Exoskeleton Simulator of Impaired Ankle: Simulation of Spasticity and Clonus

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Abstract. We developed a prototype of an exoskeletal patient simulator that allows clinical trainees to experience and learn about ankle disorders related to hemiplegia. The exoskeleton exerts abnormal joint torques by tendon mechanisms while realizing complex ankle movements and realistic bone and skin features. Using this exoskeleton, we simulated the resistances of spasticity and clonus, which are typical symptoms of hemiplegia. We demonstrated these two types of simulated symptoms and showed their validity.

Keywords: Patient simulator, Spasticity, Clonus, Physical therapy.

1 Introduction

Physical therapists (PTs) manually examine a diseased joint to understand its clinical condition based on the dynamic joint resistance. Because unlicensed PT trainees have few opportunities to treat actual patients, some researchers have developed patient robots to simulate the symptoms of diseased joints for physical therapy training. For example, Grow et al. and Park et al. developed robotic simulators of spastic elbows [3][10]. Kikuchi et al. simulated the spastic movements of the foot joint using a leg and foot robot [8][7]. In the case of robotic patient simulators, the realism or human likelihood is typically limited because humans have multiple degrees of freedom (DOF) in their joints in addition to the skin and bone features. In order to address such issues, Ishikawa et al. proposed a framework for exoskeletal patient simulators [5][6]. This concept is especially effective for complex human joints such as the feet [9].

The objective of this study is to develop a simulator for spasticity and clonus of the ankle for educational purposes. These two types of symptoms are significant and frequently developed for hemiplegia patients. The exoskeleton form and the tendon mechanism along a human muscle allow the trainees to experience high DOF ankle motion with a reduced number of actuators. PT trainees will able to learn manual examination techniques to test for clonus and spasticity by using this simulator. Because our simulator has a tendon mechanism that

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Fig. 1. Exoskeletal ankle simulator and training scene

applies torque only in the plantar direction, it seems difficult to simulate clonus, which involves both plantar and dorsal flexion movements of the ankle. However, utilizing manual force applied to the sole by a PT trainee, clonus can be simulated. We demonstrate the simulated clonus and spasticity function in this study.

2 Exoskeleton Mechanism to Simulate Spasticity and Ankle Clonus

Fig. 1 shows a prototype of the exoskeletal simulator and a training scene. The exoskeleton was constituted mainly by a shoe and cuff fixed to the upper calf. A DC motor (RE35, Maxon motor, maximum continuous torque 97.2 mN·m) with a 1/23 gear head was attached to the cuff. We used a servo amplifier (4-Q-DC ADS 50/5, Maxon motor) in the current control mode. A wire extended from the sole through an idler was wound by the DC motor, and its tip was attached to a pulley ($\phi = 20$ mm). The wire was set along the tibialis posterior muscle to simulate the disorders caused by the problems of this muscle. This wire-driven mechanism does not impede complex human ankle joint motions. One of the advantages of exoskeletal simulator is that there is no necessity to simulate the inherent mechanical impedance of human body. For example, the elasticity of the ankle muscle and tendon is presented by those of a wearer. The resistance of simulated symptom is superposed with that of the wearer's joint impedance.

3 Simulation of Spasticity

Spasticity is a disorder of the upper motor neuron, and it is characterized by a resistance proportional to the extension rate of the muscle [1]. The simulator presents the feeling of catch which PTs feel when they dorsiflex a foot of patients at higher rate than an certain value. The motor torque, τ_s, required to simulate

Fig. 2. Measurement setup; left: spasticity test and right: clonus test.

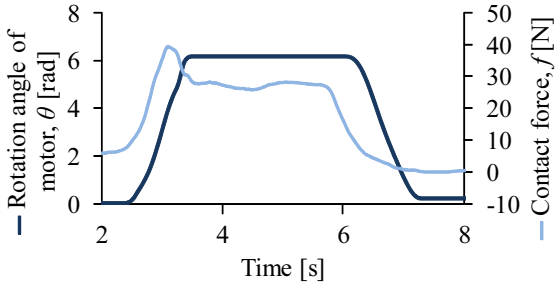

Fig. 3. Resistance force of the simulated spasticity. Force against the dorsiflexion. Angle of the DC motor with $\theta = 0$ at full plantar flexion.

spasticity was determined by

$$\tau_s = \begin{cases} \tau_0 & (\dot{\theta}(t) \leq \omega_0) \\ \tau_0 + c\dot{\theta}(t) & (\dot{\theta}(t) > \omega_0) \end{cases} \tag{1}$$

where c and $\dot{\theta}(t)$ are the coefficient of viscosity and angular velocity of the DC motor (the direction of ankle dorsiflex is the forward direction), respectively. If the angular velocity of the motor was less than or equal to ω_0, τ_s was constant at τ_0. Otherwise, τ_s was proportional to the angular velocity when $\dot{\theta}(t) > \omega_0$. This angular velocity, ω_0, represents the stretch reflex threshold [2]. We set each parameter as follows: $\tau_0 = 0.072$ N·m, $c = 9 \times 10^{-3}$ N·m·s/rad, and $\omega_0 = 4.0$ rad/s.

