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A proprioceptive neuromuscular facilitation integrated robotic ankle–foot system for post stroke rehabilitation

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HIGHLIGHTS

- We developed a proprioceptive neuromuscular facilitation (PNF) integrated robotic ankle–foot system for post stroke rehabilitation.
- It is the first time that PNF method has been used in ankle spasticity/contracture rehabilitation.
- Five able-bodied subjects participated in the experiments and five stroke patients were recruited with a six-week PNF treatment.
- The proposed system can offer more effective treatment than passive stretching in improvement of both passive and active joint properties.

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ABSTRACT

Ankle joint with spasticity and/or contracture can severely disable the mobility and the independence of stroke survivors. In this paper, we developed a proprioceptive neuromuscular facilitation (PNF) integrated robotic ankle–foot system for post stroke rehabilitation. The system consists of a robotic platform and a control system with graphic user interface. We employ five normal subjects to test the reliability and feasibility of the proposed system. To validate the effectiveness of the PNF integrated robotic system, we recruit five stroke patients and carry out a six-week PNF treatment. Treatment outcome was evaluated quantitatively in passive and active joint properties. The passive hysteresis loop shows that the maximum dorsiflexion angle increases from $32.9^\circ \pm 1.5^\circ$ to $42.0^\circ \pm 3.2^\circ$ ($p = 0.014$) while the resistance torque decreases from 45.6 Nm $\pm$ 5.8 N m to 29.8 N m $\pm$ 4.4 N m ($p = 0.019$). The active joint properties are improved significantly with the training score increasing from 5.7 ± 0.9 to 8.1 ± 0.6, and getting close to that of normal subjects (9.5 ± 0.3). In addition, muscle strength has a rising trend as time goes on. The results demonstrate that the proposed PNF integrated robotic ankle–foot rehabilitation system is effective in improving ankle spasticity and/or contracture and is a promising solution in clinical rehabilitation.

1. Introduction

Human ankle joint as a very flexible and complex skeletal structure plays an important role in providing forward propulsion force during terminal stance phase and maintaining body balance and smooth gait during the whole gait cycle [1]. Cerebrovascular accident (CVA), or stroke, is one of the leading causes of ankle disability [2,3]. For those patients, the ankle joint with spasticity and/or contracture can severely disable the mobility and the independence of stroke survivors [4–8]. The spasticity is resulted from the hypertonus and reflex hyperactivity of skeleton muscles [9,10]. Such spasticity in flexor muscles of stroke patients is a more common syndrome than extensor muscles. It reduces the range of motion (ROM) of ankle joint and may cause severe physical pain. Moreover, lack of mobilization and prolonged spasticity may further change the structure of muscle fibers and connective tissues and finally lead to permanent contracture as a result. About 34% of stroke survivors have developed ankle contracture [8,11,12]. Therefore, one of the greatest challenges in stroke survivors' rehabilitation is to improve their ankle spasticity and/or contracture, which can seriously influence its normal functional activities.

In clinic, the ankle joint with spasticity and/or contracture is generally rehabilitated via physiotherapy [13–15]. During the treatment, patient's ankle is manually moved within its ROM by

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a physical therapist. Physical rehabilitation is in need of a long-term continuous operation as short-term treatment is less effective and usually insufficient to make patients fully recuperation [16]. Even if the patients have temporarily recovered from short-term treatment, they tend to relapse and have future problems [13,17]. In addition, for some severe patients, their ankle joints have a very high stiffness and can hardly be stretched by therapists, even with strong arms. Above all, manual stretching is very time-consuming, strenuous and laborious to physical therapists. Therefore, manual rehabilitation may not last long, partly due to the limitation of stretching frequency and duration time.

In view of shortcomings of physiotherapy, a robotic ankle–foot rehabilitation system has been proposed to support physicians in providing a high-intensity therapy for the stroke patients [18]. Robotic technology can transform rehabilitation from labor-intensive operations to robot-assisted operations, which can implement different kinds of rehabilitation methods [19]. The robotic system can offer an adequate stretching force and sustaining long-term training, which can cover the limitation of manual stretching [20]. It can also record rich information, such as velocity, ROM, joint torque, electromyography (EMG) signals. Those useful signals can facilitate patient diagnosis, functional assessment, therapy customization and rehabilitation history recording. Thus, robotic rehabilitation is gradually being thought to be as good as or even better than manual therapy [21]. There are mainly two kinds of robotic ankle–foot rehabilitation systems [20]: one kind is mobile systems, e.g. [22–24], mainly focusing on improving walking gait and the other one is platform-based systems aiming at improvement of ankle performance. For ankle joint with spasticity/contracture induced by the hypertonus and reflex hyperactivity of flexor muscles, the primary work is to alleviate the spasticity of crus muscle [5,6]. Before walking rehabilitation using wearable systems, patients with ankle joint spasticity/contracture, especially those severe patients, have to use a platform-based system to ensure reliability and improve current performance.

