bioSync: A Paired Wearable Device for Blending Kinesthetic Experience

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ABSTRACT
We present a novel, paired, wearable system for combining the kinesthetic experiences of two persons. These devices allow users to sense and combine muscle contraction and joint rigidity bi-directionally. This is achieved through kinesthetic channels based on electromyogram (EMG) measurement and electrical muscle stimulation (EMS). We developed a pair of wearable kinesthetic input-output (I/O) devices called bioSync that uses specially designed electrodes to perform biosignal measurement and stimulation simultaneously on the same electrodes.

In a user study, participants successfully evaluated the strength of their partners' muscle contractions while exerting their own muscles. We confirmed that the pair of devices could help participants synchronize their hand movements through tapping, without visual and auditory feedback. The proposed interpersonal kinesthetic communication system can be used to enhance interactions such as clinical gait rehabilitation and sports training, and facilitate sharing of physical experiences with Parkinson's patients, thereby enhancing understanding of the physical challenges they face in daily life.

ACM Classification Keywords
H.5.2 User Interfaces: Haptic I/O, Interaction Styles

Author Keywords
Blending Kinesthetic Experience; Electrical Muscle Stimulation; Electromyogram Signals; Rehabilitation

INTRODUCTION
Perceiving one's own muscle activity is important to understanding one's physical actions. There are several situations in which it would be beneficial to be able to perceive another person's muscle activity and share their kinesthetic experience. Examples of such situations are interactions between sports players and coaches during physical training and interactions between physical therapists and patients with neuromuscular

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Figure 1. (a) Synchronizing and combining muscle activities among people (b) Reproducing kinesthetic experience of Parkinson's impairment for use in supporting product design (c) Participants express surprise when the muscle activity is jacked in by the demonstrator

disorders, such as Parkinson's disease during their rehabilitation. However, it is difficult for one person to perceive another person's muscle activity, and a suitable interface for perceiving and transmitting kinesthetic experience accurately in real time has not been developed yet.

In this paper, we propose a system for blended kinesthetic interaction between two persons using wearable kinesthetic input-output (I/O) devices. The system, called bioSync, is illustrated in Fig. 1(a). In developing this system, we attempted to achieve both perception and expression of bodily motions and muscle activity. Using this system, which consists primarily of a pair of devices worn by the two users, muscle contractions of one user are detected by means of electromyogram (EMG) measurement and are reproduced, by means of electrical muscle stimulation (EMS), as muscle contractions of the other user, and vice versa. We have explored the possibilities of kinesthetic synchronization and implemented very early prototypes that used five independent electrodes for the measurement and stimulation [1, 2, 3]. We hypothesized that combining the muscle activities between users in real time with the spatial consistency of muscle exertion and output presentation and with the consistency of sensation modality would provide an intuitive and easy-to-learn means of understanding both muscle activities and bodily motion.

Contribution

- Modeling of the blending of kinesthetic interaction between two persons based on EMG measurement and EMS
- Implementation of bioSync devices with the same electrodes used for EMG measurement and EMS to achieve kinesthetic I/O at 100 Hz via wireless communication
- Development of a method for muscular stimulation with dynamic adjustment over a wide frequency range
- Assessment of the interaction and the system by means of a user study in which kinesthetic I/O with low communication latency (approx. 20 ms) allowed synchronization of rhythmic muscle contraction without visual and auditory feedback

The main contribution of this paper is the presentation of a novel style of interpersonal kinesthetic communication called blended kinesthetic interaction. A key property of the blended kinesthetic interaction is that the kinesthetic feedback can be both shared and merged in that the wearers are able to simultaneously perceive the strength of voluntary contractions produced by the wearers and involuntary contractions produced by stimulation. The bioSync devices developed in this study are kinesthetic I/O devices that can estimate and interrupt a wearer's muscle activity at the same time. The devices are wearable and easy to attach to a wearer's body. We validate this concept by conducting a rhythmic synchronization experiment and demonstrating the reproduction of disease experience using bioSync devices.

RELATED WORK

Many studies on the transmission and sharing of users' sensations or skills have been conducted in field of computer-supported cooperative work.

Perspective Sharing

One effective way to convey a person's physical interactions and presence in an immersive manner is by transferring, exchanging, or blending their first-person views (FPVs) while presenting them on a head-mounted display (HMD). For instance, a wearable vision system that transfers a 360° FPV to a remote viewer has been developed to assist in remote collaboration between two people [4]. Another study reported that showing multiple FPVs in parallel on a HMD allowed people to complement and enhance each other's memories and decisions in executing a drawing task [5]. Such techniques have also been used to transfer motor performance between a teacher and a learner [6, 7]. In an user study on motion synchronization between an expert and a beginner performing juggling actions, the mixing ratio of their FPVs was found to indicate the type of motion skill to be transmitted. For example, exchanging views was found to be useful for synchronizing motion velocity, whereas blending views was useful for synchronizing the positions of limbs.

These studies have shown that perspective sharing enables the transmission of a person's bodily motions and skills to another in an immersive manner. However, it is difficult to share muscle activity since it is hard to observe it visually. We incorporate the findings on the importance of blending ratio in our kinesthetic interaction model by using a blended perceptual function f and blended stimulus function p, which are illustrated in Fig. 2.

Haptic and Kinetic Sharing

A number of devices have been developed that convey one's haptic or kinetic performance to another person for enriching mediated communication by amplifying another person's social presence. inTouch [8] allows separated users to feel virtual sensations of a shared object through somatosensory interactions by using connected mechanical rollers. Similarly, a paired shape-shifting stick [9] was proposed that allows users to feel the movements and presence of a performer by mimicking the remote user's stick movements. Another study demonstrated the ability of haptic devices to convey several emotions, including anger, disgust, fear, and joy, using handshaking actions [10]. Sharing video and haptic, or video and physical interaction with a remote user also enhances the feelings of being close to another person [11, 12]. As previous research shows, interpersonal haptic communication makes it possible to enhance not only task performance but also remote users' sensations of presence, reality of existence, and users' ratings of trust and togetherness [13]. In this study, we propose a novel style of interpersonal kinesthetic communication that permits people to perceive other people's muscle activities. We consider these the social and psychological aspects of the haptic feedback provided by this system by means of user studies and demonstrations.

