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Range-of-motion measurement with therapist-joined method for robot-assisted ankle stretching

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HIGHLIGHTS

- A robot-assisted method is proposed to improve ROM measurement accuracy.
- ROM measurements with protractor and the proposed method are compared.
- The proposed method with accurate ROM leads to improvement of ankle stiffness.

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ABSTRACT

The range of motion (ROM) measurement is an important issue in a robot-assisted ankle–foot rehabilitation. This study presents a therapist-joined method to improve the ROM measurement accuracy of a robotic ankle–foot rehabilitation system by combining therapist-joined zero-torque control and proxy-based sliding mode control. The zero-torque control is applied when measuring the subject's range of motion to obtain its extreme joint angle and largest resistance torque. Moreover, a controller switch is applied to ensure that the extreme joint angle is appropriate. Comparative studies between the ROM measurement using a protractor and the proposed method are then performed, comparing the ankle resistance torque variations during stretching under different ROM-measuring results. Ten able-bodied subjects are recruited for this experiment. The results show that the proposed method is feasible in improving the measured ROM accuracy. In addition, a more accurate ROM leads to a larger improvement of the ankle stiffness.

1. Introduction

The ankle is the most common location for joint injuries in a human body [1]. Hence, an ankle rehabilitation robot is an important part of robotic rehabilitation systems. Consequently, several research groups (e.g., [2–11]) developed robotic devices for ankle rehabilitation. Continuous passive motion (CPM) is a widely used ankle rehabilitation method based on ankle stretching. The CPM can be applied by robotic systems instead of physical therapists, and has been confirmed by studies to be effective in treating an ankle joint with spasticity and/or contracture [12].

Robot-assisted ankle stretching is classified by the stretching limit into two kinds: predefined torque-based stretching [5,6,13–15] and predefined range of motion (ROM)-based stretching [15–19]. For the former, a constant torque output is usually set for the CPM machine, thereby making the stretching stop when the resistance torque of the ankle has increased to a certain value. In [14], treated ankles were continuously stretched into dorsiflexion with a torque of 7.5 N m for 30 min each weekday for 4 weeks. In [15], the typical stretching parameters were 15–20 N m peak resistance torque in dorsiflexion and 3 N m peak resistance torque in plantar flexion. Meanwhile, the joint ROM was measured in [5]. However, the value was not used to achieve full stretching, but for safety insurance. Moreover, the control for the stretching was mainly based on the resistance torque of the ankle joint. The drawback of this method mainly lies in the difficulty of determining a proper torque limit value, which is large enough but not aggressive, to allow a strenuous and safe stretching for different subjects. A risk of injury also exists because no position limit is set. Furthermore, compared to the position information, torque features are more difficult to measure. As for the predefined ROM-based stretching, CPM machines move between two preset joint positions. The passive movement does not usually stretch into extreme positions, where contracture/spasticity is significant, when it is set within the

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flexible part of the true ROM. In contrast, setting a CPM machine too aggressively may risk injuring the joint [5]. Thus, the preset extreme positions are critical, and should be dependent on the patient's joint ROM. Therefore, the ROM measurement is important for ankle stretching. It is essential to improve the measurement accuracy [20,21].

Currently, therapists in hospitals usually do a manual measurement of a patient's ankle ROM with a protractor. The manual measurement is mainly limited by the strength of the therapists, thereby making it hard to reach the "true" extreme joint position particularly in a patient population, such as those with stroke, who often suffer from large ankle stiffness. This method is also laborious in the meantime. Thus, several robot-assisted measurement methods were proposed. For example, in [16], the footplate of the system moves forward for a certain range every time once the control button is pushed until the patient feels that the extreme position has been reached. However, such autonomous measurement may bring risk of injury and does not provide sufficiently accurate results.

In this paper, we present a therapist-joined ROM measurement method to improve the accuracy and safety of the ROM measurement of a robotic ankle–foot rehabilitation system by combining zero-torque control and proxy-based sliding mode control (PSMC). The zero-torque control is applied when measuring the range of motion of the subject to obtain its extreme joint angle. Moreover, a controller switch is applied to ensure that the extreme joint angle is appropriate and the largest resistance torque is obtained. Comparative studies between the ROM measurement using a protractor and the proposed method are then conducted to compare the ankle resistance torque variations during the stretching under different ROM measuring results. Ten able-bodied subjects are recruited for the study.

