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研究課題名（和文）Control of human upper limb by electrical stimulation for accurate motion with external mechanical assistance of high bandwidth: basic mechanism and modeling

研究課題名（英文）Control of human upper limb by electrical stimulation for accurate motion with external mechanical assistance of high bandwidth: basic mechanism and modeling

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研究成果の概要（和文）：最大1000Hzのフィードバック制御が可能な電気刺激装置を開発し，高速ビジュアルフィードバック制御により人間上肢の動作制御を実現した．今後はもっと厳密に検証を行う必要があるが，刺激周波数が高くなるほど追従性が良くなる傾向をある程度で示した．次に，高周波機械動作支援を有する両腕同期メカニズムに基づく人間-機械インタラクションを実現するためのシステムを開発した．従来の位相理論に基づく実験を行い，具体的なタスク評価を通じてその効果を定量的に分析した．全体的に，本研究プロジェクトを通じて高周波機械支援を有する電気刺激による人間上肢の制御および高周波機械支援に基づく両腕同期の研究基盤を構築した．

研究成果の学術的意義や社会的意義
We developed the very first systems to incorporate high-bandwidth mechanical assistance into control of human upper limbs, and laid the foundation for future studies on human upper limb control by electrical stimulation and by bimanual coordination under high-bandwidth mechanical assistance.

研究成果の概要（英文）：The following aspects were achieved by this study. Firstly, electrical stimulation devices that can generate two channels of programmable electrical pulses with a max frequency of 1000Hz was developed. Closed-loop visual feedback control of human upper limb by the developed electrical stimulation from a range of 10Hz - 1000Hz was realized. Secondly, we developed the human-machine interaction system utilizing human visual and force feedback modalities and conducted the primary experimental studies on the interaction between human and external mechanical assistance of bandwidth in terms of bimanual coordination. As an early-stage study, we investigated and verified the possibility of human-machine interaction for accurate manipulation under human visual and force feedback utilizing the bimanual synchronous mechanism.

研究分野：human-robot interaction

キーワード：human-robot interaction　mechanical assistance　high-speed vision　electrical stimulation　bimanual coordination

１．研究開始当初の背景

In previous studies, we investigated human-machine collaboration based on coarse-to-fine strategy by combining low-bandwidth human cognitive action to realize coarse global-motion and high-bandwidth mechanical assistance to conduct local fine-motion [1,2]. For the various modalities of human perception, we haven't studied the voluntary motion control by force feedback as well as direct control of upper limb by electrical stimulation. Specifically, we were interested in the interaction mechanism between human neuromuscular-skeletal system utilizing voluntary bimanual coordination as well as electrical stimulation and high-speed mechanical assistance.

Stimulating human muscles with programmed low-energy electrical pulses has many applications, especially in rehabilitation. Most studies on electrical stimulation have been focused on neuromuscular-skeletal models and robust control strategies in order to restore voluntary motor functions. In order to realize accurate control of body part movement by electrical stimulation, it is necessary to incorporate sensory feedback to form a closed-loop control. Recent years, closed-loop controller design based on mathematical neuromuscular-skeletal models or neural network models for FES applications has been given much attention [3,4]. However, there has been less attention paid to closed-loop control within the context of accurate motion control with high bandwidth mechanical assistance. Besides, research on basic mechanism and modeling for reconstructing cognitive action based on external mechanical assistance of high bandwidth has not been conducted and needs further investigation.

２．研究の目的

The purpose of this research is two-fold:

(1) Developing systems for human upper limb control by electrical stimulation with high-speed visual feedback. The electrical stimulation should be compatible with 1000fps visual feedback. With the developed systems, we then investigate the relationship (modeling) between frequency of electrical stimulation under high-speed mechanical sensing and human limbs control performance.

(2) Investigating the interaction mechanism between human neuromuscular-skeletal system under multimodal perception and external mechanical assistance with great bandwidth gap. Specifically, we focus on the interaction interface utilizing voluntary bimanual coordination to form a closed loop between human and machine. The voluntary bimanual coordination can be taken as a fusion of force feedback perception as well as kinesthetic perception, such that it is equivalently to realize indirect interlimb transmission of force feedback information.

３．研究の方法

(1) Human upper limbs control by electrical stimulation with high-speed visual feedback.

