Virtual Robotization of the Human Body via Data-Driven Vibrotactile Feedback

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Abstract. Worlds of science fiction frequently involve robotic heroes composed of metallic parts. Although these characters exist only in the realm of fantasy, many of us would be interested in becoming them, or becoming like them. Therefore, we developed a virtual robotization system that provides a robot-like feeling to the human body not only by using a visual display and sound effects, but also by rendering a robot's haptic vibration to the user's arm. The vibrotactile stimulus was recorded using real robot actuation and modeled using linear predictive coding (LPC). We experimentally confirmed that the subjective robot-like feeling was significantly increased by combining the robot-vibration feedback with a robot-joint animation and creaking sound effects.

Keywords: Body Sense, Material, Robotization, Vibrotactile Feedback.

1 Introduction

While there are a number of industrial robots that support our daily lives, there are also numerous fictional robots that have appeared in movies, comics and video games. Many of us would be interested in understanding the experience of having a tough iron body, hoping to become like these robotic heroes, if only for a short time. The question naturally arises: what would it feel to be a robot? While we are seldom conscious of the activities of our biological muscles or tendons, a robotic body would have a definite robotic body sense that is different from that of humans.

In this paper, we focus on the body sense of robots and simulate robot-like feelings on the human arm (**Fig. 1**). To create a realistic robot-like body sense, we provide vibrotactile feedback based on vibration recording, modeling, and rendering of a real robot's actuation. Combined with conventional visual animation and sound effects, our system allows the user to virtually robotize his or her body visually, aurally, and haptically.

This paper mainly contributes to the field of computer entertainment technology by presenting a new alternative for achieving an immersive experience in video games.

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Gesture input devices, sometimes referred to as natural user interfaces (e.g., the Kinect sensor from Microsoft, the Wii remote from Nintendo, and the Omni from Virtuix) increase the player's feeling of oneness with the game character by synchronizing the character's motion with the player's body motion, resulting in an immersive game experience. Also, some previous tactile entertainment systems have enhanced the immersive experience by displaying vibrotactile feedback to the player's body, synchronized with characters being shot [1] or getting slashed [2].

However, playable characters in video games are not always human – sometimes they are, for example, metallic robots. By creating a robot-like body sense and simulating a situation in which the player becomes the robot, experiencing the game with a robotic body could be made more immersive. Therefore, we envision that the technique of virtual robotization of the human body could enrich immersive video games by offering the experience of being a fictional robotic hero.

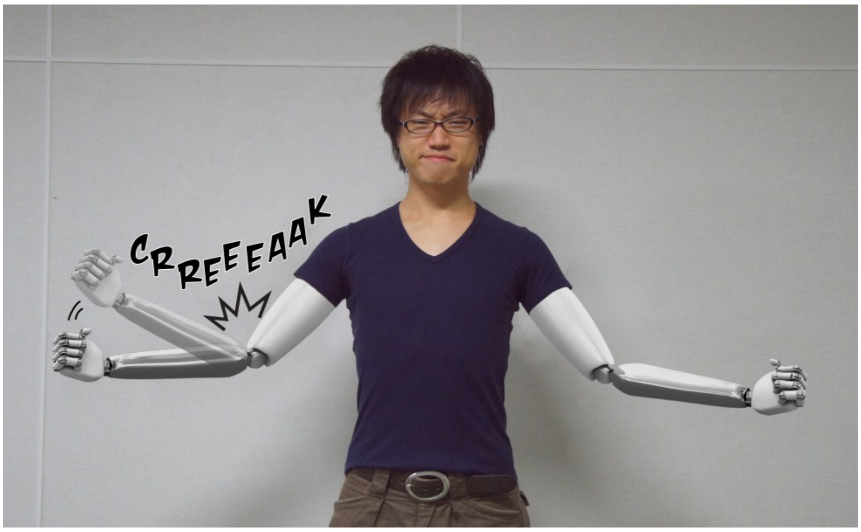

Fig. 1. Concept image of virtual robotization of human arms.

2 Related Work

2.1 Vibration of robot actuation

A robot's own internal motors and gears inevitably generate high-frequency vibrations, which are termed as ego-vibrations. These ego-vibrations cause a crucial problem in that they deteriorate acceleration and sound signals, so much research has dealt with noise subtraction to improve the sensing skill of robots [3-4].

In terms of robotization, we believe that the ego-vibrations are essential in the induction of a robot-like feeling. We propose to apply the annoying robot acceleration and noisy operating sounds to the human body and thus help to create a robotic body sense.