The rest of the paper is organized as follows: we describe the therapist joined measurement method in Section 2; the experimental results and discussion are presented in Section 3; and the conclusions are drawn in Section 4.

2. Therapist-joined measurement method

2.1. Ankle stretching system

The proposed ankle–foot rehabilitation system comprised an immobile base that contained a seat, a motor suite (Dunkermotoren, Inc.), an adjustable sliding platform in two degrees of freedom used to move the motor bracket to an appropriate position, and an adjustable leg support. The adjustable sliding platform and the leg support together ensured that the ankle axis was aligned with the motor shaft with the knee flexed at a fixed angle position (Fig. 1). One uni-axial torque sensor (Transducer Techniques, LLC) was mounted on one end of the shaft to measure the torque, while one encoder (Dunkermotoren, Inc.) was mounted on the other end of the shaft to measure the velocity. An inclinometer (CTL Components PLC), which can record the joint angle with reference to the ground, was attached under the footplate.

The motor suite consisted of a permanent magnet DC motor (Dunkermotoren Inc.) and an inline gearbox with a 250:1 gear ratio that increased the loading capacity of the motor up to 100 N m. The foot was secured on the footplate by velcro at the dorsal foot and the heel. The motor bracket with location holes on the perimeter was used to place the mechanical limit stops in our system. The operator and the patient both had their own handhold emergency switch, and either of them could shut down the motor by pressing their own switch. In addition, a customized graphical user interface (GUI) was developed in LabVIEW for the proposed rehabilitation system. Two displayers were used to interact with both the patients and the therapists. More details of the rehabilitation system can be found in [16,17].

2.2. Therapist-joined ROM measurement

Before the measurement, the lower leg length and the foot height (distance from the bottom of the foot to the lateral malleolus) were measured to determine a proper size of the adjustable mechanical components. Thus, the rotational axis of the subject's ankle joint in dorsi/plantar flexion was guaranteed to be aligned with the axis of the motor shaft. The subjects were seated comfortably with their knees flexed at 30°. The position was defined as the neutral position of the ankle joint when the shank was vertical to the foot, while the joint angle was defined to be 0. The joint angle was in neither dorsiflexion nor plantar flexion in the neutral position. The proposed method can be divided into two parts cooperating to find the proper extreme joint angle. First, zero-torque control is applied when the therapist pushes the footplate to find the proper extremity. Second, when the extremity is found, the therapist can push the switch button and thus the footplate is held by the motor under position control. Fig. 2 shows the diagram of the procedure. The method details are explained in the paragraphs that follow.

2.2.1. Zero-torque control

On safety grounds, when the subject's ROM was unknown, we let the therapist join the measuring process by having her push or pull the footplate by hand and communicate with the subject constantly. The motor was kept under zero-torque control with a torque feedback to minimize the resistance against the therapist and make the process less laborious. Fig. 3 shows that the desired torque was zero, and the controller input was the torque sensor value. Through this method, the subject's foot was passively moved from its neutral position to its dorsiflexion or plantar flexion. The therapists recorded the extreme angles obtained from the inclinometer when the extreme position was reached. These values will then be used as target values in the designed trajectory.

We applied the EPOS2 motor actuator, which has a current sensor inside, to conduct the current close-loop and ensure a precise torque control.

2.2.2. Controller switching and hold

The total torque on the footplate approached zero when the therapist measured the subject's ROM by hand with a zero-torque control on the motor Hence, the torque sensor output also approached zero, and the subject's largest resistance torque cannot be measured with the controller shown in Fig. 3. However, it must be obtained before stretching to determine the torque limit of the position controller. Moreover, holding the footplate for several seconds immediately after finding the extremity was also necessary to ensure that the subject would not suffer any discomfort at that position. We applied a controller switch to solve these two problems. Pushing the switch button provided a voltage change to the controller, as shown in Fig. 4(c). When the extreme position was confirmed, the therapist stopped moving the footplate, kept it in the extreme position, and recorded the extreme angles. The therapist or the patient was then supposed to push the switch button, and the controller would be switched to the position controller shown in Fig. 5. This controller had the extreme angle as the desired angle and an estimated torque limit within a safe margin. Thus, the footplate will be held on with the PSMC-based position controller by the motor after the switch button is pushed. The resistance torque can then be approximated from the torque sensor with the desired control command varying from the zero torque to a certain position.