter μ

is a constant that relates the FFM length to the link length depending on the robot configuration. The matrix $\aleph_{4\times3}$ relates the link length to the posture of the end effector, and it is the Jacobian matrix based on inverse kinematics. Lastly, the error $e_{4\times1}(t)$ given in Eq. 7 is input to PID controllers, and the desired pressure p of individual FFM can be calculated according to Eq. 8 with well-tuned K_p, K_i, and K_d The flow chart of the trajectory tracking controller is presented in Fig. 4

$$\theta_d(t) = \left[\, \theta_x^d(t)\ \theta_y^d(t)\ \theta_z^d(t)\,\right]^T \tag{4}$$

$$\theta_m(t) = \left[\, \theta_x^m(t)\ \theta_y^m(t)\ \theta_z^m(t)\,\right]^T \tag{5}$$

$$\begin{cases} L_{4\times1}^d(t) = \mu\aleph_{4\times3}\theta_d(t) \\ L_{4\times1}^m(t) = \mu\aleph_{4\times3}\theta_m(t) \end{cases} \tag{6}$$

$$e_{4\times1}(t) = L_{4\times1}^d(t) - L_{4\times1}^m(t) \tag{7}$$

$$p_{4\times1}(t) = K_p e_{4\times1}(t) + K_i \int_0^t e_{4\times1}(t)\,dt + K_d \frac{de_{4\times1}(t)}{dt} \tag{8}$$

2.3 Participants and Training Protocol

Three subjects with drop foot participated in this trial as a preliminary study, and their information is summarized in Table 1. All participants could follow the instruction during the robotic training, and communicated well with the physiotherapist. They all gave written consent to participate in this study, with ethics approval (011904) obtained from Human Participants Ethics Committee of the University of Auckland

Although this robot is developed with three rotational DOFs for comprehensive ankle therapy, robotic training is solely delivered along dorsiflexion and plantarflexion where patients with drop foot usually have difficulties in lifting
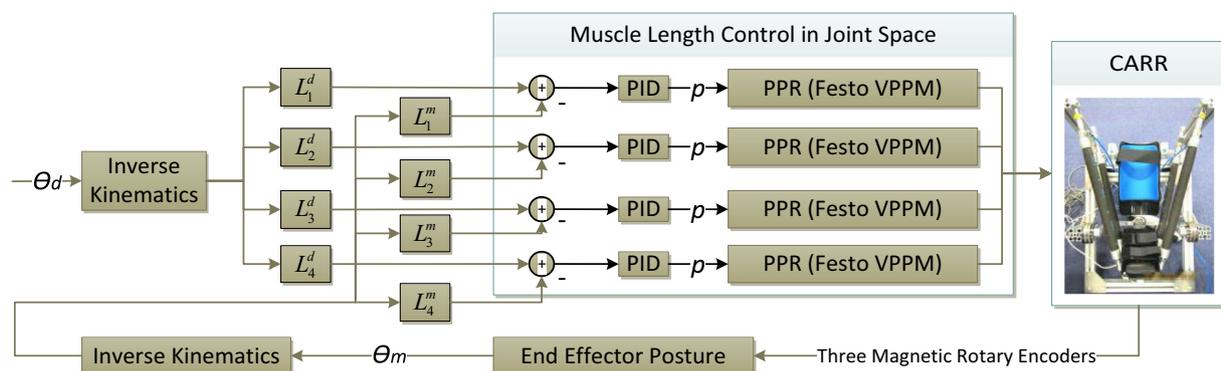
Fig. 4 The flow chart of individual muscle length control in joint space. (PID: proportional–integral–derivative; PPR: proportional pressure regulator)

Table 1 Descriptive information of three participants

Participant No.	Gender	Age	Patients' condition
A	Male	68	Drop foot on the left side six months after stroke
B	Male	50	Drop foot on the right side two months after brain trauma
C	Male	35	Drop foot on the left side three months after brain trauma

their toes. Before robot-assisted ankle training, preliminary assessments were conducted by a physiotherapist to specify an appropriate ankle range of motion for all participants. They were instructed to sit on a height-adjustable chair with their shanks free on the leg holder, with the hip joint in 90° of flexion and the knee in 60° of flexion. Their feet were strapped into an ankle orthosis that is rigidly connected with the foot plate.

