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Master's Thesis
Academic Year 2018

Artificial Muscle Memory: Facilitating Motor Learning by Wearable Soft Exoskeletons.

Keio University
Graduate School of Media Design

Takashi Goto

A Master's Thesis
submitted to Keio University Graduate School of Media Design
in partial fulfillment of the requirements for the degree of
Master of Media Design

Takashi Goto

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Abstract of Master's Thesis of Academic Year 2018

Artificial Muscle Memory: Facilitating Motor Learning by Wearable Soft Exoskeletons.

Category: Science / Engineering

Summary

We present a wearable soft exoskeleton sleeve based on Pneumatic Gel Muscle(PGM). The sleeve consists of PGMs controlled by a computing system and can actuate 4 different movements (wrist extension, flexion, pronation and supination). Depending on how strong the actuation is, the user feels a slight force (haptic feedback) or the hand moves (if the users relaxes the muscles). The thesis gives details about the system implementation and two user study. In the user study, we conducted experiments for human navigation and rhythm training. The results of former show that even if the provided air pressure into Pneumatic Gel Muscle (PGM) was minimum value(0.05 MPa), participants almost recognized their own hand movement. It indicates that our soft exoskeleton works as notification which direction our hand should be moved and it gives the direction to design of PGM actuation. In the latter, we measured delay time and number of missied beats while drumming as rhythm training. The results show that PGM is helpful in less missed beats better and the delay time tends to decrease that compared with other modality in some cases, if things get harder.

Keywords:

Wearable Devices, Pneumatic Artificial Muscle, Proprioception, Somatosensory

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Chapter 1
Introduction and Background

“ *We live in a complex world, filled with myriad objects, tools, toys, and people. Our lives are spent in diverse interaction with this environment. Yet, for the most part, our computing takes place sitting in front of, and staring at, a single glowing screen attached to an array of buttons and a mouse.* ” [1]

1.1. Introduction

Over the past few decades, Human Computer Interaction (HCI) researchers developed a wide range of interaction styles and interfaces. Technological advancements and a better understanding of the psychological and social aspects of HCI lead to a recent diversification of interfaces which are not only a mouse and keyboard. Those interfaces increasingly make narrower the gap between the real world and digital world.

In 1965, Ivan Sutherland stated that the ultimate display is a room which is capable to control the exisence of matter [2]. We storongly agree with his vision, and envision that digital resources could be interfere non-digital resources. After few decades of his work, Tangible User Interfaces (TUIs) emerged as interface that is concerned with providing tangible representation to digital information and control, *i.e.*, Tangible User Interface (TUI) overlays information onto matter. And digital devices, and these augmented physical objects function as both input and output devices with users feedback with parallel feedback loops: physical, passive haptic feedback that informs users that certain physical manipulation is complete; and digital, visual or auditory feedback that informs users of the computational interpretation of their action [3]. Ishi and his students presented the comprehensive vision of *Tangible Bit* in 1997 [4]. Their vision centered on turning the physical world into an interface by connecting objects and surfaces with digital data. Based on this work, the tangible user interface has emerged as a new interface and interaction style.

On the other hand, exoskeleton is ordinally used for supporting elderly or rehabilitation. The concept of exoskeleton was providing asssistive force to limb with increased strength and endurance. The first exoskeleton called Hardiman, which is co-developed by General Electric and the United States Armed Forces in 1960s, allowed the wearer to amplify their strength. The rigid exoskeleton, which is represented by Hybrid Assistive Limb(HAL), is same concept, although this is for rehabilitation and the purpose is different from Hardiman [5]. The point in common is that those exoskeleton allows us to enhance our physical abillities by providing force directly to our body.

In this chapter, we introduce the concept of "Artificial Muscel Memory" to classify a means of human body actuation for motor learning. We try to enable skill learning based on the combination of wearable technology and exoskeleton techniques. Skill learning is caused by motor learning. Motor learning describes the process of committing a specific repetition of motor task into memory through repetition. When we first conduct a complex motor task, it is often required a huge amount of effort. Once you will be able to do a specific motor task such as riding bike, it can be performed almost automatically and without thought. However, it doesn't mean you could explain to someone the exact sequence of movements needed in order to cycle. This is because memory for skills can be stored without any conscious awareness and the skilled action can be performed almost automatically.

Furthermore, we conduct experiment for rhythm training of drumming by means of our soft exoskeleton in this study. Drumming is one of exercises which requrie a large amount of repetitive training and the exercises consist of high speed drumming and complex beats. The human rate limit for voluntary rhythmic movement like unimanual tapping supposes 5-7 Hz, while the winner of a recent contest to find the world ' s fastest drummer (WFD) can perform such movements using a handheld drumstick at 10 Hz, which corresponds to an inter-tap interval (ITI) of 100 ms [6]. The goal of this study is that soft exoskeleton allows us to assist skill learning, which requires fine motor skill and is difficult to acquire for person, and therefore we conduct experiment of drumming as a first step.

The investigation of the usage of soft exoskeleton for motor learning open up new, fascinated opportunities for haptic/muscle interaction. We will discuss this field in greater detail in the future work section of the conclusion.

1.2. Concept: Artificial Muscle Memory

Artificial Muscle Memory means that people can feel the information naturally through their body like with an arm, torso, or leg. Artificial muscle suit we are building can also be used to supporting elderly and enhancing human motion in sports as same as previous story of exoskeleton research. Our research focus is a little different, looking into the suit's ability to bridge the gap of our mental wellbeing and the digital world. One application case, for example, is assisting navigation. The user can feel a slight drag to the left in their arm if they're supposed to take a left turn. It means people can get information directly through your body that which direction you should go. The artificial muscle suit could help create a novel sense for getting information naturally and people will be able to focus more on their essential things without any distraction.

1.3. Related Work

we can share knowledge to others, however, knowing doesn't mean to make us skilled. Skilled individual is characterized by fine-tuned perceptual and motor functions and those motor function will appear by a lot of training. This is an aspect of muscle memory. Muscle memory (or motor learning) describes the process of committing a specific motor task into memory through repetition. When we first conduct a complex motor task, it is often required a huge amount of effort. Once you will be able to do a specific motor task such as riding bike, it can be performed almost automatically and without thought. However, it doesn't mean you could explain to someone the exact sequence of movements needed in order to cycle. This is because memory for skills can be stored without any conscious awareness and the skilled action can be performed almost automatically.

Providing kinetic information helps in this situation to make us skilled. Pedro *et* *al.* proposed *proprioceptive interaction*, which is new way of eyes-free interaction for wearables based on the user's proprioceptive sense, *i.e.*, rather than seeing, hearing, or feeling an outside stimulus, users feel the pose of their own body [7]. Proprioceptive sense can give the users the sense how users should move their body and non-skilled people will be able to do a specific motor task which requires a certain amount of skills.

Although proprioceptive interaction is one of the important interaction concepts for providing kinetic information, the technology for this kinds of interaction is still non-established enough. Electrical Muscle Stimulation (EMS) and Exoskeleton are major approaches to give proprioceptive sense in previous research. Pedro *et al.* used EMS for this interaction [7]. EMS uses electric impulses to mimic the action potential that comes from the central nervous system, therefore causing a muscle to contract. Commonly, EMS is administered using electrode pads placed on the muscle group to be contracted. Researchers apply EMS mostly to influence physical movements of users: from triggering hand movements to play an instrument [8] to altering the user's walking path, a "cruise control" for pedestrians [9]. Lopes et al. investigated the use of EMS as an output modality to guide the user's hand while drawing or giving haptic feedback in VR environments [10,11]. EMS has also been used to encode notifications in an embodied manner [12]. However, EMS is often difficult to handle as it requires to find the right muscles, one has to overcome the impedance of the skin and for somebody locations, it's not saved to apply an electrical current. Therefore, better tactile feedback techniques are needed in this interaction.

Otherwhile, the approach based on rigid exoskeleton focus more on rehabilitation. The rigid exoskeleton is capable to move body more precisely that compared with EMS, therefore the exoskeleton is used for rehabilitation and assist to actuate the body correctly that wearer really intended. The exoskeleton which focus on wearable property has also appeared nowadays. The device called *mono* aim to be as a device that is wearable, portable and minimally obstructive on the hand [13]. One of the focus of conventional rigid exoskeleton is rehabilitation, therefore the exoskeleton is used to translate motor intention into real hands motions, which in turn provide a rich and coherent proprioceptive feedback to the wearer, allowing to establish closed sensorimotor loops for its users.

The approach based on soft exoskeleton has several benefits that compared with EMS and rigid exoskeleton. Pneumatic actuator doesn't restrict our body movement like rigid exoskeleton and it's easier to resist the provided force. Latter is totally different with EMS. EMS is also allows us to resist the provided force, but it's difficult to resist when a large amount of electric current flows through our muscle because our muscle actually shrinks in this case. Furthermore, PGM that we use in this study can be driven by fairly low air pressure. This allows using smaller air tank to provide air to pneumatic actuator and enable to give bigger force feedback to the users. It's also easier to make as a wearable form factor.

In this study, we aim the area between EMS and rigid exoskeleton in proprioceptive research. Soft exoskeleton is capable to provide bigger force than EMS to wearer , however, it's still smaller than conventional rigid exoskeleton. It's same at the point of control accuracy. Soft exoskeleton is more precise than EMS, while rigid exoskeleton is more precise than soft exoskeleton. There are different benefits and appropriate applications for each EMS, soft- and rigid exoskeleton. We will make clear several application scenarios of soft exoskeleton, especially for motor learning and discuss the different benefit and appropriate scenario with EMS and rigid exoskeleton.

1.4. Research Question

To investigate the use of artificial muscle to facilitate getting skills two main aspects need to be considered, namely the capability and usability. Table 1.1 lists the corresponding research questions, which have driven the research presented in this thesis.