2.2 Haptic alteration by vibration recording and rendering

Recording vibrations resulting from object interaction and rendering the modeled vibrations is often used to alter haptic perception. For instance, the feeling of walking on gravel or snow [5], plunging a hand into a volume of fluid [6], tapping on rubber, wood, or aluminum [7-8], and scraping various surface textures [9] can be realistically simulated by vibrotactile feedback. Some studies have developed haptic recording and rendering systems with simple setups that allow the sharing of haptic experience [10-11]. These systems allow the user to touch a variety of objects in the environment. However, to the best of our knowledge, none of these studies has focused on the changed presentation of the haptic properties of the human body.

We previously implemented a system that virtually alters the feeling of a material on the body using periodic vibrotactile feedback [12]. We employed a decaying sinusoidal vibration model, which simulates the haptic properties of materials when they collide [7], [13]. The periodic ticking vibrotactile feedback we created could simulate rubber, wood, and aluminum collisions, but these were not robotic sensations.

On the other hand, this paper focuses on a robot-like “creaking” sensation. The present system involves continuous vibrations captured from real robot actuation, instead of the discrete collision-based vibrations from the prior study. Furthermore, we combine the vibrotactile feedback with visual and auditory feedback to improve the robotizing effect.

2.3 Illusion of human body sense

The alteration of human proprioception has also been studied. One method of altering the sense of the body in space is called the kinesthetic illusion, which creates an illusory arm motion [14-16]. The illusion can be produced by using a vibration of about 100 Hz to activate the muscle spindles. It can be extended to the elongation of parts of the human body, which is known as the Pinocchio illusion [17].

An illusion of body-ownership called the rubber hand illusion [18-20] is provoked by simultaneously tapping on a person's hidden real hand and a visible rubber hand placed next to the real hand. The person feels as if the rubber hand has become their real hand. This illusion can also be induced by the synchronous movement of the person’s real hand and a virtual hand on a screen [20]. Additionally, the visual realism of the virtual hand does not seem to contribute much to the enhancement of the body-ownership illusion. In this study, we use this phenomenon to create the feeling of ownership of a virtual robot arm using synchronous movements of the user’s real arm and the virtual robot arm.

3 Virtual Robotization of the Human Arm

Our hypothesis is that presenting robot ego-vibrations to the user’s body in accordance with his or her motion will make users believe that their body has become robotic. Thus, we employed a data-driven approach using vibration recording, modeling, and rendering, which has been reported to be a promising method in the creation of realistic virtual textures [9], [21-22].

3.1 Haptic recording

We recorded the vibrations of the elbow joint of a robot arm (Unimate PUMA 260) that is used in general assembly lines, as shown in **Fig. 2**. After testing some other robots, we chose the PUMA because its simple servomotor and gear mechanism generates a strong vibration that humans can clearly recognize. A three-axis digital accelerometer (BMA180, Bosch Sensortec, ±16 g, 14 bit) was rigidly attached to the elbow joint with hot glue. The elbow joint was actuated at 0, 10, 20, 30 … 80 °/s in each direction. Note that actuation at 0 °/s means that the robot was actually stationary, but it still had some background vibration from its other components. We did not record the vibration at more than 80 °/s because the maximum angular velocity of the elbow joint was around 85 °/s. During each operation, the accelerometer recorded the three-axis acceleration data at a sampling rate of 2.5 kHz to capture what the robot felt as it moved at the specified angular velocity. The captured data were stored in the PC through a microcontroller (mbed NXP LPC1768, NXP semiconductors). In this vibration recording, we applied a 1.2 kHz low-pass filter to avoid an aliasing effect using a filter integrated in the accelerometer. This bandwidth covers the whole human haptic perceptual domain.