Kinesthetic Representation

Some wearable devices have been developed for identifying and representing muscle activity in medical applications. Conventional desktop-type electromyography is capable of displaying muscle activity in the form of waveforms on a monitor. This provides accurate and quantitative kinesthetic information but requires frequent sight-line movement between the monitor and the measurement point. To resolve mismatches in the spatial consistency between the presentation point and the measurement point, a wearable, light-emitting suit for sensing contraction strength using light fibers [14], and a wearable audio device that converts contraction strength into acoustic waves [15, 16] have been proposed. Research with these devices has shown that identifying and sharing kinesthetic experience with therapists assists in medical rehabilitation and sports training. However, in these visual and acoustic systems, the presentation area is limited to the user's field of vision, and the amount of information provided is limited to that from a single muscle tissue when the feedback is acoustic in nature. Furthermore, the substitution among different types of sensation modalities requires adequate prior learning procedures.

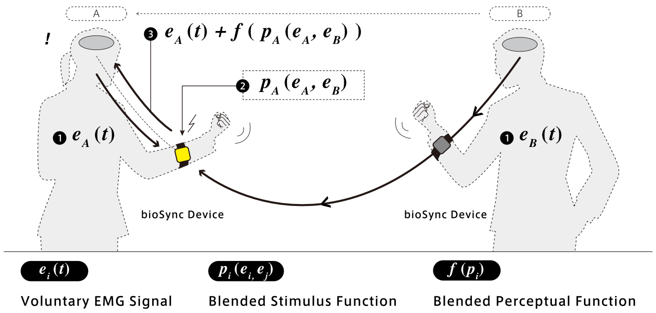

Figure 2. Model of Blended Kinesthetic Interaction

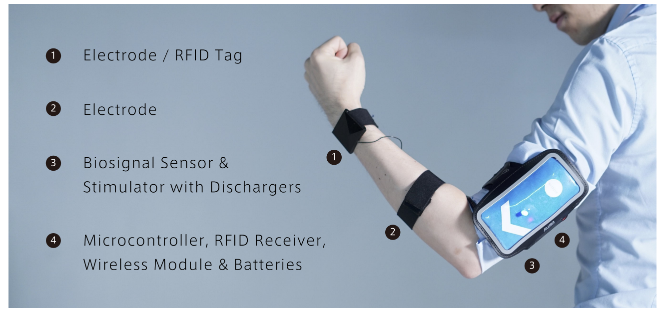

Figure 3. Overview of the developed device, bioSync

EMS Interfaces

The direct approach to presenting kinesthetic information to a body is through EMS in which muscles are actuated involuntarily through electrodes on the skin. This technique was developed for use in bio-feedback therapy [17], and has recently been used in the HCI field such as Pose-IO [18] by Lopes et al. and PossessedHand by Tamaki et al. [19]. The Pose-IO system makes use of the fact that users are able to estimate the wrist angle posed by EMS without visual feedback. They demonstrated that users could perceive the playback time of a movie through their wrist angles, and control it using hand gestures. EMS systems have the unique characteristic of being able to induce and trigger bodily motions that involve strong motion memories after stimulus, without using any actuators. This allows body actuation systems to be configured in wearable dimensions. This concept has also been used in perceiving affordance for manipulating tools and objects [20]. Wearable EMS systems are also used to generate haptic feedback from virtual reality environments to users for enriching visual feedback [21, 22]. In this manner, EMS techniques have been used for achieving communication between a user and objects or a virtual world.

BLENDING KINESTHETIC EXPERIENCE

In this study, we aim to assist mutual understanding of one's bodily activity with multiple persons, such as muscle contraction and joint rigidity, which are difficult to observe visually. To achieve this, we propose a blended kinesthetic interaction that allows the following operations: 1) Sharing (=): Synchronizes two persons' muscle activities including not only contraction strengths but also the contraction timings, 2) Subtraction (-): Perceives their difference in persons' muscle contraction strengths, and 3) Addition (+): Assists in adjusting a person's contractions by adding the other person's contraction strength. These blending operations are accomplished using a muscle I/O technique. In contrast to previously developed approaches to sharing haptic sensation [8, 9], the system developed in this study focuses not on an individual user's specific interactions with a physical interface but rather with the kinesthetic activities associated with a wide variety of interactions between two people in several situations. In previous EMS studies [18, 20], accelerators or motion capture systems were used to acquire wearer's hand gestures. The device developed in this study measures biosignals related to muscle activity, making it possible to estimate bodily activities even though the user does not move any limbs but just contracts muscles. These advantages allow physical therapists or sports instructors to understand a patient's or learner's invisible but voluntary intentions concerning bodily motions in an easy and intuitive manner through a somatosensory channel. In this paper, we discuss the validity of the interaction and feasibility of possible scenarios through its modeling, implementation, performance evaluation, and user studies.

Interaction Modeling

Figure 2 illustrates the proposed model for an interaction involving users A and B. A situation in which user A receives kinesthetic information from user B (one-way communication) is illustrated. $e_i(t), p_i(e_i, e_j)$, and $f(p_i)$ represent the wearer i's voluntary EMG signal at time t, the stimulation pulse based on the EMG signals of wearer i and the partner j, and the kinesthetic blending function, respectively. Each user's muscle contractions are detected by an EMG sensor and conveyed to the bioSync device worn by the other user via a wireless module. Each user's voluntary contractions are reproduced as the other user's muscle exertions by means of EMS. Since the stimulation and measurement are achieved at the same position, modality, and time, users are able to understand each other's activities without depending on visual observation. The interaction sequence is as follows:

1) Voluntary actions: Both users A and B perform their voluntary muscle activities. These activities $e_A(t), e_B(t)$ are estimated from measurement of surface EMG signals by the bioSync devices worn by the two users. **2) Muscle actuation**: The users' muscles are stimulated based on the blending pulse function $p_i(e_A, e_B)$, which is described by using stimulus frequency (1/T)[Hz] and pulse width $D(t)$[us] at time t as shown in Eq.(1). The stimulus frequency (1/T [Hz]) ranges from 1Hz to 100Hz while measuring e_i (Eq.(2)), and the pulse width $D(t)$ is defined by using the weighting factor $a_{i,j}$, contraction strength $e_{i,j}$, time constant $\tau_{i,j}$ of the wearer i and j, and activation function g (Eq.(3)). We used a simple step function as the activation function g with threshold θ when we conducted rhythmic action synchronization experiment. For the demonstration, we adapted another function that presents the subtraction between two users' contraction strengths.