Providing information by dynamic body movement is one of intuitive information presented method. Therefore, we first focus on **Proprioceptive sense** caused by soft exoskeleton and how it can be affect our sense(Research Question(RQ)1). With the goal of motor learning for acquisition skill, we investigate the kind of the usage, based on which users get information semalessly thorough their body. Here, we focus on the **Muscle memory** in soft exoskeletno context and whether our muscle memory can be affected by means of soft exoskeleton(RQ2).

Table 1.1 Overview of research questions that bid the base of thesis.

RQ	**Research Question**
RQ1	How can soft exoskeleton affect our proprioceptive sense?
RQ2	How can soft exoskeleton affect our muscle memory?

1.5. Thesis Outline

This thesis comprises 4 chapters and is divided into six parts, the last two of which contain the bibliography and the appendix. In the first chapter, we motivate the work, point out the intuitive method of presentation information through our body, aim of soft exoskeleton in HCI, research area of soft exoskeleton that compared with EMS and rigid exoskeleton. The second part contains the research we conducted with regard to skill learning based on proprioceptive sense. Here, we described not only possible application scenario of soft exoskeleton, but we describe the application scenario that soft exoskeleton is used for assisting our skill learning. In the third part, we show the prototype of soft exoskeleton and we apply those prototype to applications to validate our approach and explore future application scenario of Artificial Muscle Memory with regard to present information through human body. The fourth part contains an overall summary of the research contribution and discusses the overall approach and implications of this thesis.

Chapter 2
Proprioception Research

2.1. Related Work

Proprioception is a sense that tells us where our body is in space and has an important function in normal motor control and motor learning. A number of recent studies have tested the degree to which motor learning directly influences sensory perception and there is also evidence that proprioception is affected by recent motor learning. The motor learning based on proprioceptive training contributes to improve both movement speed and position error as the user ' s arm doesn ' t move actively [14].

Researchers in HCI are trying to teach a specific motion based on haptic/muscle interaction. Kon *et al.* showed walking navigation that does not require explicit interpretation by mean of Hanger Reflex [15]. Chen *et al.* showed motion guidance by means of external artificial muscle that mainly consists of stepper motors and elastic band [16]. Also, Researchers explore EMS as a mean for teaching motor skills and allowing users to interact with computer. Tamaki *et al.* guided users in learning a new instrument [8] and Pfeiffer *et al.* used EMS for steering users' while walking [9]. EMS has been applied to create simple display that provides information by feeling the pose of user ' s muscle. Lopes *et al.* developed an interactive system based on EMS that allows object to communicate their use by means of actuating user ' s muscle (*e.g.*, a spray can, by itself, show the user that shaking is mandatory before spraying) [17].

In previous researches, pneumatic soft exoskeleton, which is focused in this thesis, is used as means of an assistive device which assists wearer during walking and can reduce the fatigue compared to regular walking [18]. Those devices don't focus only on gait assistance, also it is possible to use for rehabilitation, upper body support, and for other assistance for the motion. However, those works are just the assistance for a specific motion to improve our strength and endurance.

Prementioned reserach in HCI contributes giving a sensation to improve our ability to get information by giving force feedback. However, we still have room for improvement to give more natural force feedback without any sacrifice our sense of agency and body ownership. The method like EMS is kinds of embodiment approach and it is difficult to resist provided force. Although other method allows us to resis the provided force, the limition of force direction is strict or the force is weak to make only smaller motion. Ideal force feedback for motor learning should not inhibit our body ownership, and it sould be enable to provide bigger force to the users. While, soft actuator has a potential for providing more natural force to users because of the flexibility. One point to prevent sacrifce of our body ownership is whether the restricion of body movement is strict or not. Therefore, we consider soft actuator like pneumatic tubes as useful way to allow us the interaction based on proprioceptive sense.

2.2. Motor Learning

Muscle memory is created by motor learning that involves a series of consolidating a specific motor task into memory through repetition. In each step of motor learning a specific brain region is related. Premotor cortex is the core of motor learning based on sensory information, and it especially depends on visual information at the early stage of motor learning.

One strategy that can facilitate the motor learning is the use of *augmented feedback*. Augmented feedback is external information provided about the movement that is supplemental to *inherent feedback* [19]. Inherent feedback is intrinsic sensory information that is naturally available to an individual during the movement (*e.g.*, vision or proprioception of limbs). Several studies have investigated what type or frequency of augmented feedback facilitate the retention of motor skill. The influential guidance hypothesis postulates that too much feedback is detrimental to motor skill learning. One of the assumptions of guidance hypothesis is that a reduced frequency of augmented feedback (*e.g.*, providing feedback on every other training trial) may facilitate learning because it promotes the learner to use their own inherent feedback during the no-feedback trials [20, 21]. The no-feedback trials also provide the learner with the opportunity to integrate information from previous feedback trials, with information derived from their own inherent feedback systems. The active use of inherent feedback systems during the no-feedback trials may help the learner form a motor command to execute a target movement without relying on the augmented feedback [20, 21].

In general, inherent feedback can enhance performance in the acquisition phase of learning, however, the performance gains are lost in retention phase. That is also explained in the guidance hypothesis. The guidance like visual feedback forces learners to ignore their intrinsic feedback, that is proprioception. But actually, in learning dynamic tasks, proprioception is more important than vision. We normally learn dynamic tasks equally well with or without vision. Patient who has lost proprioception have particular difficulty controlling the dynamic properties of their limbs or learning new dynamic tasks without vision [22, 23].

In one of experiments that we will describe in Chapter 3, we perform the comparison of force feedback with audio feedback in drumming task. We attempt to estimate how the force feedback is provided from soft exoskeleton affects our muscle memory. Furthermore, soft exoskeleton doesn't restrict our body movement too much and the wearer doesn't rely on force feedback as the augmented feedback completely, even if they are in feedback trial. We will discuss at this point too.

2.3. Methodology

In this Section, we describe our approach to build, apply, and evaluate soft exoskeleton. First, we will use Pneumatic Gel Muscle (PGM) as an actuator to built our soft exoskeleton. These are pneumatic "tubes" that is a type of Pneumatic Artificial Muscle (PAM) and it can be activated by fairly low air pressure compared to the conventional PAM [24]. At the core capability of our motor skill lies the ability to memorize and represent specific motions. Because soft exoskeleton is capable to actuate human body, we start by prototyping of these devices. To investigate the capability of soft exoskeleton we conduct user study too. We will built arm sleeve type of soft exoskeleton by using this PGM.

To validate the soft exoskeleton developed in the first part of this thesis we integrate them into applications which suggest different types of content in moments classified as opportune. The performance metrics for the evaluation of soft exoskeleton are strongly dependent on the application of the device, as soft exoskeleton with different purposes have different requirements and should be evaluated differently. In this thesis, we describe two kinds of user study for each human navigation and rhythm training and especially we will mention the latter because we focus on improvement by means of a soft exoskeleton.

Concluding, the first part of the thesis is to build the prototype of soft exoskeleton and the last part of the thesis comprises the application of these prototype for validation purposes and for investigating their feasibility and utility.

Chapter 3
Artificial Muscle Memory

3.1. Approach

In our concept "Artificial Muscle Memory", people can develop their motor skills by using external equipment. Our motor skills can be develped through repetation of practice of a specific motion. When we acquire a specific motor skill, our brain changed the way to react those specific motion.

Our concept is cosidered according the statement that cognition is embodied in the sense that it is critically based on reinstatement of external (perception) and internal states (proprioception) as well as bodily actions that produce simulations of previous experience. In last decades, phychological and neuro scientific research now allows answering many longstanding questions, *e.g.*issues about the nature of human cognition, objectively by measureing behavioral performance and brain activitiy during cognitive experiment. Markus *et al.* explain the difference between symbolic view and embodiment theories with teaching the use of bassoon as example(see below):

"*According to a symbolic view of cognition, it would be sufficient for the teacher to verbally describe the shape, the sound, the material, etc. of a bassoon in a written text, perhaps complemented by a picture. A direct experience with the object is not necessary. According to embodiment theories, rich knowledge about the unfamiliar bassoon can only be acquired when the students can see, hear, touch and act on the bassoon.*" [25]

In a symbolic view, it is assumed that our neuro-cognitive systems code knowledge in abstract-symbolic format, in which original modality-specific sensory-motor information is lost. In contrast, embodiment theories assume that our cognition process depends on the close links between the sensory and motor brain systems.

Artificial muscle memory assumes that the use of device, which is capable to actuate our body directly, affects our sensory-motor experience during proceeding of complex motor skills. The device give a intuitve understanding how we shoud move our body correctly, *e.g.*, both arm movement speed and its position. This allows users to acuqire motor skilles easily and efficiently.

There are a sevral way to actuate our body. EMS and rigid exoskeleton is also available for this concept. However, at This time we choose soft exoskeleton as the device for this purpose because of stable control and safety. EMS device is smaller and lighter than others, however, it is difficult to maintain same posture and there are safety issues [26]. Rigid exoskeleton is more precise than soft exoskeleton, however, it is really heavy and cause increasing the metabolic cost to users. This device also has a safety issues. Rigid exoskeleton provides strong force to wearer and if device give the force in wrong way, it could have hurted users. Therefore, we pick up soft exoskeleton for our purpose. We tried to develop the soft exoskeleton and improve peoples' motor skills during this external equipment.

3.2. Apparatus

Pneumatic Artificial Muscle (PAM) which is pneumatic tube is usually used in vast areas such as: 1) Biorobotics, 2) Medical, 3) Industrial, and 4) Aerospace applications [27]. In medical applications, the PAM actuator will be one of the actuator choices for therapeutic devices, which are designed for rehabilitation therapy of patient. The devices based on PAM focus on supporting the patients suffering from degenerative muscle diseases, extremity impairment or neurological injuries that affect their kinetic abilities. The PAM has the advantage that enables to assist people without risk of muscle injury because of the flexibility, therefore it is used for rehabilitation. Another advantage of PAM can provide large tensile force that is capable to actuate our body, *e.g.*, it is easier to actuate wrist flexion/extension as you wear on soft exoskeleton using this actuator.

