公開

# 研 究 終 了 報 告 書

## 「剛性フィードバックでの運動のトランスファーと向上」

研究期間： 2018 年 10 月～2022 年 3 月
研 究 者： 高木 敦士

### 1． 研究のねらい

The population of Japan is aging at a fast pace, with many individuals in the retiring population possessing skills acquired over many years in their field of expertise, which includes but is not limited to: medical training (e.g. surgical procedures like suturing), craftsmanship (e.g. wood carving, metal polishing), factory assembly and sports training. These skills must be passed on to new workers entering the workforce, but the time window for such a transfer is short. To address this challenge, this project aims to accelerate motor learning when practicing a new skill, and to enable the rapid transfer of motor skills between an expert and a novice. This will be facilitated by the development of new sensory feedback systems that enable individuals to visualize body states that are difficult to observe with the naked eye. Specifically, the project has focused on two types of sensory feedback: the feedback of joint stiffness and the feedback of muscle synchrony errors. Both are new in the sense that neither form of feedback has been used to facilitate motor learning.

The project has two broad objectives. The first objective is to understand the role that joint stiffness and the synchrony of muscles play during skill acquisition, and to examine how they are different between experts and novices. Many behavioral studies were conducted during the project to shed light on previously unknown changes in the joint stiffness within a movement. The role of temporal synchrony between the muscles, i.e. the timing of their activation, was also investigated in detail, hinting to their crucial role in achieving precise movements. The second objective was to deliver this newfound knowledge as feedback to users to aid and assess their motor performance in a quantitative manner.

### 2． 研究成果

| （1）概要 |
| --- |
| This project produced several significant scientific findings, culminating in a total **6 peer-reviewed** research papers. **Two new feedback systems** were realized and tested in a variety of motor tasks and environments from robotic interfaces to a smartphone.<br><br>The joint stiffness feedback system was rigorously assessed in a variety of motor learning tasks ranging from learning to insert a metallic clip to moving in unstable environments. Preliminary results from a baseball batting experiment suggests that providing feedback of each hand's stiffness during batting (like the timing of the peak, and the relative balance between the hands) may help novices achieve batting motion similar to experienced batters. |

The feedback of temporal synchrony between the muscles was realized by a **patented smartphone application**, and has so far been tested on over 50 participants. The app is capable of measuring the user's latent motor ability of the left and right hands, and it can maintain a record of the user's skill on a daily basis. This is useful to users who voluntarily train their weaker or non-dominant hand, and want a quantitative record of their progress. The app can also record a wide variety of movements like a tennis swing (forehand and backhand), golf putting and free-hand baseball batting.

（2）詳細

**Research theme A: Creation and testing of a joint stiffness feedback system**

Traditionally, joint stiffness is measured either using external force perturbation (e.g. using a robot) or via electromyography (EMG). However, both options are expensive and require expertise to use and lengthy preparation beforehand. This project proposes to use the **power grasp force as a measure of the arm's joint stiffness**, which requires only force sensing alone to measure, eliminating preparation time.

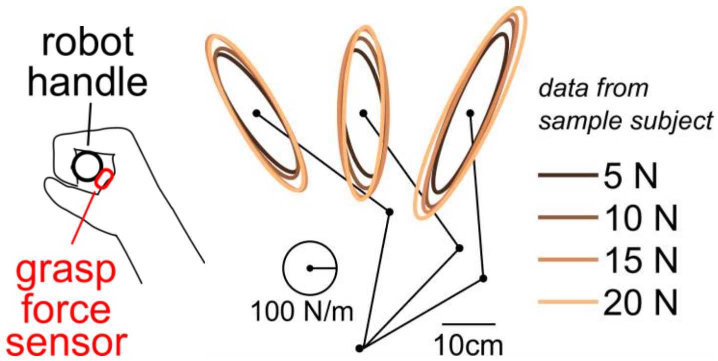


*Figure 1: Power grasp is used as a real-time measure of the arm's joint stiffness (left). A linear correlation between the power grasp and the arm's stiffness was experimentally confirmed (right) (images from* (Takagi et al., 2019, 2020b)*).*

In the peer-reviewed study of (Takagi et al., 2020b), the power grasp was shown to correspond linearly to the size of the arm's stiffness (Figure 1). To assess if the power grasp was suitable to measure arm stiffness, we replicated two studies in the literature famous for studying the change in the arm's stiffness during movements (Burdet et al., 2001; Wong et al., 2009). We were successful in reproducing these results (as reported in (Takagi et al., 2019)). Furthermore, we could observe the change in the arm's stiffness during the motion on a movement-by-movement basis, a level unprecedented in the literature (Figure 2). The grasp force methodology also revealed that the arm's stiffness increases linearly from the beginning of the movement until the end during factory clip insertion (Takagi et al., 2020a), with the overall level decaying while users become more experienced at the task.

