別紙様式第１３

学位論文の内容の要旨

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学位論文題目	Study on a Multi-modal Telerehabilitation System with Compliant Interaction Control
学位論文の内容の要旨	（日本語1,000～2,000字、又は英語400～800語） Along with the globally growing life expectancy, the incidence of age-related diseases including stroke is increasing rapidly. Acute stroke is the beginning of a long-term struggle with physical damage and subsequent disability. This situation creates a massive demand for stroke rehabilitation. However, conventional rehabilitation therapy still remains focused on the in-hospital phase, with its emphasis on intensive manual therapy by the physical therapist, which is a labor-intensive process and consumes significant medical resources. In order to reduce the therapists' burden as well as delivering meaningful restorative therapy to stroke patients, robot-assisted rehabilitation has been deployed in the recovery process. 1) In a clinical rehabilitation scenario, it is difficult to estimate the motor intention and the residual motor ability of different patients, 2) During robotic-aided rehabilitation training, it is hard to provide precise, safe, and compliant interventional assistance to patients, 3) For home-based telerehabilitation, therapists cannot feel real patient states due to the information transmission latency which also leads to the instability of remote interaction. In order to realize safe, compliant, and assist-as-needed (AAN) patient-robot interaction for interventional assistance and allow the therapists to remotely perform the recovery training task with simultaneously patient state perception for home-based upper limb telerehabilitation, a novel therapist-in-the-loop telerehabilitation system has been proposed. The contents of this doctoral thesis are as follows: **Chapter 1: Introduction** This chapter describes the importance and challenges of the telerehabilitation robotic system. Moreover, the necessity of the local assistive patient-robot interaction and remote interactive assessment method for the telerehabilitation system. **Chapter 2: sEMG-based Human Continuous Kinematics and Dynamics Estimation (Journal No.1 and No. 2)** This chapter describes a novel multi-features-based biomedical signals-driven prediction model that utilizes the neural network to extract the motor pattern of sEMG signals and predict the subject-individual motor intentions. A comparison experiment has been carried out to validate the offline, online estimation, and real-time tracking control performance of the proposed model. **Chapter 3: sEMG-based Human Joint Dynamic Reference Stiffness Model** This chapter introduces a musculoskeletal model of the human upper limb elbow joint using sEMG-driven muscle activation and muscular contraction dynamics, which is

developed to provide reference signals for the robot's real-time stiffness control.

Chapter 4: Biomimetic Stiffness Modulation Strategy for Bimanual Skills Relearning (Journal No.3)

In this chapter, a biomimetic variable stiffness modulation strategy for the variable stiffness robot is proposed to improve bilateral limb coordination and promote bilateral motor skills relearning. The muscle synergy effect on the affected side limb is analyzed and reproduced by independent real-time stiffness control.

Chapter 5: Task Performance Index-based AAN Variable Stiffness Control Framework (Journal No.4)

In chapter 5, an sEMG-driven variable stiffness control framework with a novel training task quantitative factor is proposed to promote patient's active participation in upper limb bilateral rehabilitation. The proposed Task Performance Index (TPI) is designed in the high-level multi-mode stiffness controller. In the low-level controller, a position-based bilateral impedance control and a cascaded backstepping position control were implemented for compliant task-tracking assistance.

Chapter 6: Absolute Stability Analysis and Evaluation of the Remote Collaborative System Telerehabilitation System (Journal No.5)

In chapter 6, a therapist-in-the-loop upper limb telerehabilitation robotic system with a novel state switch index-based remote therapist-patient interaction model was presented. On the therapist side, a remote patient biomechanics perception method was realized for tele-assessment. On the patient side, a variable stiffness voluntary control scheme was implemented to induce the patient's active participation. The absolute stability criterion was given and proved for the proposed telerehabilitation system under asymmetric delay conditions.

Chapter 7: Conclusions

In this research, a novel home-based telerehabilitation system has been proposed. The summary of the conclusion is as blew:

1) A novel multi-feature-based neural network model which integrates time and frequency domain information was designed and evaluated. The proposed motor intention prediction method can extract the potential motion patterns in sEMG signals and predict the continuous angle and output force of the elbow joint in real time.

2) A TPI-based sEMG-driven biomimetic variable stiffness control framework with a position-based impedance controller cascaded with a backstepping position controller was proposed to promote patient active participants and training safety during the bilateral rehabilitation process. By the proposed control strategy, the powered variable stiffness exoskeleton device (PVSED) can provide compliant AAN interaction assistance to hemiplegia patients. The stability and tracking convergence of the proposed control method was proved by Lyapunov theory.

3) A novel therapist-in-the-loop upper limb telerehabilitation system with the SSI-ba sed remote therapist-patient interaction model was proposed for providing safe remo te therapist-patient cooperative training. The absolute stability criterion of the propo sed system under asymmetric delay conditions was given and proved. The proposed system can provide safe, remote, and efficient therapist-patient collaborative trainin g, and enable therapists to percept the muscle biomechanical dynamics of patients.