Otherwhile, PAM is a conventional type of actuator that operates by compressed air, for example, the systems used by McKibben actuator require high pressure to actuate while also requiring a power source, *i.e.*, air compressors which are costly and not practical for users to wear [28]. PGM overcomes this limitation as it can be actuated at a lower pressure of approximately 20KPa compared to conventional artificial muscle. Compared to rigid exoskeletons, our artificial muscle is found to be easier to wear and integrate into a wearable form factor. Researchers use PGM to build assistive suits to support the elderly or enhance human motion in sport. For example, Ogawa *et al.* developed an assistive suit to enhance the walking gait experience [24]. Das *et al.* provides force-feedback by means of PGM [29]. Force Hand Grove is enabled with pneumatic actuators and stretch sensors which support the user in performing wrist flexion, extension, pronation, and supination. The work focuses on assistive applications our system is an improvement of the work from Das *et al.* , making the system wearable and supporting all hand movements at the same time.

We demonstrate two application scenarios for our interactive system based on PGM: enhancing human motion in sport and assisting navigation. These prototypes focus on two particular benefits of PGM: (1) strong driving force without high electricity consumption, which enables easy actuation of the user ' s muscle in mobile scenario; and, (2) lightweight and flexibility to ensure zero restriction of the user ' s motion, yet does not sacrifice a wearable form-factor.

3.3. General Consideration

There is an issue to decide the on-body placement of PGM. PGM should be placed based on the direction to actuate. In this work, the PGM glove designed for flexion, extension, pronation, and supination of the wrist as same as the work from Das *et al.* [29]. Flexion is a movement of the hand with the palm facing down, towards the wrist joint. Extension is the opposite of flexion denoting the movement of raising all fingers away from the wrist joint. These two motions are considered as one degree of freedom (DOF). Pronation is rather a motion performed not only by the wrist but by the entire forearm. It can be described as the rotation of the forearm to make the palm face downwards. On the other hand, supination is the opposite of pronation, with the hand rotating and palm facing upwards.

3.4. System Design

A system schematic is shown in Figure 2. The sleeve consists of 4 artificial muscles (from Daiya Industry Co. Ltd., Japan). Two 20cm artificial muscles are used for wrist extension and flexion, whereas two 30cm artificial muscles are used for wrist pronation and supination. Artificial muscle for extension and flexion were attached along the user ' s arm and artificial muscle for pronation and supination wrapped around the forearm in each direction of actuating. Each Artificial muscle is actuated by CO2 gas from a gas cylinder and the amount of gas is adjusted by a pressure regulator. The PGM is either actuated or deflated through a solenoid valve, which normally closed configuration. An Arduino Uno sends the signal to actuate the solenoid valves. The system is stand-alone and can be controlled just by the Arduino. For the demo interactions, we prepare a sleeve and the user can wear it and experience the different actuation types. We can extend, flex, pronate and supinate the user's wrist if the muscles are activated strongly. However, we can also give just a slight "dragging"/"pulling" feeling (haptic feedback) if the muscles are only activated softly (with less air pressure).

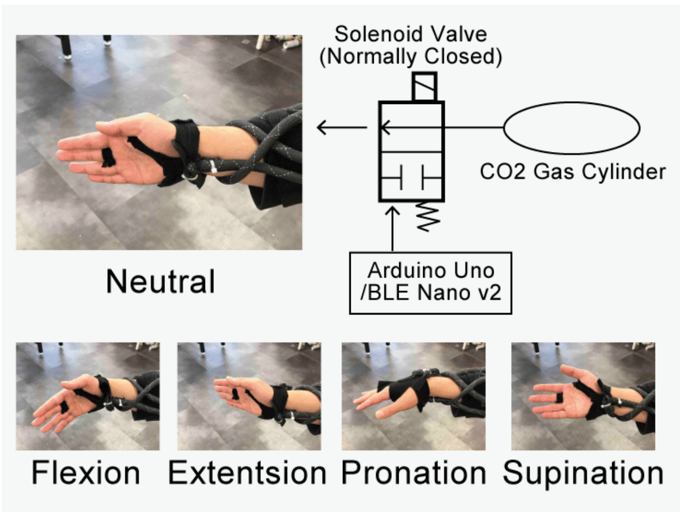


Figure 3.1 The device based on PGM is worn on user ' s forehand and it can actuate human arm. If the solenoid valve for each artificial muscle opens, the device initiate the certain movements.

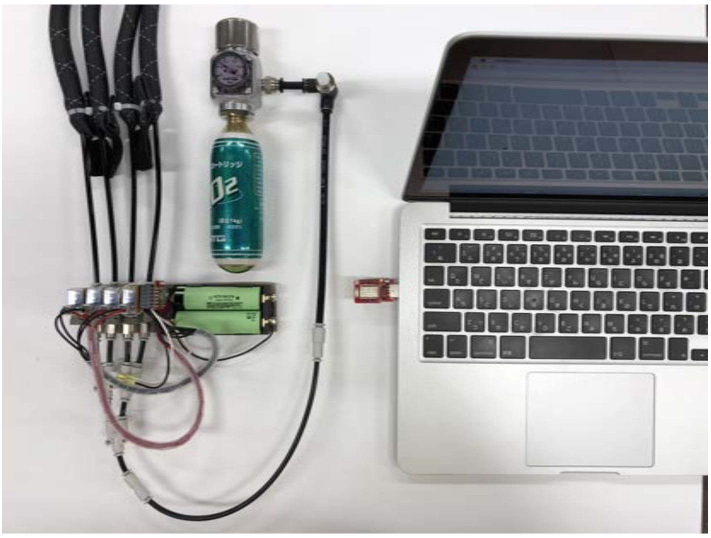


Figure 3.2 The device consists of artificial muscle, solenoid battery, BLE nano v2, gas cylinder. This allows us our prototype based on a laptop computer with a USB Bluetooth 4.2 dongle.

3.5. Evaluation on PGM for Human Navigation

There are several ideas for assisting navigation. Although navigation information is often provided on a visual display or descriptive audio, the assisting navigation based on tactile feedback is also proposed [15, 30, 31]. The artificial muscle could be helpful on assisting navigation scenarios and it indicates which direction you should go by actuating your arm. The user can feel a slight drag to the left in their arm if they are supposed to take a left turn.

Experimental Setup

In this experiment, we evaluate whether people can recognize the movement of their own hand or not when different air pressure was provided to PGM. Participants (N=6, female =2) wear on an eye mask and judge whether their hand is moved to extension, flexion, pronation or supination. PGM was actuated total 240 times in different air pressure(0.05, 0.10, 0.15, 0.20 MPa). There is a short break after each 60 times actuation of hand by PGM. The order of actuation for each participants' hand is randomized. We conducted semistructured-interview after all experiment for each participants.

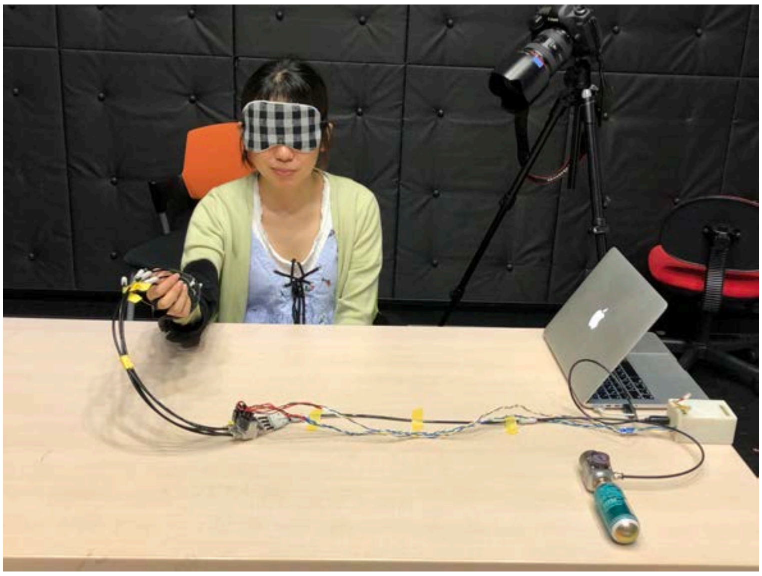


Figure 3.3 Participants wear on sleeve that consists of total 4 PGM and it shrink in random order to move participants' hand.

Experimental Results

The average of accuracy rate in different air pressure is shown in Table 3.1. The accuracy rate per motion(extension, flexion, pronation, supination) is summarazed and those results can been seen in Figure 3.4. Comments from participatns in the semistructure interview after whole experiment summarize in Table 3.2.

Table 3.1 The average of accuracy rate in different air pressure.

Air Pressure [MPa]	Average of Accuracy Rate
0.05	0.98
0.10	0.99
0.15	1.0
0.20	0.97

Table 3.2 Comments from participatns in the semistructure interview after whole experiment.

No.	Comment
P1	Weaker force felt better. My hand pulled actually, but it's not too distracted. Weaker force is good for notification.
P2	Movement of hand to left was weaker than the movement to right. This unbalance of actuation make more difficult to recognize hand movement, especially when provided stronger force. I felt like it was not my own hand and someone actuate my hand as the force would be stronger.
P3	The force to move to right was about 70% of the force to move to left.
p4	[NO COMMENT]
p5	The movement of actuate to each direction is easier to recognize after short break, but it would be difficult after actuating several times.
p6	I could feed hand moving, right turin is most strongest, left turn and left is next, right is most weakest. I feel the rotation or not through skin surface. The feeling is skin feeling, not movement feeling It's different because of setting.