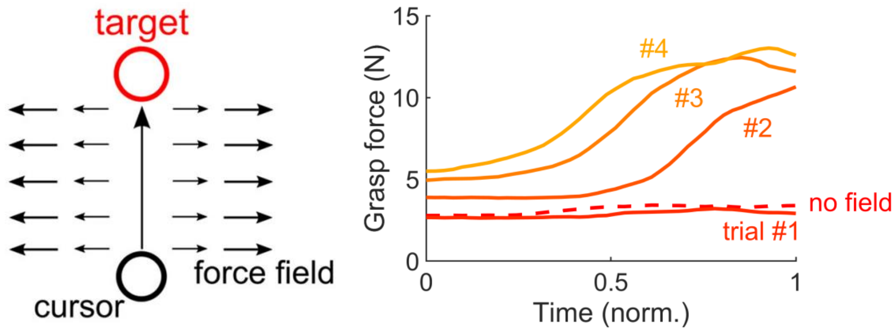


*Figure 2: The arm's stiffness is known to increase when moving in an unstable force field (left). Our grasp force measure showed that the stiffness begins to increase at the end of the motion, and gradually spreads from there to the early stage of motion (right) (images from* (Takagi et al., 2019)*).*

The next step in the project attempted to use the new joint stiffness feedback system to improve baseball batting. Specifically, we expected the arm's stiffness to change during baseball batting, but we had a suspicion that this regulation of stiffness is different between experts and novices. Indeed, preliminary tests show that the grasp force of the left and right hands in an expert baseball batter peaks perfectly at the moment of impact, whereas the novice's is either too early or late (Figure 3). Furthermore, the novice's left arm stiffness is smaller than the right's, an imbalance that affects the ability to stabilize against the ball's impact. A study is underway to use either visual or auditory feedback of the mistimed grasp force peak to enable the novice to align their peak stiffness with the moment of impact.

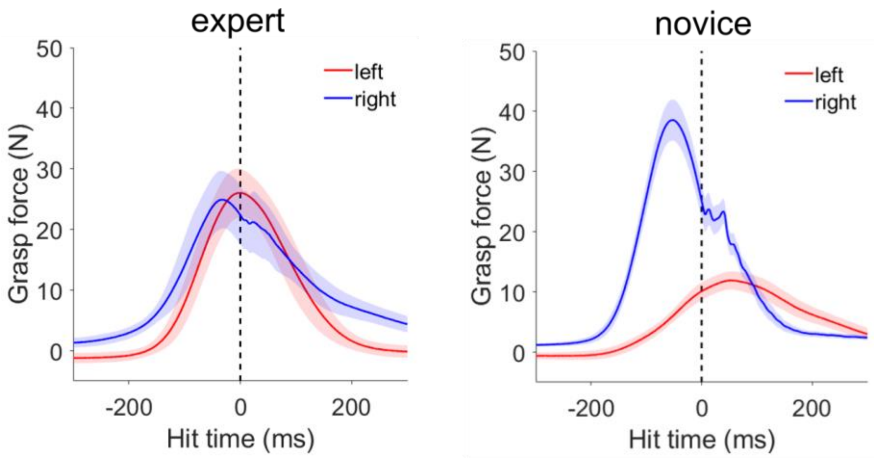


*Figure 3: Grasp force of the left and right hands when batting with the KINARM robotic interface. The expert's grasp force peaks at the moment of impact (dashed line), yet the novice's peak is mistimed. The novice also has insufficient stiffness in the left hand.*

**Research theme B: Measuring temporal synchrony between muscles**

To accelerate and improve motor learning in individuals, the project's second aim was to understand and measure the synchrony between muscles, i.e. the precision in the timing of the activation between muscles. When muscles activate at the wrong time (too early or late), this causes movement errors (Figure 4, left). First, we investigated whether such differences actually impact motor performance. Evidence of such timing errors between the left and right hands has been reported, but the effect is not well documented. We tested right-handed participants to produce a rhythmic force at increasing frequencies with the left and right shoulder, and found smaller variance in the timing of peak muscle activity in the right hand.