$$p_i(e_i, e_j) = u(T, D(t)) \tag{1}$$

$$T : 1Hz < 1/T < 100Hz \tag{2}$$

$$D(t) = g(a_i e_i(t - \tau_i) + a_j e_j(t - \tau_j))[us] \tag{3}$$

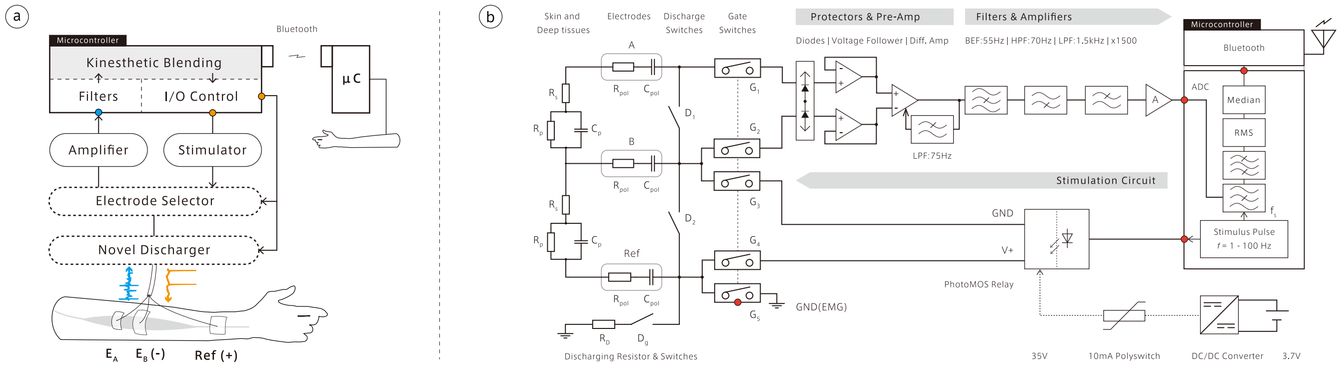

Figure 4. (a) System Architecture (b) Process Diagram

and **3) Blended feedback**: The perceived kinesthetic feedback is represented as $e_A(t)+f(p_i(e_A,e_B))$. The function f is a perceptual function that represents the blended kinesthetic feedback of a user's voluntary and involuntary movement. We investigated the behavior of the perceived function f experimentally and verified that it is a linear function.

Interaction Properties and Benefits

The proposed interaction has the following characteristics and benefits: 1) **Spatial consistency**; In the bioSync device, the stimulus circuit and biosignal measurement circuit share specially designed electrodes. The electrode matches the spatial relations of the input and output. In addition to this, the electrode positions of the two users are the same. We assume spatial consistency to simplify user interaction learning. 2) **Sensory consistency**; As the user's muscle actuation and the device's EMS presentation are performed in the same modality, kinesthesia provides a more intuitive understanding and easier perception of motion sensation, compared to sensory substitution methods, in that minimal prior learning is required. The reason for adopting EMS is that it induces strong motion memories, which assist in self-learning after training. and 3) **Temporal consistency with interactivity**; The musculoskeletal systems of the users are synchronized while they share the same time and space. This allows the device to be used to teach and be taught the contraction timings between users.

bioSync: A Paired Kinesthetic I/O Device

To achieve the proposed interpersonal kinesthetic communication in an actual environment, we developed a pair of wearable kinesthetic I/O devices, called bioSync (Fig. 3). Each bioSync device is equipped with a custom designed electrode system that performs EMG measurement and EMS simultaneously. Each bioSync is also equipped with a wireless communication module and a radio-frequency identification (RFID) tag, which is used to detect and pair with other bioSync devices by touching the wearer's wrist to the partner's bioSync device.

METHODOLOGY AND CONFIGURATION

Figure 4(a) shows the system architecture for the proposed system. It consists of electrodes, a stimulation circuit, an EMG measuring circuit, a microprocessor, and a Bluetooth module to communicate with other bioSync devices.

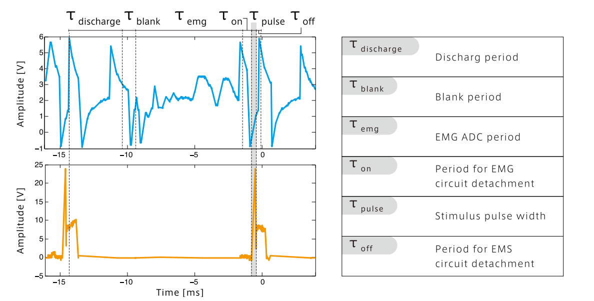

Figure 5. Timing Chart of Measurement, Stimulation and Discharge

EMG Measurement During Stimulation

Figure 4(b) illustrates the processing diagram of the developed device. In order to achieve fast and simultaneous measurement and stimulation operations using common electrodes, a gate switching mechanism and a mechanism for discharging residual potential (the body retains a net charge following the stimulus) are required. The former is designed for protecting the measurement circuit from the stimulus voltage, and the latter is used for modifying the connection path of the electrodes. Hence, the system includes three electrodes (A, B, Ref), discharge switches (D_i), and gate switches (G_i) along with an EMG measurement circuit and a stimulation circuit. Each switch is activated based on an operation timings as shown in Fig. 5. The period of discharging, blank, EMG acquisition, EMG circuit detachment, stimulus pulse width, and EMS circuit attachment are defined as $\tau_{discharge}, \tau_{blank}, \tau_{emg}, \tau_{on}, \tau_{pulse}$, and τ_{off}, respectively. The stimulation cycle can be adjusted from 1 to 100Hz, and stimulus pulse width can be adjusted from 0 to 800us. The process sequence is as follows: 1) the electrodes are connected to the input ports of the measurement circuit by the gate switches $(G_{1,2,5})$. The measurement starts after τ_{blank}[ms] which is required for stabilizing the waveform; 2) after the measurement (τ_{emg}[ms]), the electrodes are detached from the measurement circuit and connected to the stimulation circuit by the gate switches $(G_{3,4})$ after τ_{on}[ms]; 3) when the stimulus (τ_{pulse}[us]) ends, the electrodes are detached again and wait for τ_{off}[ms]. Finally, the discharging switches $(D_{1,2,g})$ are activated for $\tau_{discharge}$[ms]. This type of simultaneous operation, using a fewer number of electrodes, allows to reduce the size of the device and facilitates the configuration of the electrodes array. The timings τ_i

and resistor R_D values for a stimulus frequency of 40Hz are; $\tau_{discharge} = 7ms, \tau_{blank} = 3ms, \tau_{emg} = 10ms, \tau_{on} = 2ms, \tau_{off} = 2ms, \tau_{pulse} = 0us - 800us, R_D = 180k\Omega$.

