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Robot-Assisted Ankle Rehabilitation for the Treatment of Drop Foot: A Case Study

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***Abstract*— This paper involves the use of an intrinsically-compliant ankle rehabilitation robot for the treatment of drop foot. The robot has a bio-inspired design by employing four Festo fluidic actuators that mimic skeletal muscles to actuate three rotational degrees of freedom (DOFs). A position controller in task space was developed to track the predefined trajectory of the end effector. The position tracking was achieved by the length tracking of each actuator in joint space by inverse kinematics. A stroke patient with drop foot participated in the trial as a case study to evaluate the potential of this robot for clinical applications. The patient gave positive feedback in using the ankle robot for the treatment of drop foot, although some limitations exist. The trajectory tracking showed satisfactory accuracy throughout the whole training with varying ranges of motion, with the root mean square deviation (RMSD) value being 0.0408 rad and the normalized root mean square deviation (NRMSD) value being 8.16%. To summarize, preliminary findings support the potential of the ankle rehabilitation robot 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

I. 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 (ischemic or hemorrhagic) 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 spinal cord impairment 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. Drop foot prevents them from lifting their feet and toes properly when walking, affecting the balance, general mobility, and self-confidence. Walking like this is slow, uncomfortable and tiring, 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 such as functional electrical stimulation 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 [17].

Robot-assisted ankle rehabilitation solutions, as therapeutic adjuncts to facilitate clinical practice, have been actively researched during the past few decades. The robot could also 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, such as the MIT Anklebot developed by Roy et al. [18] and the bio-inspired soft ankle robotic device developed by Park et al. [19]. The other group consists of various platform-based robots. These robots usually have a fixed platform and a moving one [20-24]. While Zhang et al. [25] 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. Exoskeleton devices focus more on gait training rather than only ankle exercises [18, 19], which makes them unsuitable for direct

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treatment of drop foot. Some parallel robots with misaligned rotation centers with ankle joints are also unsuitable for this application [26-28]. The training using these devices requires synergic movement of the lower limb from the patient. In contrast, the manipulator wherein the rotation center of the robot coincides with the ankle joint can be considered to be suitable for the treatment of drop foot. This kind of robots can have a single range of motion (DOF) or multiple DOFs. Zhang et al. [20] presented a single-DOF ankle robot for joint stretching and its efficacy has been demonstrated on patients with spasticity or contracture. Two parallel robots [21, 22] have not been clinically evaluated due to the lack of enough driven torque.

A new ankle rehabilitation robot was recently developed using four Festo Fluidic muscles (FFMs) in our group. It has three rotational DOFs that are ankle dorsiflexion/plantarflexion, inversion/eversion, and adduction/abduction, respectively. This robot has been significantly improved with respect to previous prototypes [21, 22]. Its advantages include the use of compliant actuators, three DOFs for three-dimensional ankle training, and large driving 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 the large generation capacity of driving 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 with drop foot.

II. Methods

A. *Ankle Rehabilitation Robot*

The ankle rehabilitation robot has three rotational DOFs, see shown in Fig. 1. It has a bio-inspired design by mimicking the configuration and actuation of the ankle joint by natural muscles. Thus this robot is actuated using four FFMs (FESTO DMSP-20-400N) in parallel. Four proportional pressure regulators (FESTO VPPM-6L-L-1-G18-0L6H) are used for the pressure control of individual FFM. The robot, 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 with three rotational DOFs.

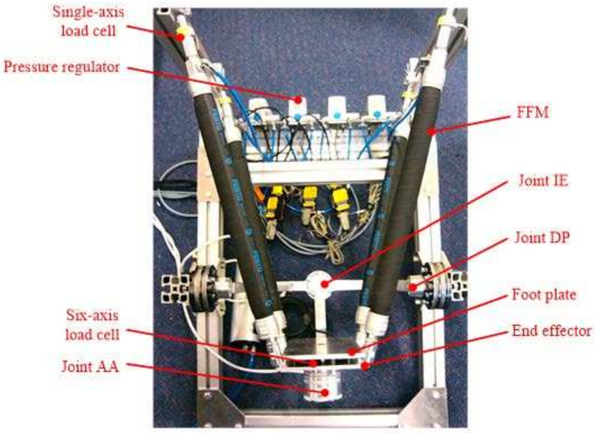

Fig. 1. An intrinsically-compliant ankle rehabilitation robot with three DOFs. (DP: dorsiflexion/plantarflexion; IE: inversion/eversion; and AA: adduction/abduction).