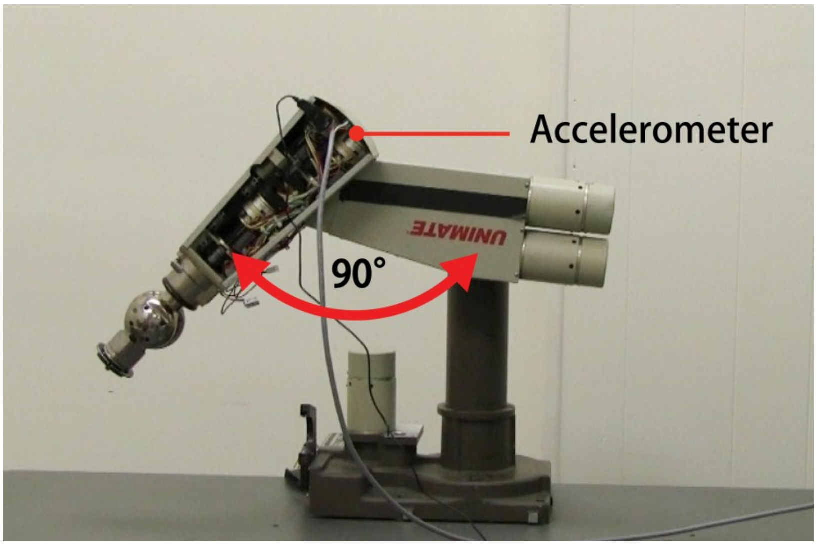

Fig. 2. Recording the vibration on the robot's elbow joint.

3.2 Acceleration data modeling

We performed off-line processing steps to create a vibration model from each set of recorded raw data. First, we applied a 20 Hz high-pass filter to remove low-frequency components attributed to the change of orientation of the robot's forearm. Next, the three acceleration channels were summed to a single wave. We normalized the duration of acceleration data captured at the various angular velocities by selecting clipping one second of data around 45°, which is the center of the range of motion.

We employed Linear Predictive Cording (LPC) to approximate the spectral density of the raw acceleration data (**Fig. 3**). LPC is known as one of the most powerful speech processing techniques, and it is also used in haptic data modeling [9][22]. To make a model that approximates the spectral density of the raw data, we applied a tenth-order finite impulse response (FIR) filter to the acceleration data, and we calculated the coefficient vectors $\vec{a}(k)$ (k=1, 2 … 10) of the LPC as a function of angular velocity, by minimizing the prediction error in the least squares sense. This calculation was performed using the `lpc` function in MATLAB (The MathWorks, Inc.).

The purpose of this modeling was to predict the next vibration value from a series of past data samples. The predicted value $\hat{x}(n)$ can be written as:

$$\hat{x}(n) = w - \sum_{k=1}^{10} a(k)\, x(n-k) \tag{1}$$

where n is the number of steps (n=0 is substituted), $x(n-k)$ is the value at the past k steps, $a(k)$ are the LPC coefficients, w is a sample of white Gaussian noise. While the model contains a similar spectral density to the raw data, the model in the time domain is not a representation of the same waves, because of the randomness of the white Gaussian noise. Therefore, users can feel natural continuous vibration.

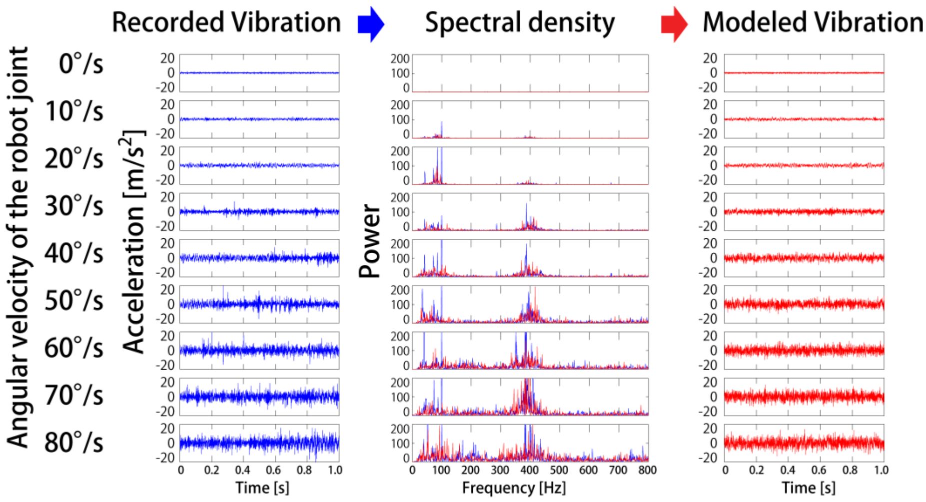

Fig. 3. Recorded vibration (left), example of LPC-modeled vibration (right), and overlaid spectral density (center).