A conventional discharging method is to short each electrode after stimulus in order to discharge the naturally existing capacitors of the body (C_p, C_{pol}) [17]. In the proposed method, a ground (0V) voltage connection following the electrode shorts is established using the discharge switch, D_g. In addition to this, a discharging register R_D is inserted between the electrodes and the ground for consuming the residual voltage, resulting in a reduction in the overshoot noise in the EMG signal. This mechanism helps in discharging of the residual potential, and stabilizing the measurements after the stimulus. We also propose a method that permits dynamic adjustment of the stimulus frequency. The stimulation cycle can be adjusted from 1Hz to 100Hz, thereby enabling dynamic adaption to various skin conditions and purposes, compared to related devices [23].

EMG Measurement
A diagram of the EMG measurement system is also shown in Fig. 4(b). The system consists of two electrodes, one reference electrode, single-pole-dual-throw analog switches (AQV252, Panasonic, Inc.) that function as a protection gate to protect the measuring circuit from stimulation pulses, a voltage follower for impedance adjustment, a differential amplifier, a Twin-T-type RC notch filter (f_c = 55Hz) to cut out AC noise, a second-order RC low pass filter (f_c = 1kHz) to remove high-frequency noise, an inverting amplifier, and a voltage limiter to protect the microprocessor (Atmel, Inc., ATmega 32U4). While the system is acquiring EMG signals, the input ports of the voltage follower are connected to the electrodes. During the period of stimulation, the input ports are grounded in order to stabilize the signal wave. Fig. 7 shows the implementation of the device.

High-order digital filters are used to cut out AC noise and pulse noise which comes from the EMS. We use bi-quad filter systems that are computationally inexpensive and easy to implement on a microcontroller. A third-order notch filter is used for reducing pulse noise from EMS. The cut-out frequency(f_c) is dynamically set to the stimulation frequency. A second-order low-pass filter is used for eliminating frequencies other than the EMG frequencies (60Hz to 1kHz). The root mean square (RMS) of 20 measured samples is calculated to estimate the muscular tension. Finally, to screen out pulse noise caused by artifacts or outliers, the median of five RMS samples is calculated and sent to the other bioSync device.

Electrode Configuration
Figure 8 illustrates the electrode placement and configuration. We used three electrode pads, A, B, and Ref of sizes 30mm × 40mm, 20mm × 40mm, and 40mm × 40mm, respectively. We set the distance between electrodes A and B to 20mm to avoid a strong effect on the measurement electrode A from the stimulus electrode B. PMMA gel pads (HV-DOUSI-310, OMRON, Inc.) were used. A pulse amplitude of 35V is generated by a DC/DC converter (INA226, Texas Instruments, Inc.) using a 3.7V Li-Po battery.

Figure 6. System Configuration

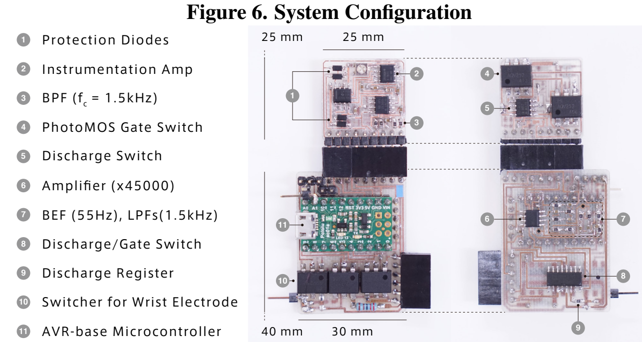

Figure 7. Device Implementation

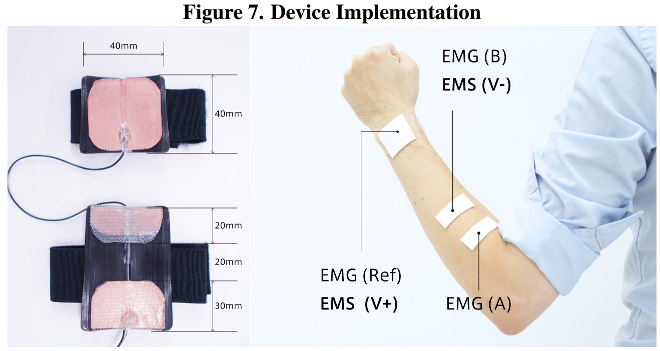

Figure 8. Electrodes Placement

RFID-based Connection
To enable users of the bioSync devices to interact intuitively with each other, an RFID tag (ISO 14443A standard tag) is embedded in the wrist electrode of each device, and an RFID receiver (NXP Semiconductors, Inc., MFRC552) is encased in the arm band. The bioSync devices can be paired by one user touching a user's wrist to the other user's arm band.

PERFORMANCE EVALUATION

1. System Latency
We evaluated the communication latency of the devices using a wireless configuration for verifying that the devices were suitable for use for bi-directional haptic communication.

Task and Apparatus
Signal triggers are generated when a bioSync measures a biosignal and the other bioSync device produces a stimulus signal. We measured the triggers from both devices by using an oscilloscope (Agilent Technologies, Inc., MSO-X3034A) and defined the temporal difference between them as the latency.

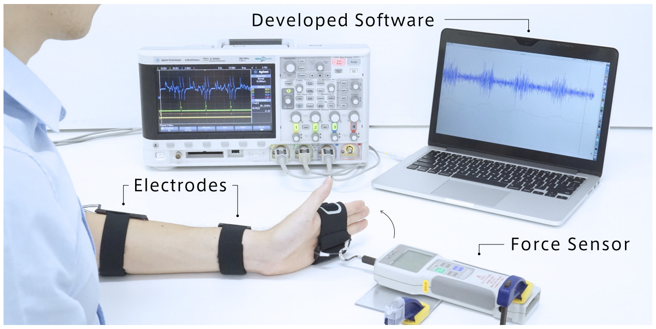

Figure 9. Experiment Setup: Performance Measurement

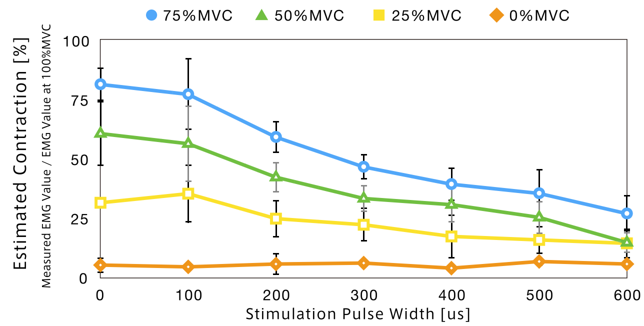

Figure 10. Experiment Result: Performance Measurement

The Bluetooth modules were paired before the start of the experiment and were placed 40cm apart, with no obstacle in their communication path. The switching (stimulus) frequency f_s was set to 40Hz in order to achieve the most intense muscle contraction in this particular subject (25-year-old male). We conducted 25 trials in this evaluation.