In this robot, three magnetic rotary encoders (AMS AS5048A) are installed along each axis for measuring three-dimensional angular positions of the footplate and the human ankle. It is assumed here that there is no relative motion between the footplate and the human foot during the training, thus the measured position of the foot plate equals that of the involved foot. There are four single-axis load cells (FUTEK LCM 300) for measuring contraction forces of four FFMs, and a six-axis load cell (SRI M3715C) for the measurement of real-time human-robot interaction forces and torques. These electronic components communicate with an embedded controller (NI Compact RIO-9022). The six-axis load cell communicates with the controller through the RS232.

B. *Muscle Length Control in Joint Space*

The trajectory control of the end effector is required to implement passive or active training on a rehabilitation robot. The position control of this ankle rehabilitation robot can be achieved by controlling individual FFM length in joint space, as shown in Fig.2. The desired individual FFM length is calculated by inverse kinematics based on the desired position of the end effector, while, as the feedback to the proportional–integral–derivative controller (PID) controller, the actual individual FFM length is obtained by inverse kinematics based on the measured position of the end effector. This joint space position controller outputs four pressure values that directly go to four proportional pressure regulators for the actuation of the robot.

Specifically, the desired trajectory can be predefined by a physiotherapist and denoted as $\theta_d(t)$ in (1). The measured trajectory is obtained from three magnetic rotary encoders and denoted as $\theta_m(t)$ in (1). Individual FFM length can be calculated using (2) based on inverse kinematics and AARR configuration, where $l^d_{4\times1}(t)$ and $l^m_{4\times1}(t)$ respectively represent desired and measured FFM lengths, μ is a coefficient that relates the FFM length to the link length and depends on the AARR configuration, $\aleph_{4\times3}$ relates the link length to the position of the robotic end effector and depends on the inverse kinematics of the AARR. Lastly, the error $e_{4\times1}(t)$ shown in (3) is input to the PID controller, and the desired individual FFM pressure can be calculated according to (4) with well-tuned K_p, K_i, and K_d.

$$\begin{cases}\theta_d(t) = [\theta^d_{DP}(t) \quad \theta^d_{IE}(t) \quad \theta^d_{AA}(t)]^T \\ \theta_m(t) = [\theta^m_{DP}(t) \quad \theta^m_{IE}(t) \quad \theta^m_{AA}(t)]^T\end{cases} \tag{1}$$

$$\begin{cases}l^d_{4\times1}(t) = \mu\aleph_{4\times3}\theta_d(t) \\ l^m_{4\times1}(t) = \mu\aleph_{4\times3}\theta_m(t)\end{cases} \tag{2}$$