The predefined trajectories were in the form of sine wave. For participants A and B, both trajectories had the frequency of 0.02 Hz, and the amplitudes were initially set at 0.1 rad, and then gradually increased until a feeling of joint tightness. The whole process for participant A lasted 15 minutes with 18 cycles, and that for participant B lasted 10 mins with 12 cycles For participant C, the frequency of the trajectory was changed to 0.03 Hz, and the amplitude was also set at 0.1 rad initially, and then gradually adjusted until a feeling of joint tightness. The whole process lasted 15 minutes with 27 cycles. All prescribed trainings were delivered in a passive mode for ankle DP using the trajectory tracking controller. The training trajectories of ankle IE and AA were set zero. Throughout the training, all participants were verbally encouraged to relax their feet to minimize the effects by active contributions

3 Experimental Results

The robot has the configuration as below. As shown in Figs. 1 and 3, the distance between the upper platform and the lower platform is 445 mm. The distance of the upper connection points of the FFMs along x-axis is 405 mm, and 280 mm along y-axis. The distance of the lower connection points of the FFMs along x-axis is 130 mm, and 120 mm along y-axis. With this configuration, based on inverse kinematics, the robot is able to achieve a range of motion from $-35.5°$ to $35.5°$ for ankle plantarflexion and dorsiflexion alone with good kinematic and dynamic performance

One of the important functions of rehabilitation robots is to guide the patient's affected joint through certain position trajectories. In this study, the trajectory tracking controller of the ankle robot was developed in joint space by controlling individual FFM length. Experimental results on the three participants are presented in Figs. 5 and 6, where the blue lines represent the desired trajectories and the measured data are plotted in red. The statistical results of trajectory tracking performance are summarized in Table 2

Specifically, for participant A in Fig. 5 (Left), in the first 100 seconds, the training trajectory had an amplitude of 0.1 rad. Based on the feeling of the patient, the range of motion
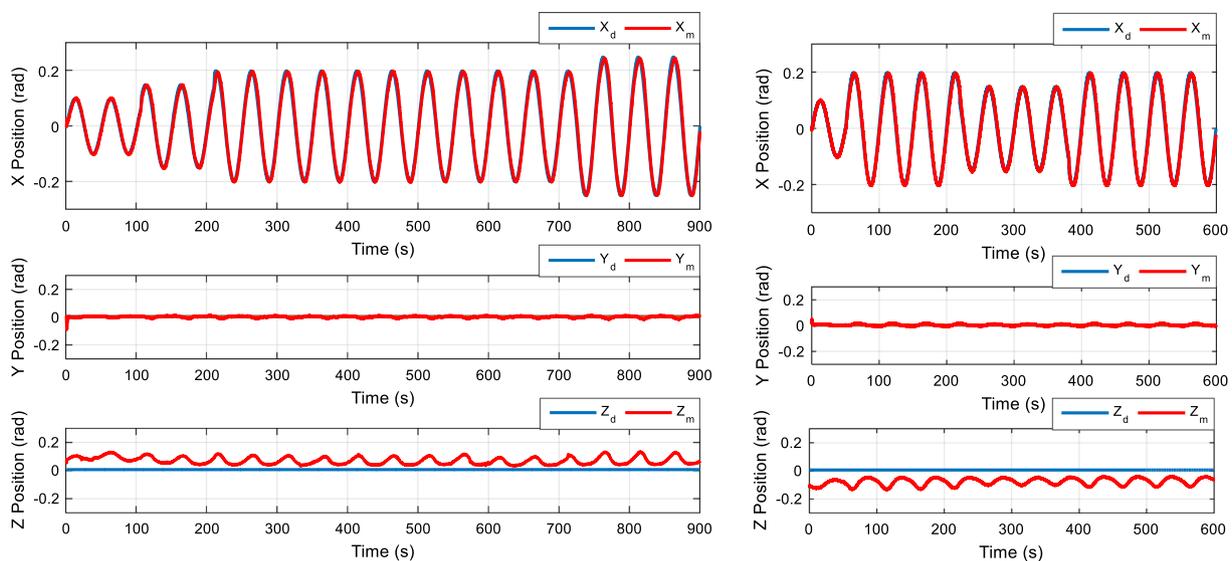
Fig. 5 The trajectory tracking responses in task space during the robot-assisted ankle training on participant A and B, respectively. (X, Y and Z refer to ankle DP, IE, and AA, respectively. The subscript d and m represent desired and measured, respectively)