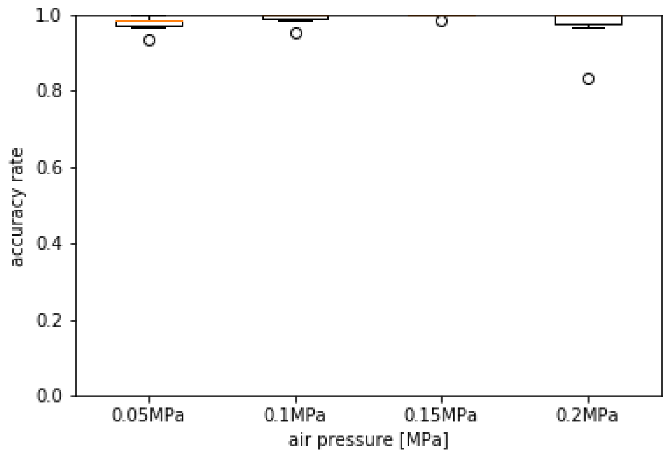


Figure 3.4 Accuracy rete per motion(extension, flexion, pronation, supination) in difference air pressure.

3.6. Evaluation on PGM for Rhythm Training

Drumming is one of good example as playing instrument in motor learning. Soft exoskeleton based on PGM is easier to make as wearable form factor, however yet how useful is the device in motor learning? We evaluate it on simple drumming tasks, which is consists of 4 different level of drumming exercise, and the results are compared as the participants are given different modality of PGM.

3.6.1 Experimental Setup

PGM and Score vs. Score

In this experiment, we compared with delay time and a number of missing beats in 4 paris of different drumming tasks when people played drum after training with force feedback and score or only score. The experiment for each drumming task was proceeded in the following order:

1. Perform the task with force feedback and score once.

2. Perform the task without force feedback and score.

3. Repeat 1 and 2 in three times.
4. Perform the task with score once.
5. Repeat the task without score.
6. Repeat 4 and 5 in three times.

The drumming tasks can be seen in Figure 3.5. Score for each task is chosen following the combination of drumming task shown in Table 3.3. If task A was used for the task with force feedback and score, then task B is used for the task with audio feedback and score. It is same when the order of task A and B exchange. It is randomized which task should apply for each participant. The pairs of score like No.1 and No.2 in drumming task shown in Table 3.3 assume to treat as same level in this experiment.

PGM and Score vs. Audio Feedback and Score

In this experiment, we compared with delay time and a number of missing beats in 4 paris of different drumming tasks when people played drum after training with force feedback and score or audio feedback and score. The experiment for each drumming task was proceeded in the following order:

1. Perform the task with force feedback and score once.
2. Perform the task without force feedback and score.
3. Repeat 1 and 2 in three times.
4. Perform the task with audio feedback and score once.
5. Repeat the task without audio feedback and score.
6. Repeat 4 and 5 in three times.

The drumming tasks can be seen in Figure 3.6. Score for each task is chosen following the combination of drumming task shown in Table 3.4. If task A was used for the task with force feedback and score, then task B is used for the task with audio feedback and score. It is same when the order of task A and B exchange. It is randomized which task should apply for each participant. The pairs of score like No.1 and No.2 in drumming task shown in Table 3.4 assume to treat as same level in this experiment.

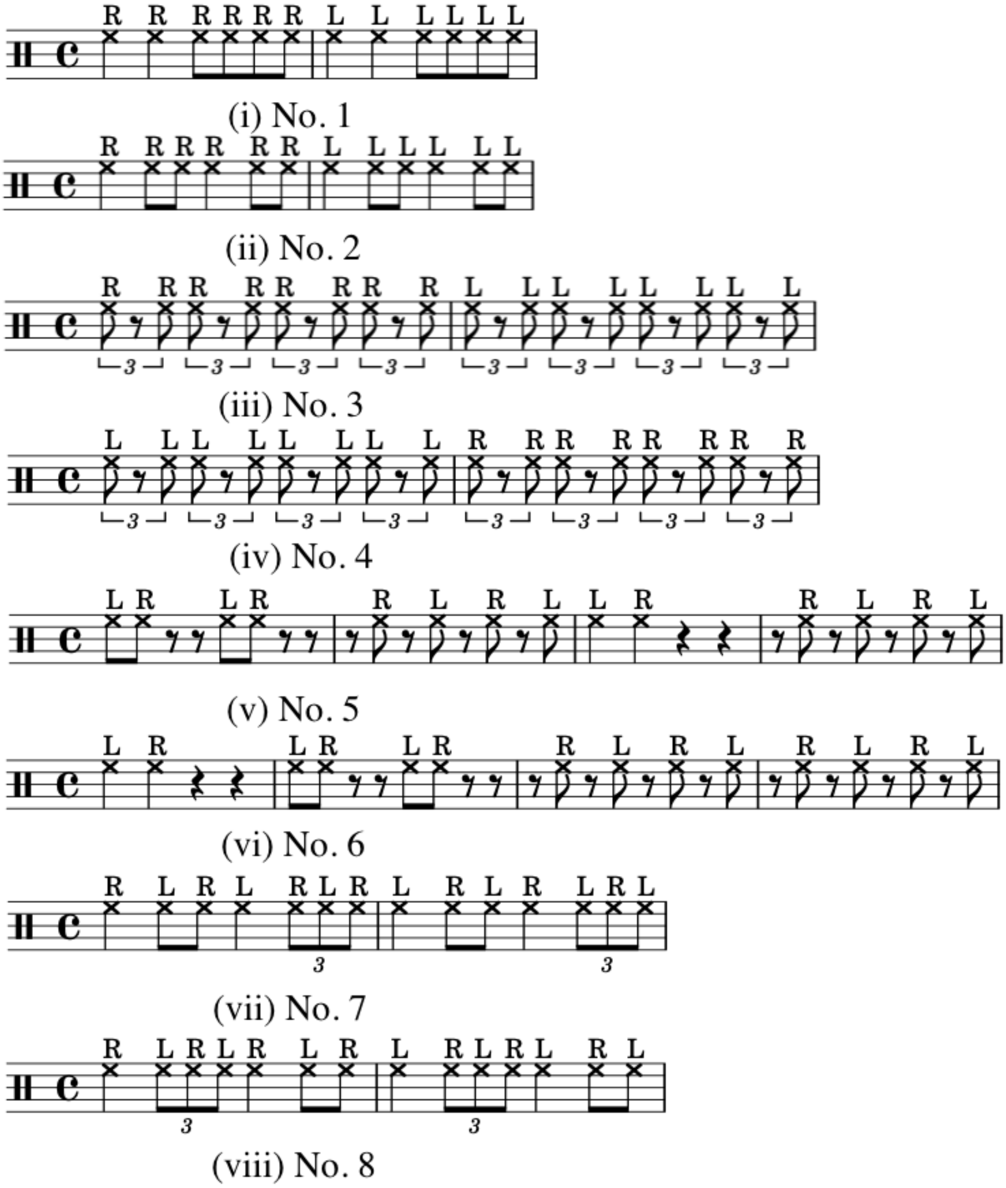


Figure 3.5 8 drumming task for the comparison force feedback and score vs. score.

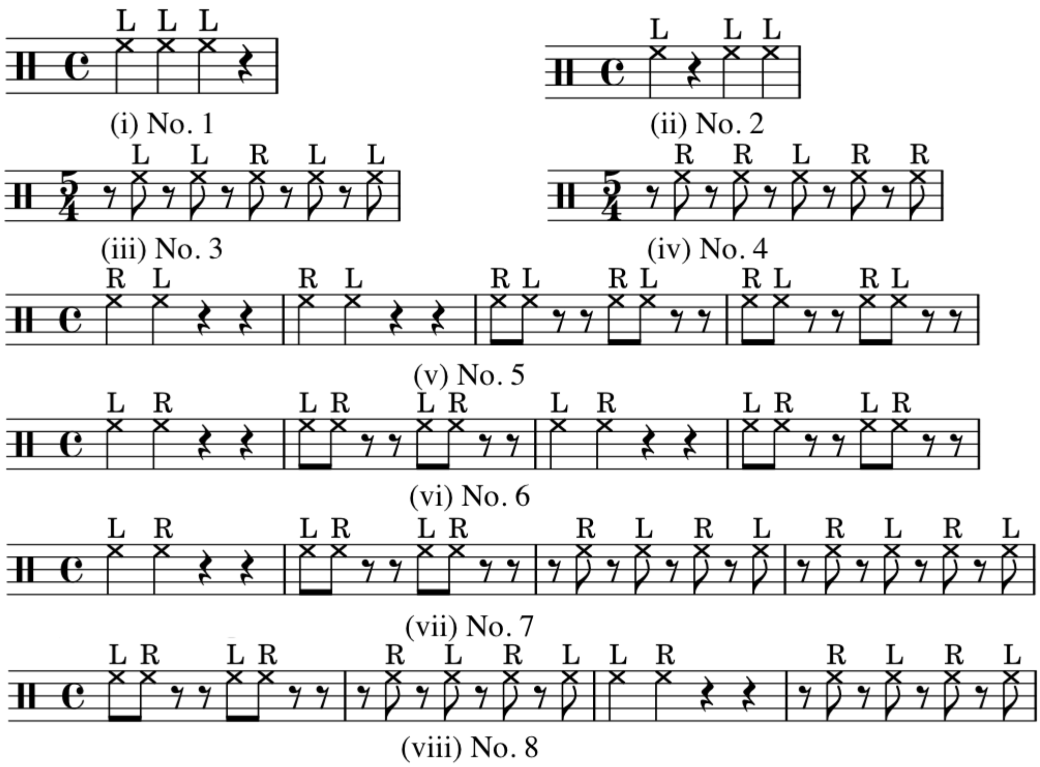


Figure 3.6 8 drumming task for the comparison force feedback and score vs. audio feedback and score.

Table 3.3 The combinations of drumming task for each participants in the comparison force feedback and score vs. score.

