Leg-robot with MR Clutch to realize virtual spastic movements

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Abstract. In this study, we propose a leg-robot with an MR clutch to realize virtual haptic control for spastic movements of brain-injured patients. This system can be used in the practical training for trainees of physical therapy. Additionally, we will study to figure out the physiological mechanism of spastic movements of human with the process to simulate patient-like spastic motion by this robot. In this paper, basic structure and mechanism of the leg-robot with the MR clutch are explained. Finally, experimental results of some kinds of haptic control for spastic movements are described.

1. Introduction
“Spasticity” is a well know syndrome, most commonly arising after stroke [1]. Spasticity is defined as a velocity-dependent increase in resistance to muscle stretch. In severe case, spasticity can cause reduced flexibility, posture, and functional mobility, as well as joint pain, contracture, and difficulty with positioning for comfort and hygiene. In stroke, an increase occurs in both tonic and phasic reflexes. Loss of upper motor neuron control causes disinhibited alpha and gamma motor neuron activity and heightened sensitivity to class 1a and 2 muscle spindle afferents [2]. Consequently, monosynaptic and multi-synaptic spinal reflexes become hyperactive. In many cases, “clasp-knife phenomenon” and “clonus” appear with spasticity. However, theoretical models for such phenomenon are not unveiled.

Clinical diagnosis methods for spasticity depend on skills of physical therapists. Our purpose of this study is to develop a haptic controllable leg-robot for education of physical therapists. Our targets of this study are spastic movements of an ankle joint. Therefore, this leg-robot was developed to realize virtual haptic force and movement of its ankle joints. At same time, this robot must be developed to have same level of the mass (inertia) characteristics of human. In conventional educational setting of physical therapists, students can not have sufficient experiences to diagnose real patients with spasticity. However, by using our leg-robot, they can practice their techniques as much as they want to do. It will cause upskilling for therapists.

In this study, an MR fluid clutch works as a safety mechanism and a haptic generator of the system. The MR fluid [3] is one of functional fluids which can change its viscosity with application of a magnetic field. And they respond with a good repeatability and good rapidity. In many researches, such functional fluid devices are utilized for therapy / rehabilitation application [4], [5]. However, almost all application has targeted trainings or assists for patients. The system that enables trainings of therapeutic treatments for therapist is novel application of the functional fluids device. In this paper,
basic structure and control method of the leg-robot with MR clutch are described. Additionally, two types of spastic movements are conducted with this system and suggested control methods.

2. Structure of leg-robot with MR clutch

Figure 1 shows the basic structure of our leg-robot to realize ankle-spastic movement. This system has an MR fluid (MRF) clutch between a user (e.g. therapist) and an actuator. The system with clutch-driving mechanism has several merits by comparing with direct-driving mechanism as follows;

1) The MRF clutch works as a torque limiter with a maximum transmittable torque of the clutch. Additionally, we can disconnect transmitting torque instantly when the system become uncontrollable state for the motor.
2) When the system performs a spastic movement that does not require active movement, e.g. spasticity and clasp-knife phenomenon, we can use this MRF clutch as a controllable brake without actuating the motors. In this case, this system becomes passive haptic devices with high safety.
3) When the clutch is in free-state, the system does not transmit inertias and friction force of the motor side. This makes it possible to realize weak force like relaxed joint. An MR brake (RD-2085-02, LORD Corp.) was used as a clutch by rotating its body in this prototype.

3. Control method

3.1. Clasp-knife phenomenon

A flow chart for “clasp-knife phenomenon” is shown in figure 2. In this process, the DD motor is servo-locked at initial position. If an operator pushes up the foot with the angular velocity of \( \omega \) toward dorsiflexion, the robot outputs resistant torque depending on the level of \( \omega \). If \( \omega \) is larger than \( \omega_{\text{clasp}} \) [rad/s], the output torque is controlled with “clasp-knife mode” framed by broken lines of bottom side of figure 2. In clasp-knife mode, the robot fixed its ankle angle with maximum braking torque of \( T_{\text{max}} \) [Nm] (12Nm) for a time limit of \( t_{\text{clasp}} \) [s]. If the time passed over \( t_{\text{clasp}} \), the braking torque becomes zero instantly. This algorithm is proposed by a physical therapist to express a patient-like behavior. If \( \omega \) is not larger than \( \omega_{\text{clasp}} \), the output torque is controlled with “spasticity mode”, in which the resistant torque is proportional to the rotational peed of \( \omega \).

3.2. Ankle clonus

A flow chart for “ankle clonus” is shown in figure 3. In this process, the motor is servo-locked initially. However, in “ankle clonus mode”, the DD motor is rotated with constant velocity. If an operator pushes up the foot with the angular velocity of \( \omega \) [rad/s] toward dorsiflexion, the robot outputs resistant torque depending on the level of \( \omega \). If \( \omega \) is larger than \( \omega_{\text{clonus}} \) [rad/s], the output torque is controlled with “clonus mode” framed by broken lines of bottom side of figure 3. In clonus mode, the robot outputs oscillatory torque with on-off control between +3deg and -3deg with \( T_{\text{max}} \) [Nm] and 0. The operator must apply force toward dorsiflexion in order to continue the ankle clonus mode. If applied force is not sufficient to keep that, control mode becomes “spasticity mode”. In the spasticity mode, the robot outputs resistant torque depending on ankle's rotational velocity with a proportional coefficient \( \alpha \) [Nms].
4. Experimental Result
The operator is a well experienced physical therapist. A scene of experiment is shown in figure 4. All variables were decided based on his subjective evaluations.

**Figure 4.** Scene of experiment

4.1. Clasp-knife phenomenon
Figure 5 shows an experimental result of “clasp-knife phenomenon” control. \( \alpha, \omega_{\text{clasp}} \) and \( t_{\text{clasp}} \) are set to 2.35Nms, 0.64rad/s and 2.3s, respectively. The ankle angle was stopped during the “clasp-knife mode” and after 2.3 seconds, it was released instantly. A rapid peak that appears at the end of the period shows that the foot hit a stopper.
4.2. Ankle clonus

Figure 6 shows an experimental result of “ankle clonus” control. $\alpha$ and $\omega_{\text{clonus}}$ are set to 2.35Nms and 0.21rad/s, respectively. The angle moves in the oscillatory manner in the “clonus mode”. However, the oscillation does not continue if operators do not keep lightly pushing the foot.

![Figure 5](image1.png)  
**Figure 5.** Experimental result of clasp-knife phenomenon

![Figure 6](image2.png)  
**Figure 6.** Experimental result of ankle clonus

5. Conclusion

In this study, we proposed a leg-robot with an MR clutch to realize several kinds of haptic characteristics of spastic movements. This robot system has high safety depending on the clutch-type actuation mechanism. Two types of the control method for spastic motions (clasp-knife phenomenon and ankle clonus) were proposed and conducted experimentally. Experimental results show good reality for these spastic motions.

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