3.3 Rendering the robot-like feeling

Fig. 4 illustrates the configuration of the virtual robotization system. First, a motion tracking camera (Kinect sensor, Microsoft Corp.) captures the three-dimensional positions of the user's right shoulder, elbow, and hand at a sampling rate of 30 Hz. Next, the PC calculates the angular velocity of the user's right elbow joint from the three sets of position data and sends this value to the mbed microcontroller. The LPC coefficients for each angular velocity (0, 10, 20…80°/s), which were calculated in advance, are stored in the microcontroller. The microcontroller perform the real-time rendering based on Eq. 1 using a sample of white Gaussian noise and the LPC coefficients related to the closest elbow angular velocity. For example, when the user moves his or her elbow at angular velocity within the 35-44 °/s range, the system performs the rendering with the coefficients for 40 °/s. While the LPC coefficients for the rendering switch at the specific angular velocity (i.e., 34-35 or 44-45 °/s), none of the participants (see Section 4) noticed the transition. Then, the microcontroller outputs the modeled signal through a D/A converter (LTC1660, Linear Technology Corp., 10 bit) at a refresh rate of 2.5 kHz. The output is amplified by an audio amplifier (RSDA202, Rasteme Systems Co., Ltd.), and finally it is used to actuate the vibrotactile transducer (Force Reactor, Alps Electronic Co., Ltd.) mounted under an armband. The armband is attached to the right forearm close to the elbow joint so that the transducer makes contact with the lateral side of the elbow joint.

The armband also includes a small speaker that is actuated by the same signal as the transducer to emit an operating sound. However, we used headphones instead of the speaker in the experiment (see Section 4) to control the conditions. The visual model of the PUMA 260 robot is displayed and animated synchronously with the user's right forearm motion.

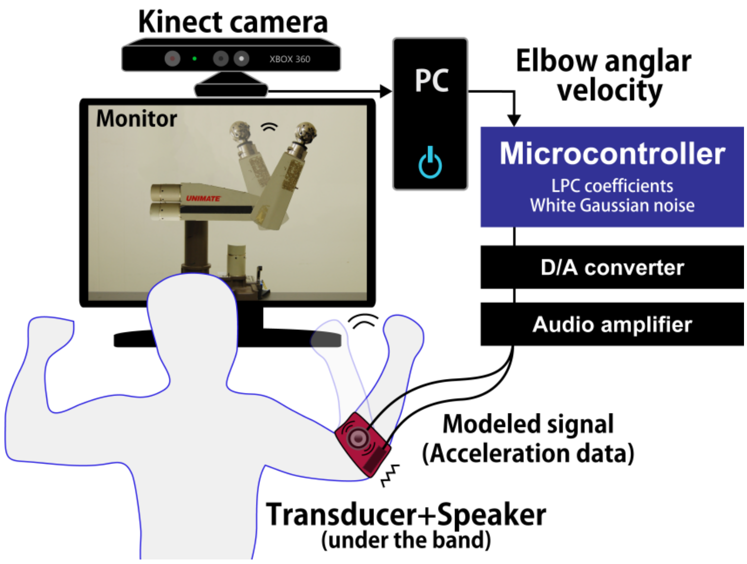

Fig. 4. The prototype of virtual robotization system.

3.4 Latency evaluation

We measured the latency from the movement of the user's real arm to animation of virtual robot arm. When the real arm movement was about 90 °/s angular speed, the latency was approximately 50 ms. Most of the latency was due to the camera. Because the gap was less than the latency (100-200ms) allowable between human motion and graphical responses [23], we considered it to be sufficiently small.

We demonstrated a preliminary version of the system to laboratory members who had never experienced the system (**Fig. 5**). None of the participants noticed the latency. The reactions of the participants appeared to be positive, including comments such as "My arm became the robot's arm" or "I have motors and gears in my elbow".

