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| 学位論文題目 | Study on a Multi-modal Telerehabilitation System with Compliant Interaction Control |
| 論文審査委員 | (主査) 鈴木　桂輔<br>(副査) 前山　祥一<br>(副査) 佐々木　大輔 |

# 論文内容の要旨

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-based remote therapist-patient interaction model was proposed for providing safe remote therapist-patient cooperative training. The absolute stability criterion of the proposed system under asymmetric delay conditions was given and proved. The proposed system can provide safe, remote, and efficient therapist-patient collaborative training, and enable therapists to percept the muscle biomechanical dynamics of patients.

## 審査結果の要旨

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:

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# 最終試験結果の要旨

令和 5 年 7 月 14 日に公聴会ならびに最終試験を実施した。公聴会では審査申請者に学位論文の内容に関する発表を課した（40 分間）。その後、口述試験として学位論文の内容に関わる審査委員の質疑に対して的確に答えることを求め、学位論文に関連した分野の専門知識を確認した（30 分間）。以上の結果、審査員の質疑に対して適切に回答がなされた。主たる質疑に対する回答を以下に示す。

１）　提案する遠隔リハビリシステムを、実際の病院や自宅において実用化する場合の課題は何か？

【回答】医師側と患者側とを繋ぐ相互通信の状態が悪い状態では、独自に提案する安全機能が作動し、トレーニングが停止する。これがリハビリ支援機能の低下につながるため、通信回線の信頼性の確保が重要である。このほか、医師側には多自由度のマニピュレータが必要であり、患者側には、ウェアラブルの外骨格型のリハビリ機器が必要となる。実用化にあたっては、低価格でこれらのシステムを開発する必要がある。

２）　実際のリハビリでは、今回の実験での模擬患者と比較して、体型の差がより大きいであろう。そのような場合でも、個々の患者の体型に対応した最適な力フィードバックは実現可能か？

【回答】今回の実験では、体型が比較的類似した 10 名の学生を被験者としている。実用化にあたっては、ご指摘のように体型の差がより大きな場合も想定されるため、より細やかな被験者の体型ごとの制御パラメータの最適化が必要である。

３）　提案する可変スティフネスアクチェータは、バネ要素のみで構成されており、ダンパー要素が無いように思われる。リハビリ支援の力フィードバックを行う際に、ダンピングが抑制できず振動現象が発生する危険性は無いか？

【回答】機械式のダンパーは備えていないが、提案するスティフネスの制御機構により減衰の程度をリアルタイムで制御することが可能であるため、振動が発生することは無いと判断している。

本審査委員会における審査は、学位論文の内容、研究方法について審査および確認するものである。博士の学位論文を作成するにあたり、主論文として４件の査読つき学術論文と１件の国際会議 Proceedings がある。本審査委員会は、提出された博士学位請求論文が博士（工学）の学位に値するものであり、審査申請者は専門領域に関する十分な学識と研究能力を有するものと判断した。以上より、本最終試験の評価を合格とする。