$$e_{4\times1}(t) = l^d_{4\times1}(t) - l^m_{4\times1}(t) \tag{3}$$

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

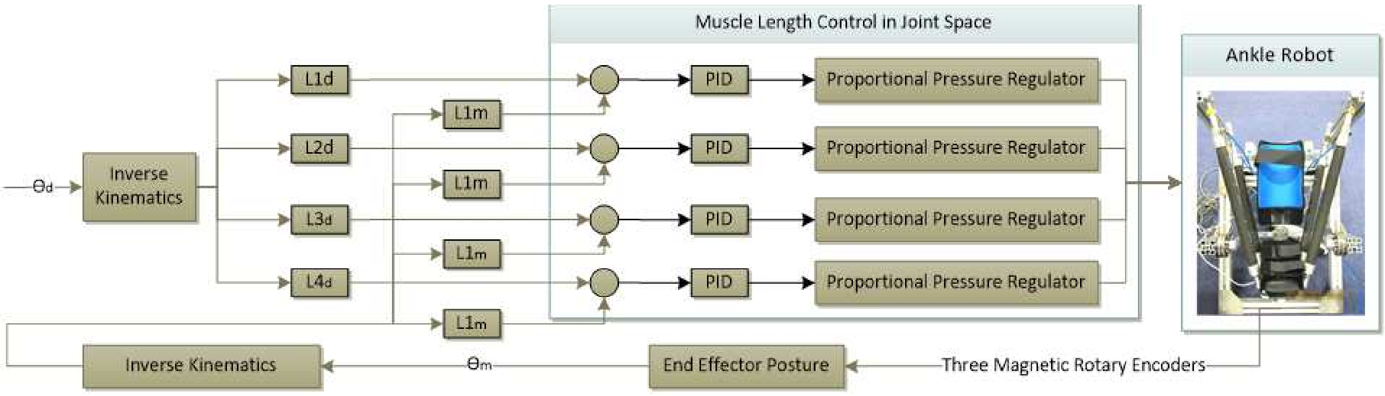

Fig. 2. The flow chart of individual muscle length control in joint space. (PID: proportional–integral–derivative controller)

C. *Participant and Training Protocol*

A subject (male, 68 years, six months post stroke) with drop foot on the left participated in this trial as a preliminary study. This participant can follow the instruction during the training, and communicate well with the physiotherapist. The subject gave written consent to participate in the trial. This ethics approval was obtained from the University of Auckland, Human Participants Ethics Committee (011904).

Although this robot is developed with three rotational DOFs (including ankle dorsiflexion/plantarflexion, inversion/eversion, and adduction/abduction), training therapy is solely conducted along dorsiflexion and plantarflexion where patients with drop foot usually have difficulties in lifting their toes. Before robot-assisted ankle training, a preliminary assessment was conducted by a physiotherapist to specify an appropriate joint range of motion for the patient. The participant was instructed to sit on a height-adjustable chair with the shank free on the leg holder, with the hip and knee joints in 90° of flexion. His ankle-foot complex was strapped into an ankle orthosis. The ankle orthosis is rigidly connected with the foot plate.

The ankle robot was operated in a passive mode using the joint space controller. The trajectory of ankle training is a sine wave along dorsiflexion and plantarflexion, with the frequency being 0.02 Hz. The amplitude of the sine wave was initially set at 0.1 rad, and then gradually increased until a feeling of joint tightness. During the training, the subject was verbally encouraged to relax his foot to minimize the effects by active contributions. The training trajectories of inversion/eversion and adduction/abduction are set zero. The whole process lasted 15 minutes with 18 cycles.

III. Results

One of the important functions of rehabilitation robots is to guide the patient's affected joint through certain position trajectories. In this study, the position controller of the ankle robot was developed in joint space. Experimental results on the participant are presented in Fig.3. In the first 100 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 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 the period of 200 to 725 seconds. As the patient required, the amplitude of the training trajectory was finally adjusted to 0.25 rad, when the patient felt obvious ankle stretching. The whole training lasted about 15 minutes (900 seconds).

The experimental data are plotted in Fig. 3 with satisfactory trajectory tracking responses. The statistical results of the trajectory tracking accuracy are summarized in TABLE I. For ankle training in dorsiflexion and plantarflexion, the root mean square deviation (RMSD) value is 0.0408 rad and the (normalized root mean square deviation) NRMSD value is 8.16%. For ankle training in inversion/eversion and adduction/abduction, the RMSD values are 0.0064 rad and 0.0714 rad, respectively. It should be noted that the training in dorsiflexion and plantarflexion was controlled while the training for the other two DOFs was kept free. The trajectory deviation of training in adduction/abduction may be caused by the foot abnormality.