Recently, several research groups have developed different robotic platform-based ankle–foot rehabilitation devices [25–33]. Continuous passive motion (CPM) is mainly applied in those devices. It has been confirmed in their studies that passive stretching is effective in treating the ankle joint with spasticity and/or contracture. CPM devices can provide regular and consistent passive stretching. The ankle joint is moved between two predefined positions which usually not cover the whole ankle ROM. Therefore, calf muscle may not be fully stretched into the extreme position of dorsiflexion where the spasticity and/or contracture is significant. In addition, most of the ankle CPM devices run at a set velocity and do not provide motions with velocity change during one reciprocation. Different from those devices, Zhang et al. has developed an intelligent stretching device for the patients with contracture/spasticity and the stretching velocity is inversely proportional to the joint resistance torque [25–27]. However, during passive stretching since lower limb is totally relaxed, the improvement of muscle strength and coordination are limited and patients can hardly get functional recovery. In addition, passive stretching is only a kind of mechanically reciprocating motion without involving patient's active participation, which makes their acceptance and initiative not high.

To address these problems, we choose an active rehabilitation method, namely proprioceptive neuromuscular facilitation (PNF) technique. Different from the passive stretching, here the active method is specified from the subject point of view, which means the active participation of the patient. Common PNF stretching involves a shortening contraction of the opposing muscle to place the target muscle on stretch. It was firstly proposed by Kabat and Knott for the rehabilitation of polio patients with paralysis [34]. Klein et al. reported that PNF treatment in elderly will significantly improve flexibility, ROM, muscle strength and ADL function [35]. The PNF is even found effective to increase muscle volume and alter muscle fiber types [36]. Thus, PNF is widely used for physical therapist and athletic trainers [37]. Above all, PNF technique can cover the problems in the previous treatment and is more effective than passive stretching [38]. Moreover, the active participation in PNF treatment can improve their compliance and initiative.

In this paper, we develop a PNF integrated robotic ankle–foot system for ankle joint with spasticity/contracture of post stroke rehabilitation. The robotic system can provide the required motion of plantar flexion and dorsiflexion, and has nine degrees of freedom (DOFs) to conveniently adjust the position of footplate for the sake of avoiding misalignment between biological ankle axis and robotic system axis [39]. A graphic user interface (GUI) developed in the Labview environment is customized friendly and concisely for both patients and operators. Moreover, in consideration of the safety in human–machine interaction (HMI) [40], protection on control system and GUI, mechanical limits and emergency switches are all designed in the proposed system. Five post stroke patients participate in our pilot experiment and accept a course of six-week PNF rehabilitation treatment using the robotic ankle–foot system. Experimental results including changes of both passive and active properties of ankle joint after training show the improvement of spasticity and/or contracture.

This paper is organized as follows. Section 2 presents the details of the robotic ankle–foot rehabilitation system. PNF technique, experiment protocol and evaluation methods are illustrated in Section 3. Performance of the proposed robotic ankle–foot rehabilitation system and results of PNF rehabilitation for five post stroke patients are shown in Section 4. Finally, we make discussion in Section 5 and conclude in Section 6.

2. Robotic ankle–foot system

This section presents the main technical solutions of the robotic ankle–foot system (see Fig. 1) which is functionally divided into two parts: GUI (top layer) and hardware (bottom layer). Three subsystems are implemented on the platform and described hereafter. They contains the mechanical design, the sensory and control system, and the graphical user interface. Safety of patients for the rehabilitation devices is placed at the first place. Once the danger happens, it would cause a destructive injury to patients. Therefore, protection on control system and GUI, mechanical stops and emergency switches are redundantly designed to ensure the absolute safety of patient in our system.

2.1. Mechanical design

The proposed robotic ankle–foot rehabilitation system consists of an immobile base that contains a comfortable seat, a motor suite (dunkermotoren Inc.), an adjustable sliding platform in three degrees of freedom which is used to move the motor bracket to an appropriate position, an adjustable leg support and a control cabinet (see Fig. 2). The motor and the footplate are fixed on the sliding platform. The leg support can be adjusted in four degrees of freedom and the leg was strapped to the leg support by the leg belt. The adjustable sliding platform and leg support together ensure that ankle axis is aligned with the motor shaft while knee is flexed at a fixed degree for each training. They are all locked by the lock plungers after being adjusted to the desired position. Since the rehabilitation technique that we are adopted is a kind of active method which need the patient to perform his maximum force during the treatment, the hardware structure must have high mechanical strength and stiffness to make the patient and guarantee the device to be at a relative standstill. Therefore the