Fig. 6 The trajectory tracking responses in task space during the robot-assisted ankle training on participant C, respectively. (X, Y and Z refer to ankle DP, IE, and AA, respectively. The subscript d and m represent desired and measured, respectively)
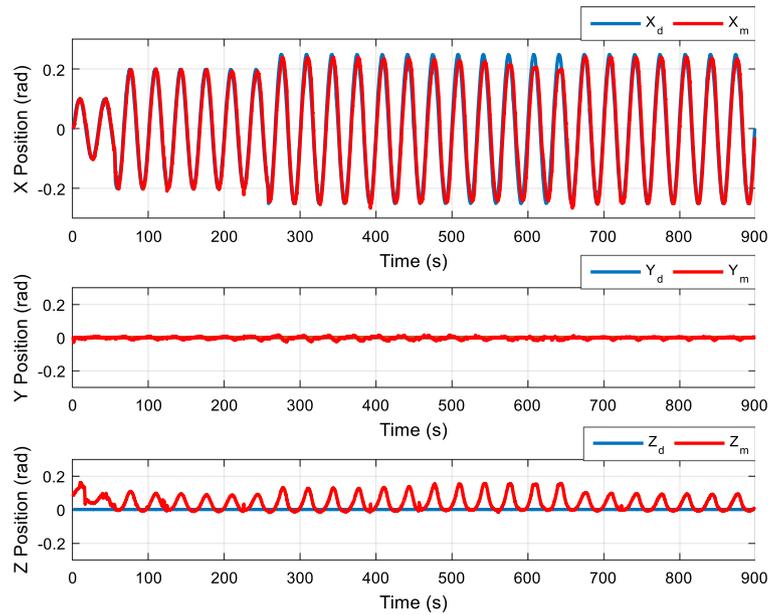
was gradually increased until the patient felt tight at the ankle joint. During the period of 100 to 200 seconds, the amplitude of the trajectory was increased to 0.15 rad. It was further increased to 0.2 rad after the moment of the 200th second, when the patient felt slightly tight at his ankle joint. The robot kept this range of motion for the training during

Table 2 The statistical Trajectory tracking performance of the ankle rehabilitation robot on three participants

Participant No.	Ankle DOFs	Tracking accuracy	
A	DP	RMSD (rad)	0.0179
		NRMSD (%)	3.58
	IE	RMSD (rad)	0.0065
		NRMSD (%)	NA
	AA	RMSD (rad)	0.0696
		NRMSD (%)	NA
B	DP	RMSD (rad)	0.0163
		NRMSD (%)	4.07
	IE	RMSD (rad)	0.0065
		NRMSD (%)	NA
	AA	RMSD (rad)	0.0714
		NRMSD (%)	NA
C	DP	RMSD (rad)	0.0335
		NRMSD (%)	6.69
	IE	RMSD (rad)	0.0071
		NRMSD (%)	NA
	AA	RMSD (rad)	0.0618
		NRMSD (%)	NA

RMSD: Root mean square deviation; NRMSD: Normalized root mean square deviation; RMSD and NRMSD are defined in Eqs. 9 and 10; NA: Not applicable

the period of 200 to 725 seconds. As the patient requested, the amplitude of the training trajectory was finally adjusted to 0.25 rad, when the patient felt obvious ankle stretching. For participant B in Fig. 5 (Right), in the first 50 seconds, the training trajectory has an amplitude of 0.1 rad. Based on the feeling of the patient, the range of motion was gradually increased until the patient felt tight at the ankle joint. During the period of 50 to 225 seconds, the amplitude of the trajectory was increased to 0.2 rad. It was then decreased to 0.15 rad as the patient required. After the moment of the 375th second, the amplitude was again adjusted to 0.2 rad when the patient felt slightly tight at his ankle joint. For participant C in Fig. 6, in the first 65 seconds, the training trajectory has an amplitude of 0.1 rad. Based on the feeling of the patient, the range of motion was gradually increased until the patient felt tight at the ankle joint. During the period of 65 to 250 seconds, the amplitude of the trajectory was increased to 0.2 rad. It was then increased to 0.25 rad until the training finished.