Results

The average latency was 20.9ms (SD=5.6ms). The device performed a loop program consists of the measurement with discharging, a filtering process, UART output and reading via the Bluetooth module, and stimulation. Thus, the maximum latency depends on the stimulation frequency. In this experiment, the frequency was 40Hz, and the theoretical maximum latency was 25ms. This is almost the same as the average measured latency. In the bioSync device, the stimulus frequency can be adjusted from 1Hz to 100Hz. Muscle actuation is usually achieved when the stimulus frequency is higher than 20Hz. We therefore set 20Hz as the minimum stimulus frequency.

2. Performance Measurement

We next evaluated the biosignal measurement performance under various stimulus conditions for understanding the electrical characteristics of the I/O circuit. EMG signals can be affected by the stimulus signals even if the discharging time $\tau_{discharge}$ is fixed. By investigating the relation between the applied pulse strength and the measured contraction strength, we were able to identify the appropriate software compensation for the electrical characteristics.

Task and Apparatus

Figure 9 illustrates the experimental setup. Each participant wears a bioSync device, and pulls the tip of the digital force sensor (IMADA, Inc., ZP-1000N) using the cuff, by extending the wrist. Before the experiment is started, each participant's 100% maximum voluntary contraction (MVC) is measured using the force sensor and the developed EMG recording software. Then each participant is asked to reproduce his 75%MVC[N], 50%MVC[N], 25%MVC[N] and 0%MVC[N], while stimulus with durations in the range of 0 to 600 us (in increments of 100 us) were applied. The measured EMG signals were converted to percentages of the EMG value at 100%MVC. The participants were able to see a display of the force sensor to check the accuracy of each percentage of the MVC. The electrodes were placed on the extensor digitorum muscle.

Participants

Five healthy subjects from our local organization participated in a total of 420 trials (5 participants $\times$ 7 stimulus strengths $\times$ 4 levels of %MVC strengths $\times$ 3 repetitions). The trials required approximately 20 minutes per participant.

Results

Figure 10 illustrates the measured contraction percentage and applied stimulus width results. As the stimulus pulse width increased, the measured contraction decreased almost linearly.

USER STUDY

3. Subjective Perceptual Experiment

In this experiment, we investigated how bioSync users recognized their partners' contraction strength, as reproduced by the stimulation, while the users were contracting their own muscles simultaneously. The results were used to identify the blended perceptual function f illustrated in Fig. 2.

Task and Apparatus

The participants evaluated and reported the applied stimulus level on a five-point scale while they contracted their own muscles at 50%MVC, 25%MVC, and 0%MVC. The bioSync device, the force sensor, and the cuff were used in the same manner as the previous experiment, but this time the participants were only able to look at the display of the force sensor only before the start of each session. In addition, to eliminate the influence of visual feedback, they were not allowed to look at their arms during the session. The 100%MVC was measured before the start of the experiment, in the same manner as in the previous performance experiment.

Participants

Five healthy participants from our local organization participated in a total of 375 trials (5 participants $\times$ 5 stimulus strengths $\times$ 3 type of %MVC strength $\times$ 5 repetitions; 2 female, mean age = 24.6 years, SD=1.85 years). Two out of five participants had experienced EMS before. The trials require approximately 20 minutes per participant.

Results

Figure 11(a) illustrates the results for the perceived strength. The results confirm that the users were able to recognize both their voluntary contractions and reproduced muscle contractions at the same time on a five-point scale. The perceived

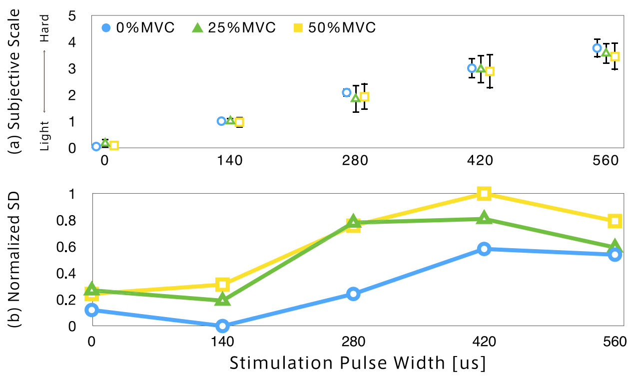

Figure 11. Experiment Result: Subjective Perceptual Evaluation

strength can be approximated linearly. Fig. 11(b) illustrates the normalized standard deviation of each pulse width. As the stimulus strength increased, the standard deviation increased.

4. Rhythmic Activity Synchronization

We also conducted a series of tests to verify that the interpersonal communication via the kinesthetic channel could support the synchronization of two persons' rhythmic muscle contraction timing. The results were used to assess whether the bioSync device could be employed in practical scenarios, such as clinical gait rehabilitation and sports training, in which the synchronization of timing plays an important role.

Task and Apparatus

Figure 12 illustrates the experimental setup. Each participant and the experimenter participated in a follower-experimenter and experimenter-follower session twice. The experimenter was a colleague (25 years old), who participated in the entire experiment (24 trials).

Initially, both the experimenter and the participant performed rhythmic wrist actions according to their own frequencies. After 3-4 seconds, the bioSync devices were activated, and then kinesthetic cues were exchanged between these two persons. Once the participant recognized that the rhythmic action was synchronized with the master side, time measurement was commenced using a stopwatch to record the sync time reported by the participant.