We measured the resistance forces of the simulated spasticity in the setup shown in Fig. 2. A force sensor (USL06-H5-200N-C, Tec Gihan Co. Ltd, Japan.) was installed on the fore part of the sole such that it covered the load path over the fore foot. A PT dorsiflexed the ankle of the exoskeleton wearer, in a way similar to how it is usually performed in a clinical setting. Fig. 3 shows a sample of the measured force and $\theta(t)$. The ankle was dorsiflexed quickly at $t = 3$, and an abrupt rise in the force was observed during this phase. Such a sharp increase

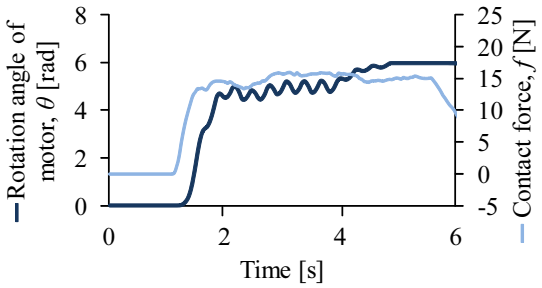

Fig. 4. Measurement results for ankle clonus (ankle was quickly dorsiflexed)

in the interaction force was regarded as a typical velocity-dependent resistance of a spastic ankle.

4 Simulation of Clonus

Clonus is also caused by disorders of the upper motor neuron, and it is characterized by an involuntary rhythmic contraction of muscles [4]. To test for ankle clonus, PTs quickly flex the ankle in the dorsal direction. When clonus occurs, PTs receive rhythmical and repetitive plantar and dorsal flexion of the ankle. The motor torque, τ_c, to simulate ankle clonus was determined by

$$\tau_c = \begin{cases} \tau_1 & (\dot{\theta}(t) \leq \omega_t) \\ \tau_2 & (\dot{\theta}(t) > \omega_t, nt_s \leq t < (n+1)t_s, n = 0, 2, 4, \cdots 20) \\ 0 & (\dot{\theta}(t) > \omega_t, nt_s \leq t < (n+1)t_s, n = 1, 3, 5, \cdots 21) \end{cases} \tag{2}$$

where$\tau_{1,\ 2}$ and t_s are the constant resistance torques and rhythmic period of the ankle movements, respectively. When $\dot{\theta}(t)$ was smaller than ω_t, the reflective contraction did not occur and a weak constant resistance of τ_1 was set. When the ankle was dorsiflexed quickly and $\dot{\theta}(t)$ became larger than ω_t, a large resistance of τ_2 was set. τ_2 was sufficiently large to plantarflex the ankle joint, opposing the PT's manual force. This strong reflexive muscle contracture was then turned on and off at a period of $2t_s$. As a result, rhythmic plantar and dorsal flexion movements were produced. To express the moderate disappearance of clonus, we set each parameter as follows: $\tau_1 = 0.072$ N·m, $t_s = 0.15$ s, $\tau_2 = 0.28$ N·m for $n = 0, 2, \cdots 8$, 0.18 N·m for $n = 10$, 0.14 N·m for $n = 12$, and 0.12 N·m for $n = 14$.

We also measured the force that a PT experience on his/her hand, as shown in Fig. 2. A PT pushed the fore part of the sole manually to test for ankle clonus. Fig. 4 shows a sample of the measured contact forces normal to the sole. The rhythmic motions were observed clearly at approximately 2 to 4 s at 3.4 Hz, which is in a typical range [4]. Although the tendon mechanism of the

exoskeleton could exert force in the direction of plantar flexion, rhythmic clonus was simulated using the manual force of the PT in the direction of dorsiflexion.

5 Conclusion

In this study, we expanded the functions of the exoskeletal ankle simulator to simulate spasticity and clonus. Because our exoskeleton was based on a tendon mechanism, it was challenging to simulate clonus, which involves both plantar and dorsal flexion movements. However, utilizing the manual force applied to the sole by a PT trainee, we could realize the typical abnormality of clonus. During manual examination toward each simulated symptom, resistance patterns characteristic to clonus and spasticity were observed between the wearer's fore foot and the trainee's hand or arm, suggesting the authenticity of the simulated symptoms. PT trainees will able to learn manual examination techniques to test for clonus and spasticity by using this simulator.

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