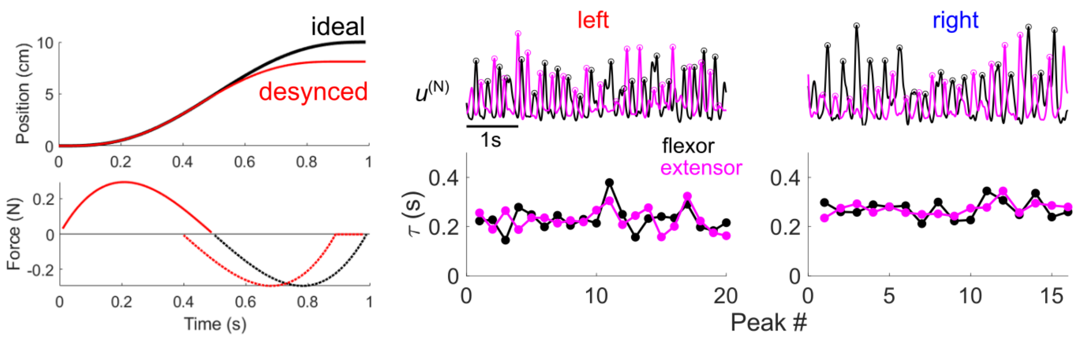


*Figure 4: (Left panel) When muscle activity loses temporal synchrony from the ideal (black) timing, a movement error occurs (red). (Right) Right-handed individuals had higher temporal synchrony with their dominant right hand.*

Based on this finding, a prediction was made that rapid motion like whole-arm circle tracing should elicit consistent differences between the hands, and could serve as a measure of temporal synchrony between muscles. A smartphone application (patented) was created to measure and provide feedback to the user on a daily basis (Figure 5).

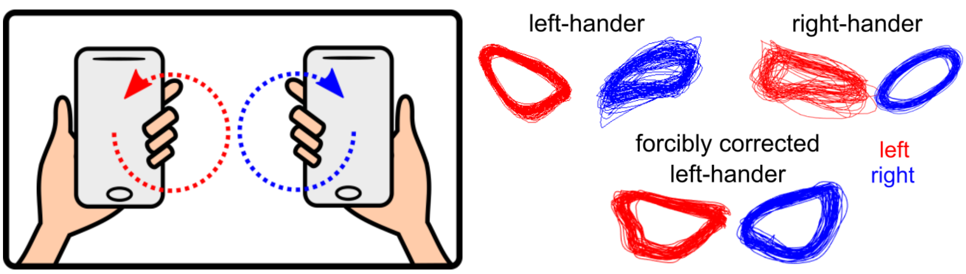


*Figure 5: Repeated cyclical motion of the left and right hand is measured with a smartphone, which reveals more variability in the non-dominant hand. Forcibly corrected individuals show relatively comparable variability between the left and right hands.*

The smartphone app shows consistent differences between the left and right hand movement variability between left-handers and right-handers, while forcibly corrected left-handers show equal performance between the hands, possibly an effect of training with the right from an early age.

## 3. 今後の展開

Both feedback systems show promise in aiding skill learning. The grasp force method can be applied to several tasks from baseball batting to tennis swings. The work on improving baseball batting in novices is ongoing, and will require fine-tuning to find the form of feedback most intuitive to users (e.g. visual display of grasp force in real-time or after a trial, stereo auditory feedback or vibrational feedback at peak grasp force timing). This can be concluded within 12 months. This joint stiffness feedback system could also be used on other tasks like dentistry and polishing, but it would require fine-tuning of the feedback system for each task (to identify what and where to deliver it), which could take 1-2 years. The system must first convince experts that it can show novices new information that was previously difficult to perceive and understand (even when described by the expert) before it can be accepted for use.

The temporal synchrony smartphone feedback system is ready for deployment to the wider population, but it will require 6-12 months of work before it can accept a wider range of movements. For researchers who intend to use it as a supplementary measure to the Edinburgh Inventory (that assesses handedness), it is ready for use. This app is expected to have a wide impact to society because of the ubiquity of the smartphone in the general population, and the ease of measurement (which only takes 30 seconds).

## 4. 自己評価

### 研究目的の達成状況

The initial aim of the project was to understand the role of joint stiffness during motor learning, and to develop a joint stiffness feedback system to accelerate motor learning. This system would then be used to transfer motor skills from an expert to a novice learner. Due to COVID-19, the transfer experiment with two people (one novice learning from an expert) had to be cancelled, and was instead replaced with a new objective to research and develop a measure of temporal synchrony between the muscles.

While the motor skill transfer objective could not be accomplished, the project succeeded in creating and assessing a feedback system for temporal synchrony that has wide-reaching applications. The joint stiffness feedback system (grasp force methodology) is also showing promise in the learning of baseball batting, and shows potential for use in sports training and other manuals skills where timing and stiffness play a major role.