A partition was placed between the demonstrator and the participant so that the participant and the demonstrator could not recognize the partner's contraction timings. The wrist angles and periods of the rhythmic action were calculated from the measured marker positions (OptiTrack Inc., V100:R2). The thresholds were adjusted before the experiments were started. In this experiment, to simplify the exchanging signals, we configured weighting factors a as $a_i = 0$, $a_j = 1$. Hence, the wearer i's stimulus function p_i was a stepping function using threshold θ as shown in Eq.(4).

$$D(t) = \begin{cases} 600us & (e_j(t) > \theta) \\ 0us & (otherwise) \end{cases} \quad (4)$$

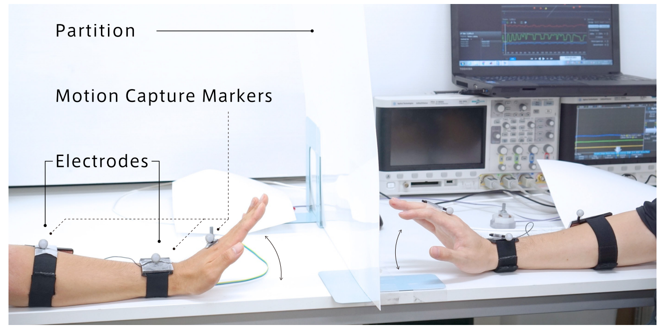

Figure 12. Experiment Setup: Rhythmic Activity Synchronization

Participants

Six healthy participants from our local organization participated in a total of 24 trials (6 participants × 2 follower-experimenter sessions × 2 experimenter-follower sessions). The trials required approximately 35 minutes per participant.

Results

Figure 13 presents the measured sync time and sync time reported by the participant (the participants followed the experimenter's timing). The average measured sync time was 8.1s (SD=3.91s), and the average reported sync time was 13.8s (SD=3.94s). In all cases, the measured sync time was shorter than the reported sync time. Note that Subject 1 required more time to synchronize with the experimenter than the other subjects did. After the experiment, Subject 1 stated that the contractions reproduced by the stimulus were strong and that his voluntary contractions were interrupted excessively, resulting in his having difficulty in controlling his voluntary movements. Figure 14 shows the time-series graph of the rhythmic action period for Subject 2 and the experimenter. After the sync started, the follower immediately changed his rhythm to that of the experimenter and tried to maintain the same period.

5. Embodied Impairment Experience

Using the bioSync devices, it is possible to not only blend users' kinesthetic experiences but also simulate Parkinson's motor impairments by providing stimulus in the frequency range of 8Hz to 15Hz. We employed this capability to gain insight into the bodily movements of Parkinson's sufferers during the activities in daily life (ADL). As described in the applications section, simulating and/or transferring physiological tremors from patients to healthy people, including designers and caregivers, could assist in product design procedures and their understanding of the disease. In this pilot study, we simulated Parkinson's tremors in participants to investigate the similarity of the simulated tremors with actual tremors and the feasibility of using the bioSync device to observe users' tremor behaviors.

Task and Apparatus

Figure 15(a) illustrates the experimental setup for the tremor evaluation. One participant wore a bioSync while holding a spoon. A three-axis accelerometer was placed on the tip of the index finger, as shown in Fig. 15(b). In the observation

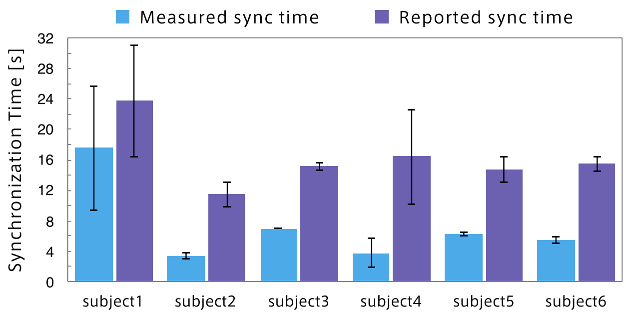

Figure 13. Experiment Result: Rhythmic Activity Synchronization

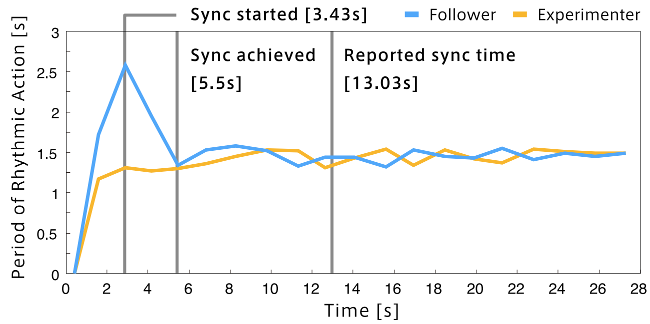

Figure 14. Experiment Result: Rhythmic Activity Synchronization. Subject 2 successfully followed the experimenter's rhythm.

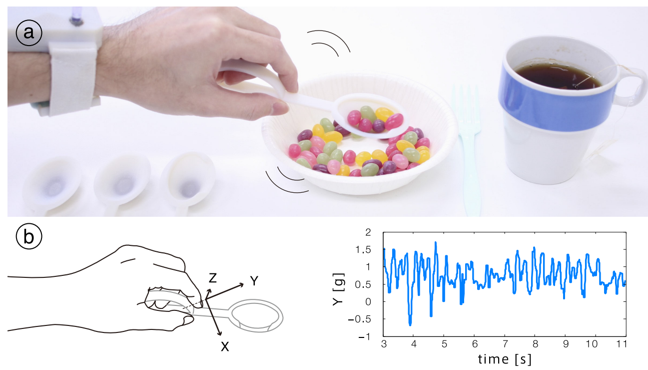

Figure 15. Experiment Setup and Result: Impairment Experience

experiment, demo visitors tried to scoop up gummy candies by using various types of spoons, as shown in Fig. 16(b), while undergoing the reproduced action of physiological hand tremors. We then asked the visitors to choose the spoon type best suited to the task, and collected feedback comment about the experience. The spoon types used in the experiment are described next. The (b-1) sample is a spoon that is available in the market. The dimensions are 33mm × 50mm × 8mm (depth). The (b-2) spoon has an additional 5 mm of depth. The (b-3) spoon has a bend added to the b-1 form to make it easier to keep food inside. The (b-4) spoon has a curved handle added to the b-3 spoon to make it easier to pick up.

Participants

One healthy participant (25 years old) participated in the preliminary evaluation. The other participants consisted of more than 100 visitors whose age ranged from 20 to 60 years.

Results

Figure 15(b) illustrates the measured fingertip accelerations. Frequencies in the range of 3Hz to 20 Hz were measured. This frequency range is almost the same as that of actual Parkinson's tremors, as described in related study [27].