Firstly, system design for human upper limbs control by electrical stimulation with high-speed visual feedback was implemented as shown in Fig.1. For simplification, we only considered the bend and extend motion of one's forearm within the horizontal plane around his (her) elbow by electrical stimulation. In order to counter the gravity force, a support link with a rotational passive-joint was configured on an experimental desk. A participant's elbow was almost aligned with the rotation axis during the experimental studies. Real-time controller was realized by configuring a dSPACE ds1104 R&D controller board to a desktop

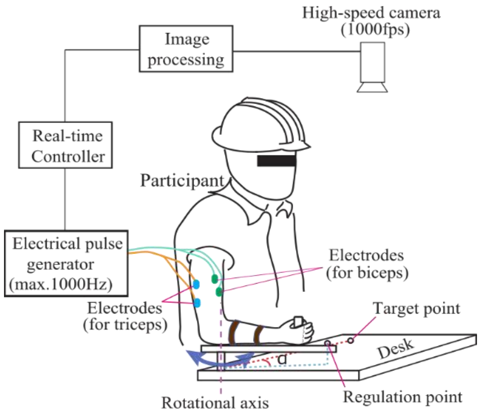

Fig.1 System design of human upper limbs control by electrical stimulation with high-speed visual feedback.

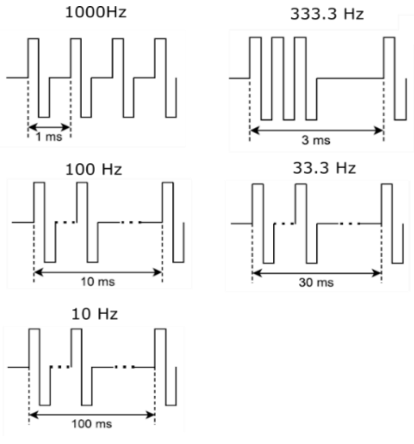

Fig.2. Frequency modulation method for the electrical stimulation

computer. A Photron IDP-Express R2000 was adopted as the high-speed vision system which could acquire 24-bit color images with a resolution of 512×512 pixels at 1000 fps. Image processing was implemented by the same desktop computer to detect two markers representing the rotational angle of the participant's forearm as well as the target point. Besides of visual feedback, an incremental encoder was configured at the rotation axis to record the rotation angle. A pulse counter board was configured to the desktop computer to realize pulse counting. Besides, multiple 16-bit D/A channels were used to send high-speed visual feedback information to the real-time controller board. The electrical stimulation generator was programmed to generate a basic unite of bipolar square wave with 0.25ms pulse width. Electrical stimulation frequency was modulated by adjusting the combination of the basic unite such that 50% duty cycle was realized for each frequency as shown in Fig.2. The amplitude of the electrical stimulation pulses was between -10v ~ +10v, and was modulated by the feedback control information. Finally, the -10v ~ +10v voltage stimulation converted into -20mA ~ +20mA current stimulation with a two-channel isolator (made by UNIQUE MEDICAL). Therefore, we could change the frequency of the stimulation with a same duty cycle for comparison study while making the feedback control information embedded within the safety standards.

(2) human bimanual coordination control study with high-speed mechanical assistance

System design for synchronous coordination study between human upper limbs with high-speed mechanical assistance was implemented as shown in Fig.3. For simplification, this study only considered one direction motion (left-right) of one's forearm within the horizontal plane. The human-robot collaboration was realized by the integration of the machine side (consisting of an assistant robotic module and a force feedback device) for accurate local motion and the human side for coarse global motion. 1000 fps visual feedback and high-speed actuators were utilized in the assistant robotic module, to realize high bandwidth feedback control in a limited work range. The human side guided the assistant robotic module in a global motion manner such that a manipulation target should be always kept within the work range of the assistant robotic module, under force feedback. Force feedback generated by a device based on the sensor information of the assistant robotic module was provided to the left hand of the human operator. The human operator precepted the force feedback information and moved the left arm according to the force feedback protocol. At the same time, he/she should move the right hand, which was holding the assistant robotic module, to conduct the same motion as the left arm, forming the naturally synchronous bimanual coordination. Therefore, a closed-loop for coarse global motion with the aim of keeping the target to be always within the work range of the assistant robotic module was realized. On the other hand, accurate local motion by the assistant robotic module was implemented simultaneously, forming the human-robot collaboration in a coarse-to-fine manner.