### 研究の進め方(研究実施体制及び研究費執行状況)

Many of the research objectives were completed within the time-frame originally proposed at the beginning of the project, but the motor skill transfer experiment had to be cancelled and replaced with the research and development of the temporal synchrony

feedback system.
In total, 6 peer-reviewed research papers in international journals were published from the research conducted within the project, and one patent application has been made concerning the temporal synchrony feedback system.
While the purchase and installation of the bimanual robotic interface was bumpy due to COVID-19, most of the funds have been fully spent and have been utilized to accomplish the project's objectives.

**研究成果の科学技術及び社会・経済への波及効果**

Two new feedback systems to aid the acquisition of motor skills were developed and assessed in this project. The joint feedback system directly addresses the problem of the aging population in Japan, where the system can assist individuals with expert skills (e.g. surgery, manufacturing and craftsmanship) mediate the transfer of their skills to novices who have just entered the workforce. Through self-monitoring of the body's stiffness during the task, the expert can provide meaningful advice like "relax here" or "be stiffer here" and the novice can immediately see if their body's state has changed as it should. This technology lets both experts and novices see their body as they could not before, promising to accelerate the transfer of expert skills to new users, partially reducing the loss of skill and expertise due to an aging population.

The second feedback system, which enables users to see the temporal synchrony of their muscles, will have a broad impact both domestic and abroad. This technology leverages the large ownership of smartphones to allow users to readily measure the skill of each hand. This ability to monitor motor coordination will have significant impact in healthcare, e.g. helping doctors to remotely assess an aging patient's health status, and for a physiotherapist to judge a patient's rehabilitation status. This could reduce healthcare costs in the long-term as preemptive measures can be taken if a person's motor coordination suddenly worsens (potentially a sign of stroke or the triggering of a neurodegenerative disease like Parkinson's). The research finding of temporal muscle synchrony being a critical element of dexterity also has large scientific impact as it explains the common origins of asymmetry in the brain concerning language and handedness, which opens up new avenues to investigate the specific brain areas that contribute to precise timing in the central nervous system.

## 5. 主な研究成果リスト

### （1）代表的な論文（原著論文）発表

研究期間累積件数：3件

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|---|
| 1. Takagi, A., Kambara, H., and Koike, Y. (2019). Increase in Grasp Force Reflects a Desire to Improve Movement Precision. *eNeuro* 6, ENEURO.0095-19.2019. doi:10.1523/ENEURO.0095-19.2019. |
| This paper presents the grasp force method of estimating the user's joint stiffness during motion. Two studies are replicated, showing comparable changes in the grasp force as reported in the earlier studies. Furthermore, the paper reveals the intricate details of how the grasp force changes along the movement when learning to move in unstable environments. |
| 2. Takagi, A., Xiong, G., Kambara, H., and Koike, Y. (2020). Endpoint stiffness magnitude increases linearly with a stronger power grasp. *Sci. Rep.* 10, 1–9. doi:10.1038/s41598-019-57267-0. |
| While the paper of 2019 showed that the grasp force mimics the changes in joint stiffness reported in earlier studies, here we show that the grasp force is linearly and positively related to the size of the arm's stiffness. |
| 3. Takagi, A., De Magistris, G., Xiong, G., Micaelli, A., Kambara, H., Koike, Y., et al. (2020a). Analogous adaptations in speed, impulse and endpoint stiffness when learning a real and virtual insertion task with haptic feedback. *Sci. Rep.* 10, 22342. doi:10.1038/s41598-020-79433-5. |
| The grasp force was measured during the motor learning of a factory insertion task, which increased smoothly from the beginning to the end of the movement. The mean grasp reduced over time with learning. Interestingly, the reduction in joint stiffness took significantly longer than the reduction in peak insertion force, suggesting that joint stiffness takes longer to optimize and learn. |

（2）特許出願

研究期間全出願件数：1 件（特許公開前のものも含む）

| | | |
|---|---|---|
| 1 | 発明者 | 高木 敦士 |
| | 発明の名称 | 運動能力推定装置、運動能力推定方法、プログラム |
| | 出願人 | 日本電信電話株式会社 |
| | 出願日 | 2020/04/28 |
| | 出願番号 | 5201458 |
| | 概要 | A method to use the accelerometer on a smartphone to assess the motor performance of the left and right hands. |

（3）その他の成果（主要な学会発表、受賞、著作物、プレスリリース等）

**学会発表**

- モーターコントロール研究会 (2018, 2019)
- Neural Control of Movement (2019)
- 日本神経回路学会(2019, 2021)

**受賞**

日本神経回路学会若手研究発表賞（2021）