All of the visitors agreed that the b-4 spoon shown in Fig. 16, which had a handle and a bend, was the most useful spoon and the easiest to maintain in a stable grasp. Most of the visitors reported that it was somewhat difficult to hold the candies inside the b-1 spoon because the depth was not sufficient to keep the candies inside with shaking hands. In addition, some participants dropped the b-1 spoon as shown in Fig. 16(a)-1,2. Some visitors reported that the b-2 spoon was easy to use to hold candies while subjected to tremors because of its greater depth; however, they found it slightly difficult to place all of the scooped candies into their mouths because of the depth. The b-3 spoon was described by some as being a usable spoon; however, the visitors commented on not only the ease of using the spoon to scoop up candies but also the ease of picking up the spoon itself. The b-4 spoon was identified as the most usable spoon and the easiest spoon to pick up by hand when experiencing tremors (Fig. 16(a)-3). We also obtained several feedback comments from the visitors that indicate their surprise at the new experiences and difficulties in manipulating their fingers and objects such as: "I never imagined tremors would be like this!", "Now I understand what the disease is like and the difficulties patients face in daily life", "It's very hard to control my smartphone using my fingers", "It's scary! stop!", "Now I feel relieved..." (after the device was turned off). We also acquired comments after we demonstrated the synchronization interaction "I feel very weird because it is like someone is inside my arm and manipulating muscles..".

DISCUSSIONS

System Evaluation, Latency, and Performance

From the performance experiment, we observed that the measured contractions decreased when the applied pulse increased. This linear trend can be attributed to the electrical characteristics of the I/O circuit. The changes could be fitted linearly, hence it is possible to compensate by a linear function. In the future, we plan to conduct another perceptual experiment to investigate the reduction in a bioSync device wearer's voluntary contractions with reproduced contractions, and assess the effects of both the electrical and perceptual characteristics.

Subjective Perceptual Experiment

In the perceptual experiment, the participants could recognize reproduced muscle contractions and rate them on a five-point scale accurately, while they were contracting their own muscles. A similar result was obtained in [18], where the participants could recognize their wrist angle accurately using EMS based on their kinesthetic feedback. Hence, we confirm that the kinesthetic feedback mechanism in our setup also works correctly. We also observe that the standard deviation increased when the pulse width increased. This might be the effect of the wearer's voluntary contractions on the perception of the reproduced contractions. Another perceptual experiment would be required to study this phenomenon in detail and to assess the relevance of the signal-dependency noise theory [24]. According to this, neural control signals are corrupted by noise that increases in variance as with the size of the motor control signal increases.

Rhythmic Activity Synchronization

In the user study of the synchronization of rhythmic action, subject 1 reported that excessive involuntary contractions affected the performance of the synchronization. This could have been caused by the electrode positioning and personal muscular characteristics. This indicates that a prior adjustment is required for each subject to normalize the perceptual and kinesthetic experience among users. We discuss the positional optimization issue in the limitations section. In future work, we plan to investigate the relationship between kinesthetic communication latency and synchronization performance. Another aspect we would like to address is the learning effect, which we could not verify in the current experiment since the number of trials for each participant was small. However, we found that synchronization time is always shorter when the experimenter who had longer prior training and participated in the entire experiment, follows the participant's rhythmic action. Some participants also stated that, at the beginning of the experiment, they did not have enough confidence to recognize and report the time when sync was accomplished. These results suggest that several trials are required to understand new interpersonal kinesthetic communication. Another preliminary experiment showed that the rhythmic actions of two persons could be synchronized even if they are not assigned as an experimenter or a follower, and are treated equally.

Embodied Impairment Experience

In the pilot study on the simulated embodied Parkinson's experience, we received considerable feedback comments that indicated the existence of kinesthetic memory after the experiment. This suggests that reproduced kinesthetic impairment experience may be more effective in learning the neurological characteristics of the impairment than learning through some other modality. We would like to verify the practicality of this approach in a future study. Some visitors also reported experiencing the existence of a remote user's presence through the kinesthetic channel, while synchronizing muscle activity between two persons. Thus, interpersonal kinesthetic communication is capable of enhancing the feeling of togetherness and reality of existence, in a manner similar to that of interpersonal haptic communication [8, 12, 13].

LIMITATIONS

Electrode Placement

In the bioSync device proposed in this study, one set of electrodes is used for both stimulation and measurement. This limits the bandwidth of the kinesthetic information exchanged. By placing more electrodes encircling the forearm, it would be possible to transmit expressive cues through kinesthetic channels in a manner similar to that of haptic manipulators [10]. Placing more electrodes on muscles would require positional optimization. This is a common issue in EMS research

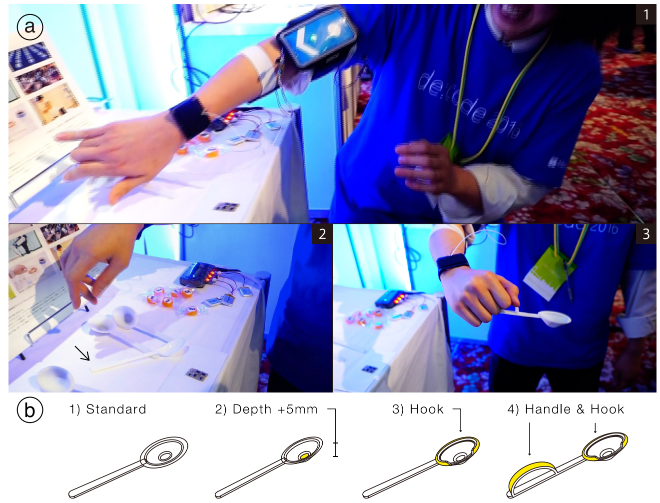

Figure 16. Demonstration at Exhibition: Impairment Experience

field because the perceived strength and involuntary contraction level depend on the stimulated muscle. In the proposed system, the electrode position is established empirically based on several trials. Hence, the positional optimization of the common electrodes is required in our system as well. There have been several studies on placement optimization for EMG or EMS using array electrodes and machine learning systems [19, 25]. These techniques can be applied to the bioSync system. The discharging effect in a multi-electrode environment should be investigated as well.

Blending of Contraction Strength

In this study, we focused mainly on the implementation of bidirectional communication and the temporal characteristics of blended kinesthetic interaction rather than on contraction strength. Although we have reported the results of a perceptual study involving the blended muscle activity and contraction strength of two users, the further qualitative evaluation of the proposed interaction is required. The difference between muscle activity and the perception of it will also be investigated in a future study.