Task A	Task B	Tempo[bpm]	Task No.
No.1	No.2	75	Task 1
No.3	No.4	50	Task 2
No.5	No.6	50	Task 3
No.7	No.8	50	Task 4

Table 3.4 The combinations of drumming task for each participants in the comparison force feedback and score vs. audio feedback and score.

Task A	Task B	Tempo[bpm]	Task No.
No.1	No.2	75	Task 1
No.3	No.4	50	Task 2
No.5	No.6	50	Task 3
No.7	No.8	50	Task 4

Figure 3.7 The each arm is wrap up with two PGM to actuate hand for pronation and supination.

Figure 3.8 PGM is attached with both arm and it actuates the arm for drumming.

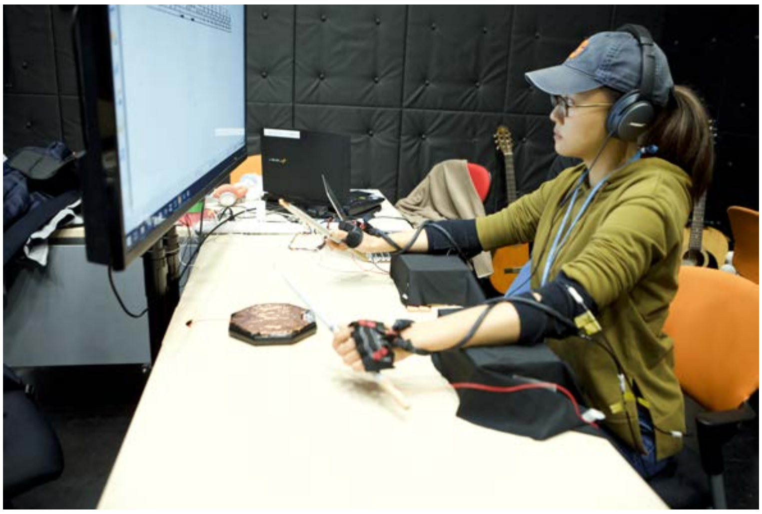


Figure 3.9 A 48-inch display places in front of each participant to show score and the participant performs training with force feedback and score or audio feedback and score in each drumming task.

3.6.2 Experimetal Resutls

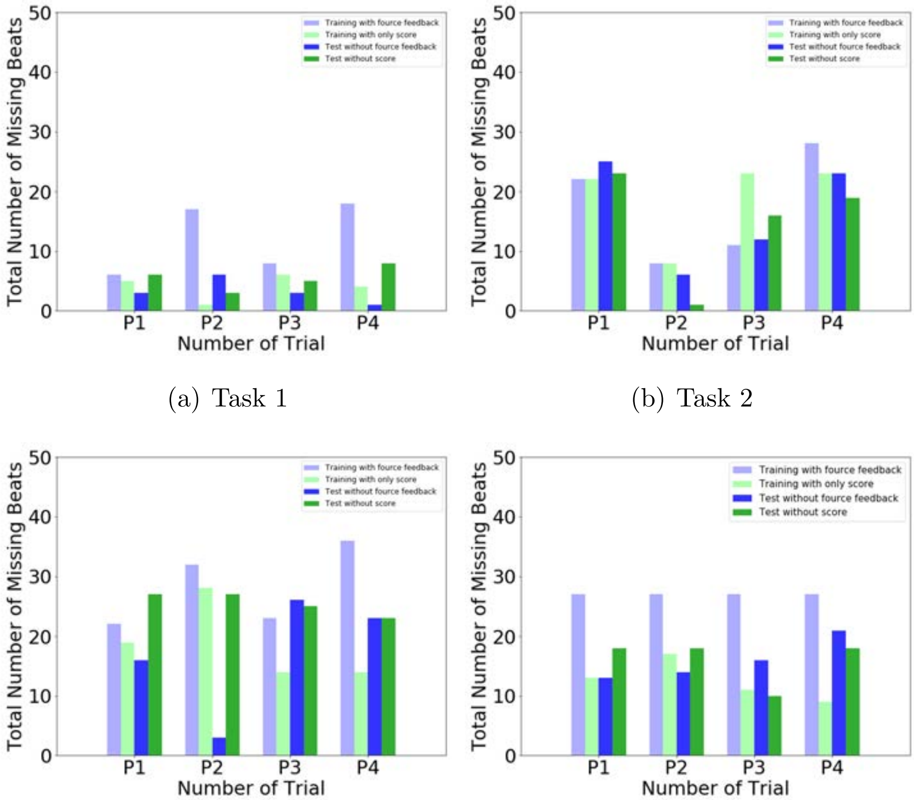
The number of missed beats was estimated depending on whether each hit beat exists between adjacent beats or not. Each delay time was calculated as difference between starting time of each feedback in training and actual hitting time in both training and test.

PGM and Score vs. Score

The results of total number of missed beats for each participants and average delay time for each task are shown in Figure 3.10, 3.12. The results of number of missed beats in each trial and average delay time for each participants can be found in the Appendix. In task 1, 3 and 4, 2 out of 4 participants made less missed beat after training with PGM that compared with results after training with only score, while the another half the participants shows the opposite results. In task 2, only one participnats made less beats after training with PGM. In this experiments the order whether participants train PGM first or not changed and it depends on partcipants because of counterbalancing. The less beats made by PGM training is just because of orderinig effect. The results also didn't show significant difference between the results after training with PGM and only score. Therefore addinig proprioceptive training by our soft exoskeleton didn't have large effect for the results of total missed beats. On the other hand, the results of average delay time in task 3 and 4 after training with PGM shows the improvement, which didn't appear in the results after training with only score. People tend to play drum ahead of correct timing. They play the drum about 0.2 seconds ahead, however it will be more precise after training with PGM from about 0 to 0.1 seconds. Therefore adding pripriocepting training with soft exoskeleton affects the hitting timing and the performance could be improve, if things get harder.

PGM and Score vs. Audio Feedback and Score

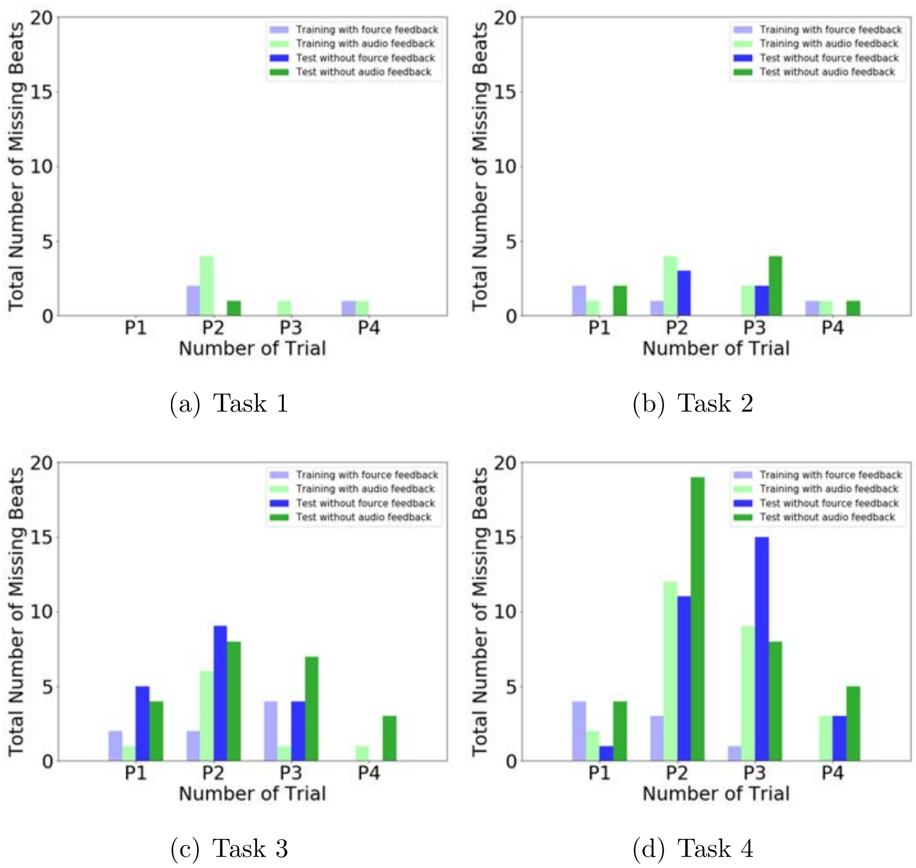
The results of total number of missed beats for each participants and average delay time for each task are shown in Figure 3.11, 3.13. The results of the number of missed beats tends to increase when the task was relatively longer score like task no.7 and no.8. Furthermore, the results when force feedback is provided in training is better than the results when audio feedback is provided. At the results of delay time, there is constant delay about 0.2 sec. when force feedback was provided in training, while there is not large difference between training and test in some results when audio feedback was provided. Although participants drummed following feedback when they receive the force feedback, they drummed just only following score, not audio feedback when they received the feedback. Participants were looked annoying while receiving audio feedback. In general the simple reaction time of human for audio- or visual stimulus is around 0.2 sec. If there is not large delay, it means people play drum depending on their prediction based on score or their memory.



(a) Task 1 (b) Task 2

(c) Task 3 (d) Task 4

Figure 3.10 Results of total missed beats when partcipants trained with or without force feedback by PGM.



(a) Task 1

(b) Task 2

(c) Task 3

(d) Task 4

Figure 3.11 Results of total missed beats when partcipants trained with force-feedback by PGM or audio feedback.