TABLE I. THE STATISTICAL TRAJECTORY TRACKING PERFORMANCE OF THE ANKLE REHABILITATION ROBOT

Motions	Tracking Accuracy	
Dorsiflexion/Plantarflexion	RMSD (rad)	0.0408
	NRMSD (%)	8.16
Inversion/Eversion	RMSD (rad)	0.0064
	NRMSD (%)	NA
Adduction/abduction	RMSD (rad)	0.0714
	NRMSD (%)	NA

RMSD: Root mean square deviation; NRMSD: Normalized root mean square deviation; RMSD and NRMSD are defined in (5) and (6), where Δ is the range of experimental values defined as the difference between the maximum and the minimum values in a data set. NA: Not applicable.

$$MSD = \sqrt{\sum_{i=1}^{n}(m_i - e_i)^2/n} \quad (5)$$

$$NRMSD = \frac{RMSD}{\Delta} \times 100\% \quad (6)$$

The patient gave positive feedack in using this robot 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 torque is applied to the human ankle, for example in extreme dorsiflexion, the strap may become loose and the patient's heel will be lifted up. This could have made the actual ankle motion different with the predefined trajectory due to relative movement between the footplate and the human foot. This can be considered as a limitation of this device when used for ankle stretching.

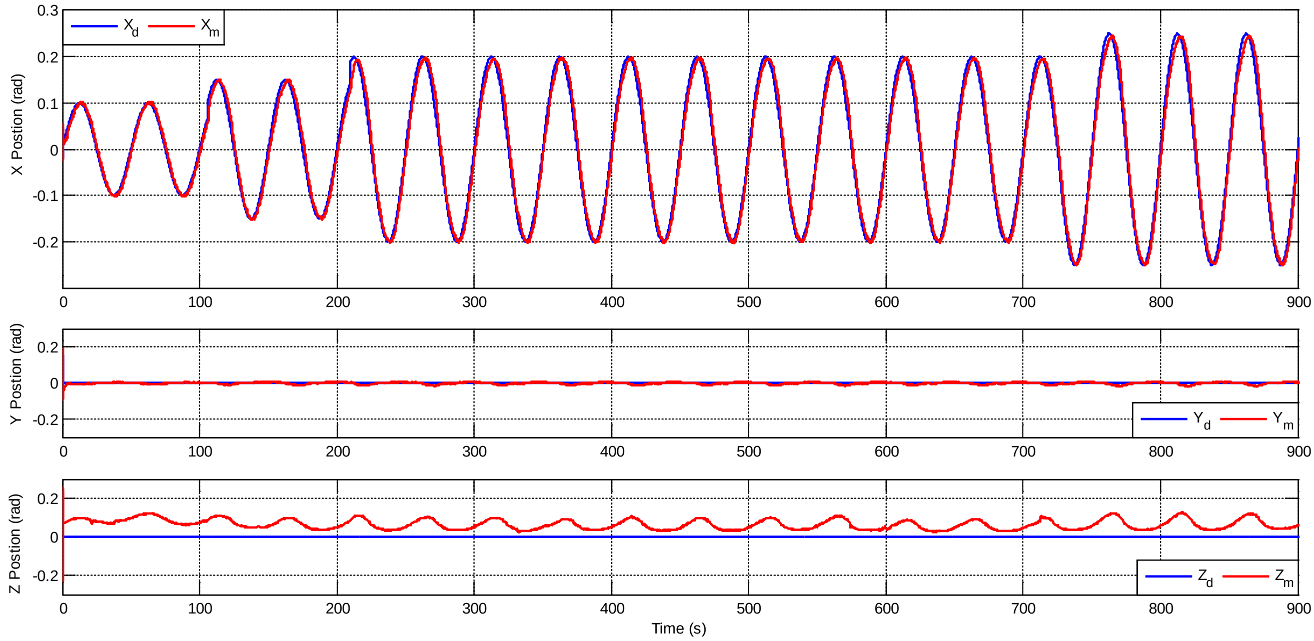

Fig. 3. The trajectory tracking responses in task space during the robot-assisted ankle stretching. (X, Y and Z refer to ankle dorsiflexion/plantarflexion, inversion/eversion, and adduciton/abduction, respectively. The subscript d and m represent desired and measured, respectively.)

IV. Conclusions and Future Work

This study involves the use of an intrinsically compliant rehabilitation robot for ankle stretching on patients with drop foot. A stroke patient participated in the trial as a case study. Results show this ankle rehabilitation robot can accurately and reliably stretch the patient's ankle joint to a specified position. Preliminary findings using this ankle robot are promising for the treatment of drop foot and support 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. The fixation of ankle joint during the training will be also solved to allow more accurate ankle exercises following the predefined trajectory.

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