POSSIBLE APPLICATIONS

(a) Shared Embodied Experience

It is very difficult for people to understand the characteristics of a patient's experience of physical impairment. For instance, product and architectural designers should fully understand how the symptoms affect physical interactions in a daily life, in order to be able to apply this knowledge in improving tools and residential buildings. Checklists and guidelines such as housing enabler models [26] or field evaluations involving patients have typically been used as tools in design. In addition to these, we propose a virtualized Parkinson's embodiment using the bioSync devices so that people who do not have Parkinson's, including caregivers, can easily experience and understand the tremors and challenges that Parkinson's sufferers face in the daily life (Fig. 17(a)). This can provide empirical and embodied knowledge of the impairments, which are usually difficult to explain using words. The amplitude, frequency

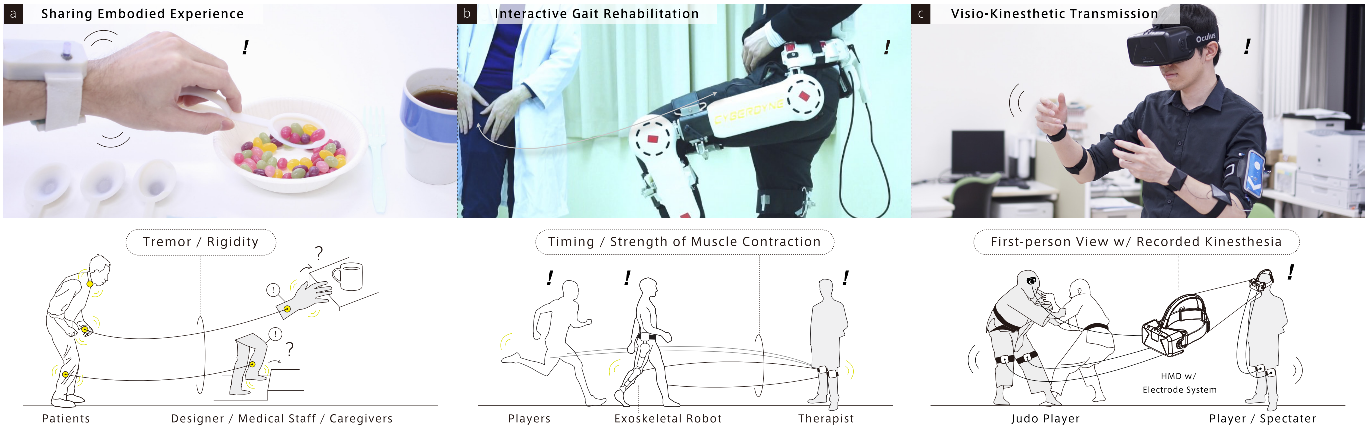

Figure 17. Concrete Scenarios: (a) Neuromuscular symptoms such as those of Parkinson's impairment can be recorded and reproduced for evaluating product and spatial design. (b) Interactive gait training with a power-assist exoskeletal robot accomplished by sharing the timing of the backward kick-out, and sports training by sharing muscle tensions with trainers. (c) Reviewing physical body motions by experiencing recorded kinesthetic feedback with a first-person view through a HMD system.

and target body are variable; as a consequence, designers can perform a number of different experimental trials and evaluate the usability of products and spaces under various conditions. Compared with a conventional tremor desktop-type simulator [27], transforming the wearer's embodiment into that of another would provide more realistic and persuasive experience, likewise transforming visual and haptic sensation [28].

(b) Interactive Rehabilitation and Sports Training

Gait training with a power-assist exoskeletal robot is increasingly becoming popular. The Hybrid Assistive Limb (HAL) developed by Sankai et al. [29], which consists of EMG sensors and lower-limb exoskeletons, was developed for intention-based walking support for paraplegia patients. It is important to learn the timing of each gate phase, such as backward kick-out, during gait training. However, the motors in the exoskeletons are limited in that they can not produce instantaneous actions to the user. bioSync can enable a patient and a therapist to share and learn the timings for such quick exertions, thereby creating the possibility for enhanced monitoring and interactive teaching. In sports training, it is important for coaches to perceive not only players' form and motions but also player's muscle activities. The timing of muscle exertion is important in running and swimming training, for instance, and the flow of muscle exertion is important in pitching and gymnastics motion training, for instance. Interactive kinesthetic feedback between players and coaches would allow players to perceive the correct forms and motions.

(c) Visio-kinesthetic Transmission

To achieve an effective training procedure with immersive and realistic feedback for sports spectating and skill transmission, we propose the use of a visio-kinesthetic experience transmission system using the bioSync device with a HMD system. The user can record and replay not only physical bodily movements but also muscle activities simultaneously. Combining these modalities would help in gaining body ownership and togetherness for a remote user, in the similar manner to the related work [30] that shares visual and tactile sensation to be another.

CONCLUSION

In this paper, we proposed and modeled a novel style of interpersonal kinesthetic communication, called the blended kinesthetic interaction that allows people to mutually perceive and interrupt each other's muscle activity. To achieve this interaction, we developed paired wearable kinesthetic I/O devices that are equipped with a specially designed electrodes system for simultaneous EMG measurement and stimulation at 100Hz via low-latency wireless communication (approx. 20ms). We also proposed dynamically adjustable frequency stimulation over a wide range of frequencies (1-100Hz), which allows the bioSync device to be adapted to various skin conditions and purposes. Through the perceptual experiment, it was verified that the bioSync users were able to recognize reproduced muscle contractions and rate them on a five-point scale while they were contracting their own muscles. It was also verified that the kinesthetic interpersonal communication allows people to synchronize the rhythmic action without visual and audio feedback. We also conducted a pilot study on providing a simulated embodied impairment experience. The results suggested that reproducing the neurological action of Parkinson's tremors could enhance the understanding of the disease. These findings would provide design ideas for the kinesthetic interaction, and contribute to potential applications such as education, design, and medical activities, that reveals new aspects of human behaviors for embodied and social experiences.

APPENDIX

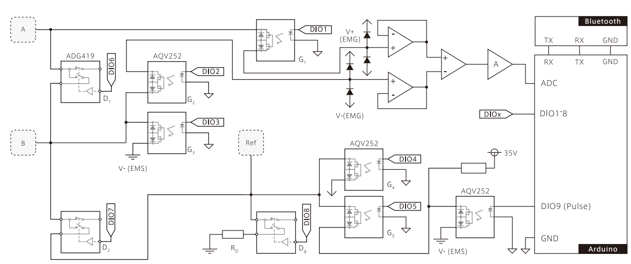

Figure 18. Schematic of bioSync's Circuitry

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