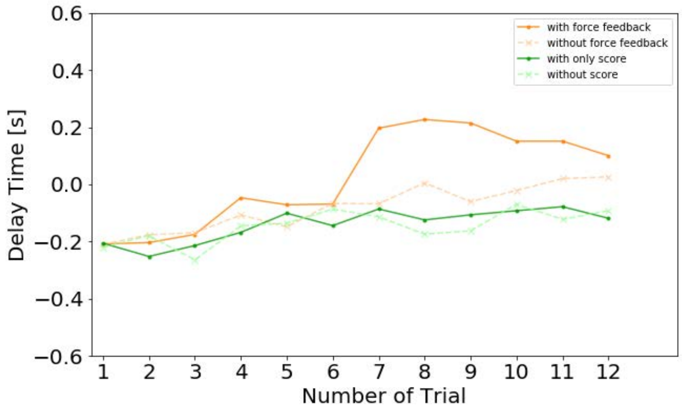


Figure 3.12 Results of delay time when participants trained with or without force feedback by PGM

3.7. Discussion

3.7.1 Soft exoskelton for Human Navigation

In the result shown in Figure 3.4, it indicates that even if the provided air pressure into PGM was the minimum value(0.05 MPa), participants almost recognized their own hand movement. This doesn't mean that PGM is enabled to use for Human Navigation because the participants sat on the chair and didn't move during the whole experiments. Although he experimental setting was not-distracted for the participants, the results still indicated that our soft exoskeleton works as notification which direction our hand should be moved and it gives some direction to design of PGM actuation, *i.e.*the small air pressure like 0.05 MPa is enough as notification in non-distracted situation. Furthermore, the problem about unbalance of provided force from PGM is made clear from participants comments(see Table 3.2). This problem caused by hardware setting of soft exoskeleton. The stretch arm supporter and glove was used to attach PGM with arm and the PGM use velcro for attaching with it. Therefore, whole hardware setup is flexible and it requires to take into account the effect for actuation of hand and the control accuracy in specific application scenario.

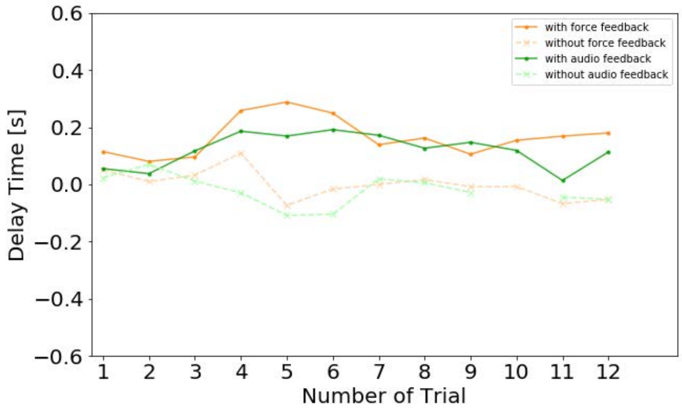


Figure 3.13 Results of delay time when participants trained with forcefeedback by PGM or audio feedback.

3.7.2 Soft exoskeleton for Rhythm Trainning

The point of this user study is finally whether soft exoskeleton helps to make our muscle memory or not. The experiment we conducted is very short for estimating our muscle memory, it was only around half hour and estimating our muscle memory is taken at least few days because we need take into account of the change for the muscle memory as time progressed. However, the result still indicated that force feedback by using soft exoskeleton helps to memorize longer score because total number of score was fewer than the result as audio feedback provided. This indicates that soft exoskeleton could be helpful to memorize the more complicated motion.

When we give audio feedback to participants, they didn't utilize the audio feedback enough. This is infered from the result of delay time. Participants look they almost depend on both their own proprioceptive sense as inherent feedback and visual feedback of score as augmented feedback, they doesn't depend audio feedback as augmented feedback. This situation is close to the situation that suppose in guidance hypothesis, which is mentioned provision of too much augmented feedback during practice may cause the learner to develop a harmful dependency on this source of feedback, and the audio feedback inhibit to learn complicated movement. This is one of the reason why the result of missing beat when audio feedback was provided was more. Otherwhile, force feedback didn't inhibit to learn and it make better dependency of the participants on the source of feedback. Finally, our results indicate could be helpful to make muscle memory in short time.

Chapter 4
Conclusion and Future Work

4.1. Summary

We showed the potential interaction by means of interactive system based on PGM. The system has potential to be capable to tell the skills or information for human navigation. The user can get these information without any interpretation of text or figures. In this thesis, we mentioned about our prototype based on PGM, which is pneumatic tubes could be shrunk in fairly low air pressure, and potential interaction, which especially focuses on improving our muscle memory based on our proprioceptive sense. We only showed two user study by means of soft exoskeleton, however, there is more potential interaction because of the feature of PGM that can actuate human muscle directly.

4.2. Limitation

First, there is the limitation of actuation speed for PGM. To implement constant and obvious PGM actuation for drumming task, the tempo of task was set up around 50-75 bpm. This is too slow tempo as rhythm training. Although giving force feedback to teach correct timing in slow tempo for wearer is valid yet, the motion that required too fast actuation isn't currently appropriate for this exoskeleton. If we implement motion that interacts outside environment by using the soft exoskeleton based on PGM we need the prediction for environment for actuation in correct timing.

The problem of operating time as wearable device is still remaining. Operating time is one of the important aspects of wearable device. The PGM is smaller than conventional PAM and it works in low air pressure, however, it requires the tank enclosing compressed air or small compressor to get compressed air. When we use a gas cylinder enclosing 74g CO2 gas as air resource for PGM, we could continue to drum only around 10 min.

We used only solenoid valve for our prototype based on PGM. The solenoid valve allows only ON/OFF control of PGM actuation and the actuation is not precise. Even if we put air pressure sensor for feedback control, the actuation will be more precisely, but it's not accurate yet because of nonlinear property of the pneumatic actuator. To use promotional valve instead of our valve is one solution for this problem, however, we need to take account of trade off precision against air speed.

While the results of rhythm training presented in Chapter 3 shows that force feedback provided from soft exoskeleton let us to help to memorize sequence better than audio feedback, we still need the comparison with haptic, for example, as other modality. This includes the user study for exploring what kinds of training is appropriate to improve our muscle memory that compared with other modality. This investigation will need to be picked up by future work for which this thesis provides a starting point.

4.3. Future Work

This thesis provides a prototype based on PGM and design tips for future research on interaction of soft exoskeleton. While we especially focused on their applications for skill learning, we came across a number of application scenarios and use cases these might be used for. Also, during the course of our research on building these prototype and applications, we identified several additional research challenges. In the following, we will lay out how future research and development can be continued.

Research projects that should be immediately picked up concern the difference between EMS, soft- and rigid exoskeleton to make clear the appropriate usage of soft exoskeleton in HCI. The research about rigid exoskeleton continues in past decades and the use of exoskeleton for not only rehabilitation, but assisting elderly in daily living is discussed even in HCI research area [32]. The reserach by means of EMS in HCI begin from appearance of *PossessedHand* by Tamaki *et al.* and many novel interaction based on EMS are proposed in recent years [7, 8, 10, 11, 17]. If we make clear the point of soft exoskeleton research, we can distinguish the usage of those technology explicitly depending on what those method gives benefit. While we mainly focused on teaching correct timing in our motion, future experiments could focus on calibrating our posture. Tsuneyasu *et al.* tried to reduce muscle fatigue to assist beding and streching motion by means of PGM based soft exoskelton [33]. The research purpose of this is reducing muscle fatigue for aging worker, but actually this means soft exoskeleton facilitate to make us to certain posture. This approach could be lead the resarch for preventing health problem caused by poor posture that may invoke back pain. Clarification of the benefit and the user study of soft exoskeleton in HCI could be helpful to direct designing future usage in real works.

Resarch projects with more longer term could forcus on how to implement soft exoskeleton in daily living. Rightly, wearable is closely related whether we can use those device in daily living or not and the soft exoskeleton should be implement minimally obstructive on our body in addition to prementioned limitation in this chapter. If we can make soft exoskeleton as completely wearable, we can consider further application and it facilitate to implement in real world.

Furthermore, although we conducted experiment for rhythm training in this thesis, we need to explore more scientific effects for body and brain based on our proprioception sense. It's obivious that soft exoskeleton can be useful to give force feedback. However, still we need to explore how the use of those exoskeleton affect our physical performace, especially muscle memory. This is not problem for only soft exoskeleton, it's common problem for both EMS and rigid exoskeleton. People dream acquisition of professional skill and they train themself everyday. Soft exoskeleton has also potential to contribute to get professional skills. In order to realize that soft exoskeleton needs to be proven useful first.