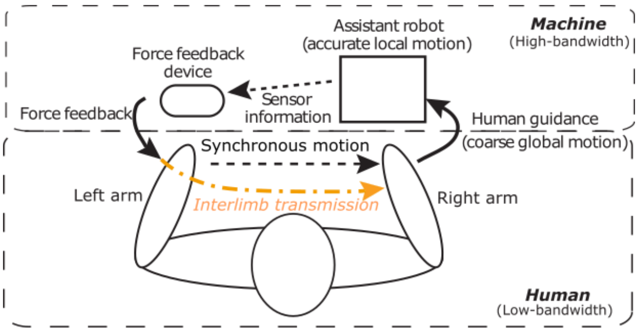

Fig.3. System design of human bimanual coordination motion study with high-speed mechanical assistance

4．研究成果

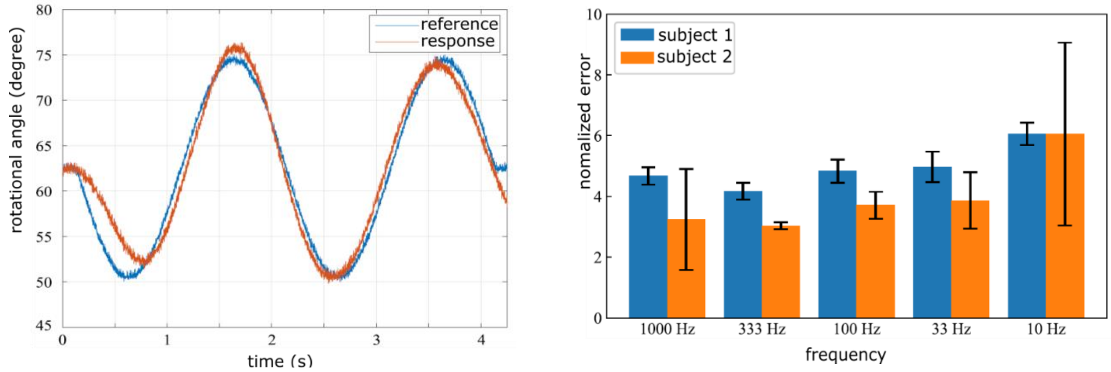

Fig.4. (Left) One trial of Sine wave motion by 1000Hz electrical stimulation control. (Right) Results of two subjects for Sine wave motion under electrical stimulation control with different frequency.

(1) **Human upper limbs control by electrical stimulation with high-speed visual feedback.**

The developed system is shown in Fig.5. Tracking motion of a sine wave (frequency between 0.2 ~ 0.6 Hz) by controlling the bend and extend motion of a participant's right arm was primary studied under several frequency patterns of visual feedback rate and stimulation pulses (10Hz, 33Hz, 100Hz, 333Hz, 1000Hz) [5]. Feedback control was implemented by PD control, combining a feedforward term to reduce the bad effect of time delay that was calibrated before the experiment study. A participant was asked to sit in front of the system with his (her) right upper limb to be examined. The safety button was hold by the participant's left hand during the whole experiment to allow him (her) to stop the electrical stimulation should he (she) feel uncomfortable. At first, 15 minutes of calibration and excises for each participant were scheduled. Each stimulation trial lasting for 5 seconds and 30 seconds break was configured. For study, the frequency pattern was randomly determined for each trial. The primary experimental results on two participants are shown in Fig.4. The left figure illustrates the tracking result of one trial under 1000Hz visual feedback and electrical stimulation control. It shows that the response realized good tracking of the target motion (a Sine wave with 0.5Hz). The comparison study on five different frequency patterns was implemented for a total of 60 trials (4 trials for each frequency pattern in one day: 4×5= 20 trials for 3 days) for each of the participants. As shown in right of Fig.4, although further quantitative study is needed, the normalized tracking error for the five frequency patterns tells the possible intendency of advantages brought by a higher frequency of visual feedback as well as electrical stimulation.

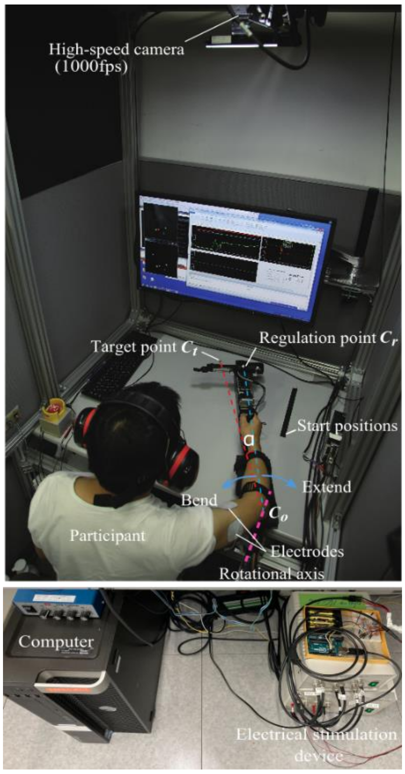

Fig.5. Developed system for upper limbs control by electrical stimulation with high-speed visual feedback

(2) human bimanual coordination control study with high-speed mechanical assistance