To quantitatively evaluate the trajectory tracking accuracy, the root mean square deviation (RMSD) and the normalized root mean square deviation NRMSD are used. They are defined in Eqs. 9 and 10, where Δ is the range of desired trajectory defined as the difference between the maximum and the minimum values in a data set In Table 2, for participant A, the RMSD value of ankle DP training is 0.0179 rad and the NRMSD value is 3.58%. For ankle IE and AA, the RMSD values are 0.0065 rad and 0.0696 rad, respectively. For participant B, the RMSD value of ankle DP training is 0.0163 rad and the NRMSD value is 4.07%. For ankle IE and AA, the RMSD values are 0.0065 rad and 0.0714 rad, respectively. For participant C, the RMSD value of ankle DP training is 0.0335 rad and the NRMSD value is

6.69%. For ankle IE and AA, the RMSD values are 0.0071 rad and 0.0618 rad, respectively. It should be noted that the training along ankle DP was controlled with satisfactory tracking accuracy (all NRMSD values less than 6.69%). The trajectory deviation along ankle AA may be caused by the foot abnormality, with all RMSD values no less than 0.0696 rad

$$RMSD = \sqrt{\sum_{i=1}^{n} (m_i - e_i)^2 / n} \qquad (9)$$

$$NRMSD = \frac{RMSD}{\Delta} \times 100\% \qquad (10)$$

All patients gave positive feedback in using the CARR for ankle stretching exercises, although some issues exist and may have affected the rehabilitation efficacy. The biggest issue is the fixation of the human foot during the training. When large robot torque was applied to the human ankle, for example in extreme dorsiflexion, the strap could become loose and the patient's heel was lifted up. This could have made the actual ankle motion different with the predefined trajectory due to relative movement between the foot plate and the human foot. This can be considered as a limitation of this device when used for ankle stretching, and a better way to fix the patient's foot should be investigated

As in Figs. 5 and 6, there are large deviations of the z-axis position tracking. Three main factors are as follows. First, the FFM is soft with intrinsic compliance as a pneumatic actuator. Thus, real-time human-robot interaction force can bring certain length change of the actuators. Compared with about x- and y-axis, the rotation about z-axis is more sensitive to the length change of the actuators. Second, the ankle robot used aluminium extruded sections to construct the device base and the platform for actuator attachments, as shown in Fig 1. There are certain deformations on the aluminium frames during the robotic operation. Third, the low assembly precision can be also a factor due to the lack of locating parts between the fixed platform and the base.

4 Discussion and Conclusions

Considering the control scheme of a parallel manipulator, a typical method is to control individual length of actuators in the joint space. The joint-space controller, as a conventional control scheme, is to make the actual link lengths conform to the desired lengths based on inverse kinematics [34]. An example is the control of the ankle robot developed by Jamwal et al. [23]. In this study, direct posture measurement of the end effector of the CARR was employed to facilitate control feedback and inverse kinematics. However, the robot torque and stiffness are not controlled using this joint-space trajectory tracking controller.

Lower limb training generally aims to restore normal gait in the patient, through treadmill based exercises and drop foot gait prevention [35] A typical example is the active ankle-foot orthoses developed by Blaya and Herr [17] where the impedance of the orthotic joint is modulated throughout the walking cycle to treat drop-foot gait. It was found that actively adjusting joint impedance could reduce the occurrence of slap foot. These results indicated that a variable-impedance orthosis may have certain clinical benefits for the treatment of drop-foot gait compared to conventional ankle-foot orthoses having zero or constant stiffness joint behaviors. The Anklebot developed by Roy et al. [20] has been tested to train stroke survivors to overcome common foot drop and balance problems in order to improve their ambulatory performance. Compared with these powered foot orthoses, the CARR was designed for more comprehensive ankle training in a three-dimensional space. This preliminary study was conducted on three patients with drop foot to evaluate the mechanical design of the robot, the trajectory tracking, and its torque actuation capacity.

Data from three patients have shown satisfactory trajectory tracking accuracy and torque actuation capacity of the CARR. However, some limitations exist. First, only the trajectory of ankle DP was delivered and a multi-DOF training should be delivered for the treatment of drop foot. Second, the maximum torque capacity of the CARR should be theoretically identified and experimentally validated to assess its use for ankle stretching exercises. Third, only three subjects were recruited in this study, and experiments should be conducted with more patients over longer training period.

This study involves the use of the CARR for ankle stretching on patients with drop foot. Preliminary results show that this robot can accurately and reliably stretch the patient's ankle joint to a specified position, thus demonstrating its promise for the treatment of drop foot and supporting its clinical applications Future work will investigate the effectiveness of this ankle robot for the treatment of drop foot on a large sample of patients over longer period Ankle stretching combining ankle DP and IE should be also explored for better rehabilitation efficacy.

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