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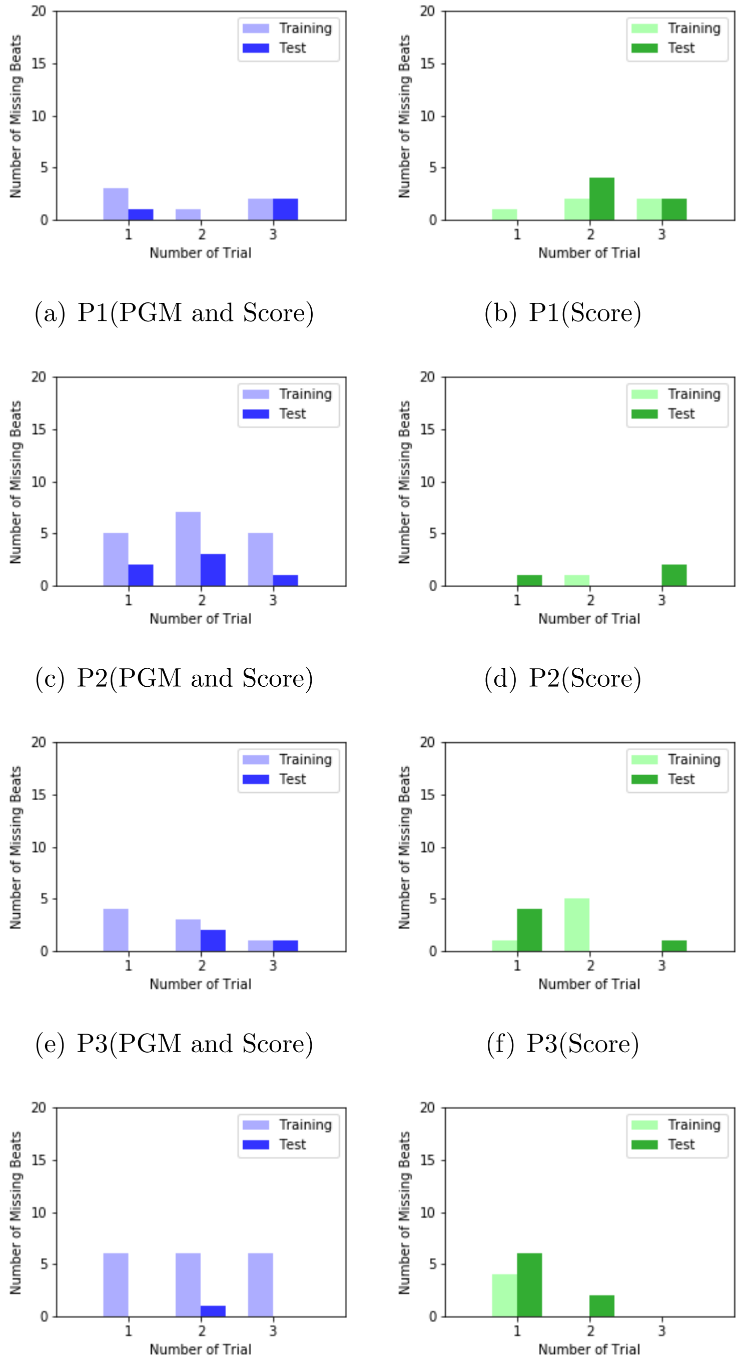
Appendices

A. Reuslts of number of missied beats for each trial during drumming experiment between PGM and score vs. score



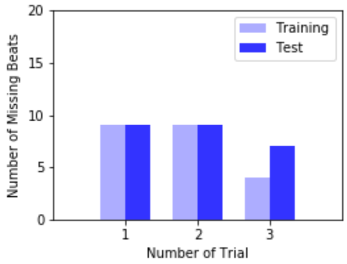
(a) P1(PGM and Score) (b) P1(Score)

(c) P2(PGM and Score) (d) P2(Score)

(e) P3(PGM and Score) (f) P3(Score)

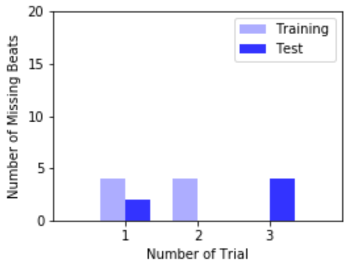
(g) P4(PGM and Score) (h) P4(Score)

Figure A.1 Number of missied beats for each trial in task No.1 and No.2 for the comparison between force feedback and score vs. score.



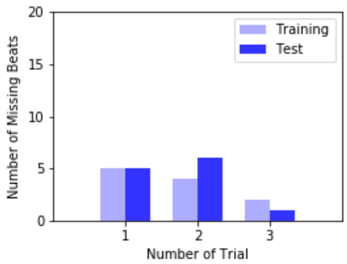
(a) P1(PGM and Score)

(b) P1(Score)



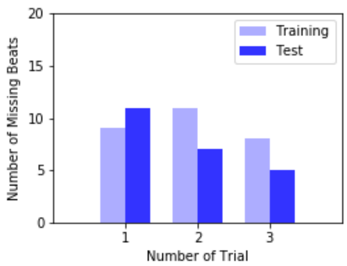
(c) P2(PGM and Score)

(d) P2(Score)



(e) P3(PGM and Score)

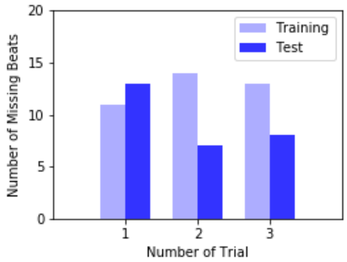
(f) P3(Score)



(g) P4(PGM and Score)

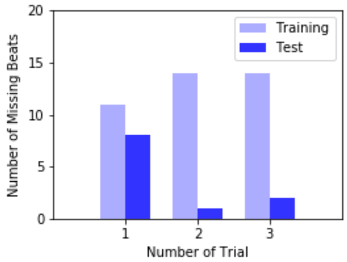
(h) P4(Score)

Figure A.2 Number of missied beats for each trial in task No.3 and No.4 for the comparison between force feedback and score vs. score.



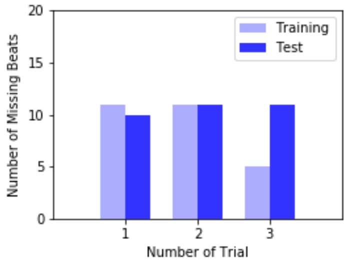
(a) P1(PGM and Score)

(b) P1(Score)



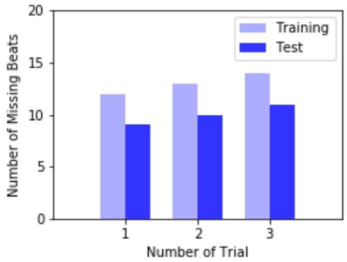
(c) P2(PGM and Score)

(d) P2(Score)



(e) P3(PGM and Score)

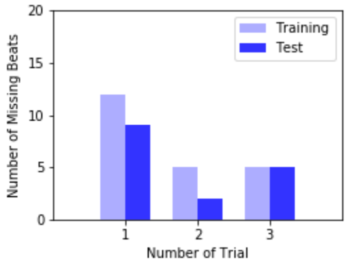
(f) P3(Score)



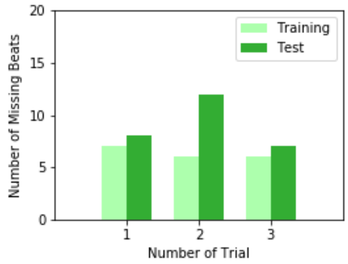
(g) P4(PGM and Score)

(h) P4(Score)

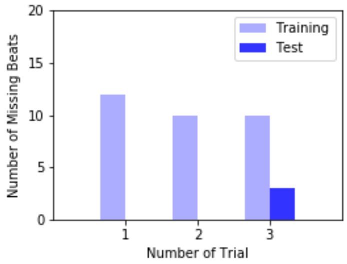
Figure A.3 Number of missied beats for each trial in task No.5 and No.6 for the comparison between force feedback and score vs. score.



(a) P1(PGM and Score)

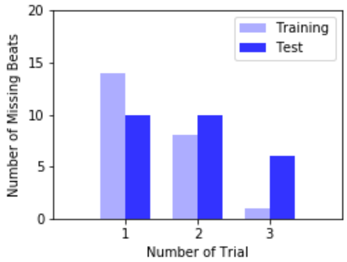


(b) P1(Score)



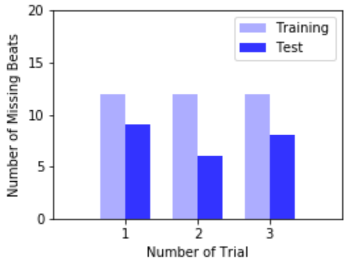
(c) P2(PGM and Score)

(d) P2(Score)



(e) P3(PGM and Score)

(f) P3(Score)

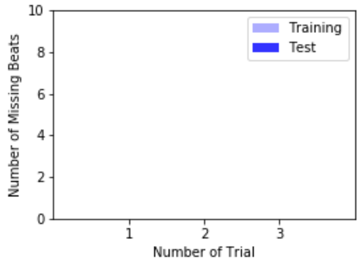


(g) P4(PGM and Score)

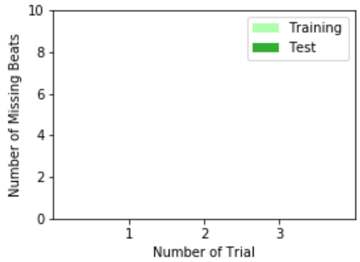
(h) P4(Score)

Figure A.4 Number of missied beats for each trial in task No.7 and No.8 for the comparison between force feedback and score vs. score.

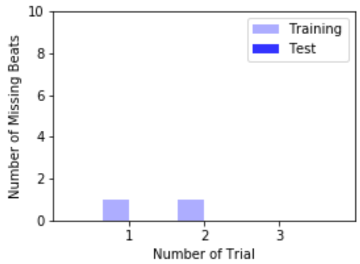
B. Reuslts of number of missied beats for each trial during drumming experiment between PGM and score vs. audio feedback and score



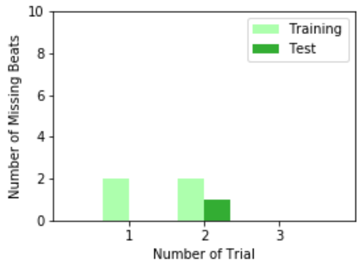
(a) P1(PGM)



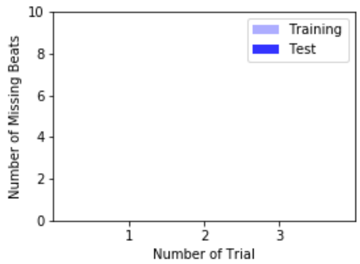
(b) P1(Audio Feedback)



(c) P2(PGM)

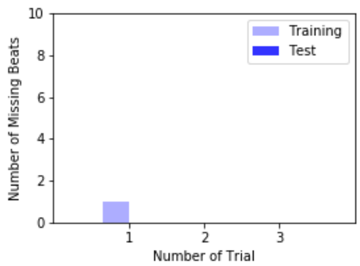


(d) P2(Audio Feedback)