As shown in Fig.7, we developed the human-machine interaction system utilizing rotational joints as well as linear joints to implement the force feedback and conducted the primary experimental studies on the interaction between human and external mechanical assistance of bandwidth in terms of bimanual coordination [6,7]. Fig.6 shows one example of the force feedback reference for the left hand and the corresponding synchronous motion of the right hand. As an early-stage study, we investigated and verified the possibility of human-machine interaction for accurate manipulation under human visual and force feedback utilizing the bimanual synchronous mechanism. Particularly, studies on the synchronous motion protocols considering the phase theory of bimanual coordination were conducted. Normalized scores of 9 participants' experiments for voluntary bimanual coordination of kinesthetic in-phase as well as kinesthetic anti-phase protocols were analyzed. The results showed that synchronous motion under kinesthetic anti-phase protocol had higher scores than the other way, in three motion speed levels. Besides, we demonstrated the effectiveness of combining voluntary bimanual coordination and visual perception to realize accurate tracking of a moving object (tracking error realized smaller than 1mm) by human under high-bandwidth mechanical assistance.

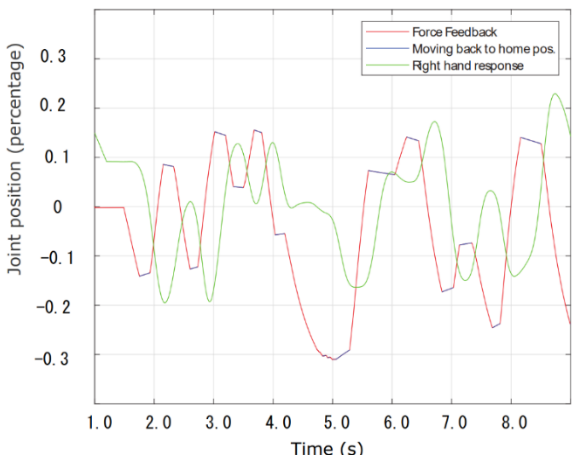

Fig.6. One example of force feedback reference and the corresponding synchronous movement of right hand.

Overall, with the studies carried out in this research project, we successfully developed the systems according to our plans and managed to lay the foundation for further studies on human upper limb control by electrical stimulation as well as by voluntary bimanual coordination mechanism with high bandwidth mechanical assistance.

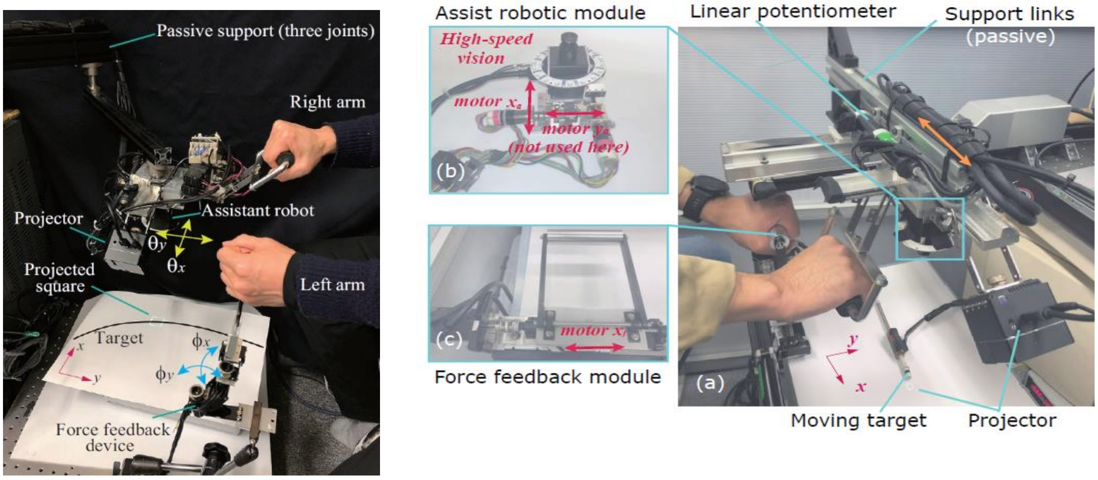

Fig.7. (Left) System with rotational joints. (Right) System with linear joints

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５．主な発表論文等

〔雑誌論文〕　計0件

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４．発表年 2022年

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２．発表標題 上腕の一自由度回転運動に向けた高周波電気刺激フィードバック制御システムの構築
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４．発表年 2021年

１．発表者名 Shouren Huang, Keisuke Koyama, Masatoshi Ishikawa, and Yuji Yamakawa
２．発表標題 Human-Robot Collaboration with Force Feedback Utilizing Bimanual Coordination
３．学会等名 2021 ACM/IEEE International Conference on Human-Robot Interaction（国際学会）
４．発表年 2021年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

http://ishikawa-vision.org/fusion/BimanualCoord/index-e.html

６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関