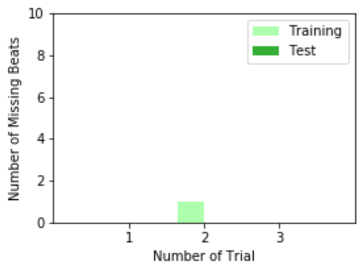


(e) P3(PGM)

(f) P3(Audio Feedback)

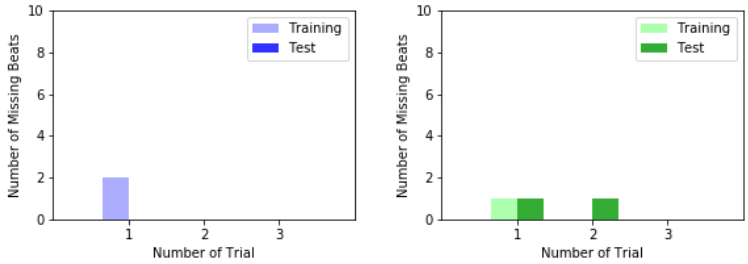


(g) P4(PGM)

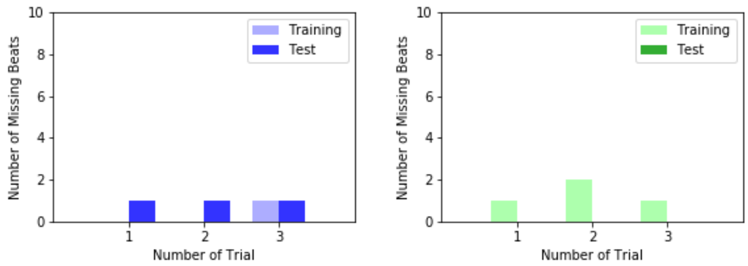


(h) P4(Audio Feedback)

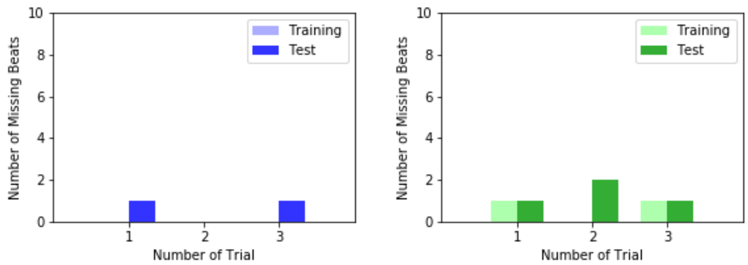
Figure B.1 Number of missied beats for each trial in task No.1 and No.2 for the comparison between force feedback and score vs. audio feedback and score.



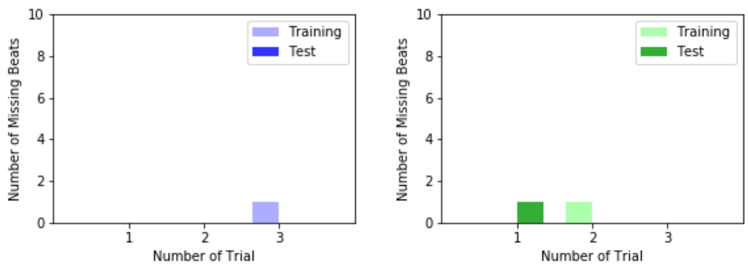
(a) P1(PGM) (b) P1(Audio Feedback)



(c) P2(PGM) (d) P2(Audio Feedback)

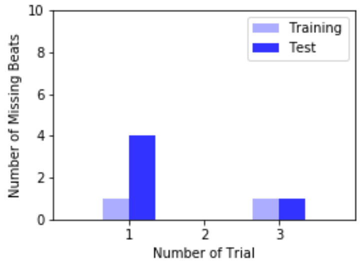


(e) P3(PGM) (f) P3(Audio Feedback)

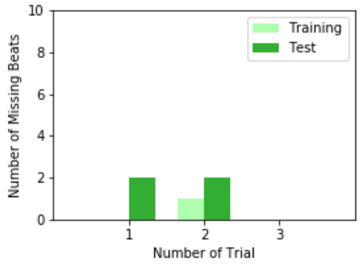


(g) P4(PGM) (h) P4(Audio Feedback)

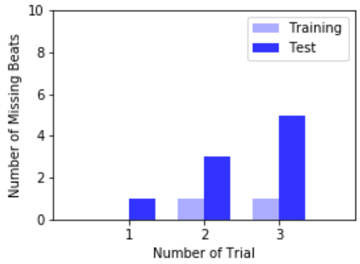
Figure B.2 Number of missied beats for each trial in task No.3 and No.4 for the comparison between force feedback and score vs. audio feedback and score.



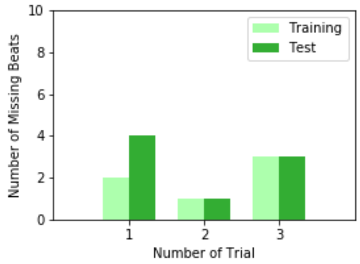
(a) P1(PGM)



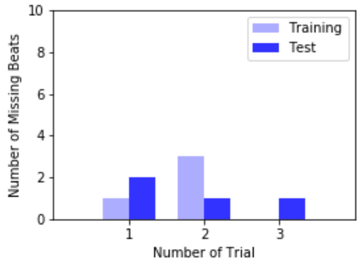
(b) P1(Audio Feedback)



(c) P2(PGM)

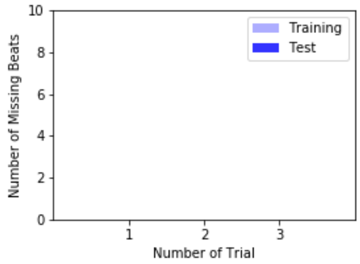


(d) P2(Audio Feedback)

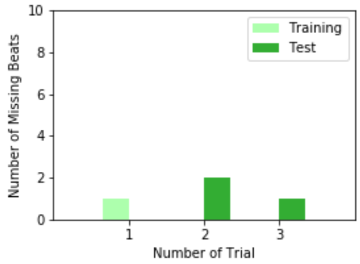


(e) P3(PGM)

(f) P3(Audio Feedback)

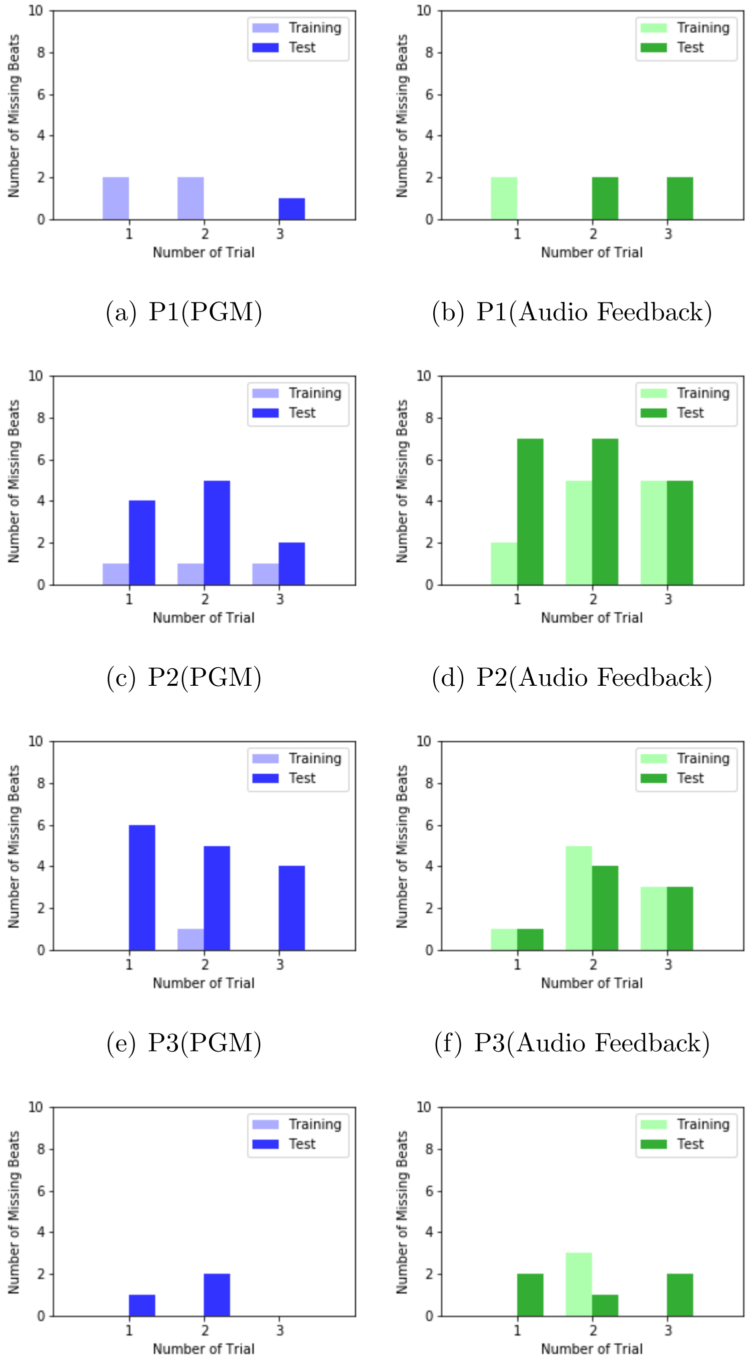


(g) P4(PGM)



(h) P4(Audio Feedback)

Figure B.3 Number of missied beats for each trial in task No.5 and No.6 for the comparison between force feedback and score vs. audio feedback and score.



(a) P1(PGM) (b) P1(Audio Feedback)

(c) P2(PGM) (d) P2(Audio Feedback)

(e) P3(PGM) (f) P3(Audio Feedback)

(g) P4(PGM) (h) P4(Audio Feedback)

Figure B.4 Number of missied beats for each trial in task No.7 and No.8 for the comparison between force feedback and score vs. audio feedback and score.