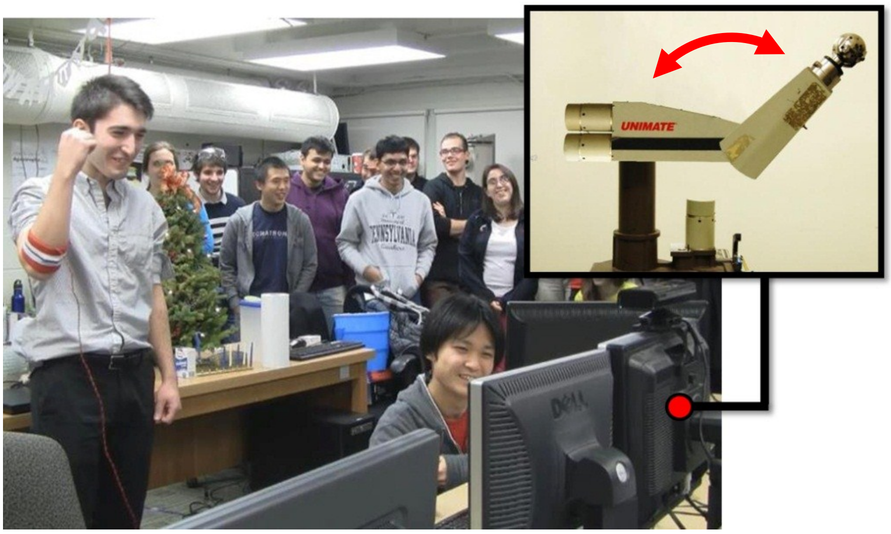

Fig. 5. User reactions at the demonstration.

4 Verification of robot-like feeling

The purpose of this psychophysical experiment was to verify the contribution of vibrotactile feedback to the subjective robot-like feeling. Using our virtual robotization system, we compared four sensory feedback conditions: visual only (V), visual + auditory (V+A), visual + haptic (V+H), and visual + auditory + haptic (V+A+H) by means of questionnaires.

4.1 Experimental environment

We recruited six males and one female (aged 21-23, right-handed) who had never experienced the system. As shown in **Fig. 6**, all participants stood in front of the Kinect camera and wore the armband on their right elbow. The participants also wore noise-canceling headphones (QuietComfort 15, BOSE Corp.) to cancel out any sound generated by the actuation of the transducer. The operating sound of the robot was emitted from the right channel only because the position of the auditory and vibrotactile feedback should be the same for a more realistic robot-like feeling. The experimenter confirmed with the participants that they could feel the vibrotactile stimuli clearly.

The participants were asked to flex and extend their right elbow at various velocities, looking at the robot arm animation in the monitor. Each trial was 15 seconds long. After each trial, the participants were asked to answer the following two questions:

How much did you feel the robot-like feeling in your arm? The participants evaluated their confidence about whether their right arm felt like the robot in the monitor, on a visual analog scale (0: not robot at all, 100: totally robot). Note that we defined the central point (50) as the robot-like feeling in the V+A condition, since the participants had never before experienced a robot-like body sense and the reference point of the evaluation would be different between participants. In other conditions, the participants evaluated the robot-like feeling by comparing with the V+A condition.

How much did you feel a reaction force? The typical expectation of a robotic body would be a friction-like force opposing the direction of body movement. Therefore, if the participants felt a resistance force when the there was none, as in this system, it might be a good quantitative measure of the perceived robot-like feeling. The participants answered the amount of the perceived reaction force with the visual-analog scale (0: completely smooth, 50: the same as usual, 100: felt strong force). Scores less than 50 points meant that the arm movement felt smoother than usual.

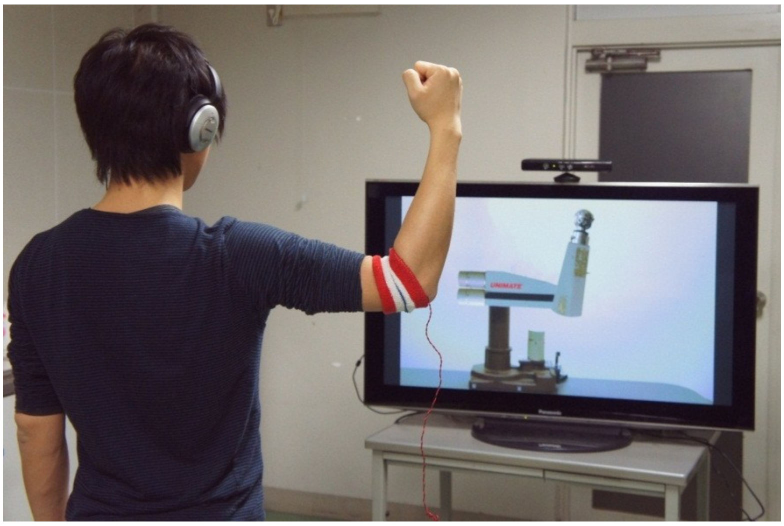

Fig. 6. Overview of the experiment.

4.2 Experimental procedure

First, the participants preliminarily experienced all four conditions once to ensure they understood the experimental procedures. The participants did not answer the two questions in this preliminary sequence, but the experimenter asked them to evaluate them in their mind. All participants started in the V+A condition, which corresponds to the reference point (50 points) of the robot-like feeling evaluation, and then they experienced the other three conditions in a random order.

In the main sequence, the participant first experienced the V+A condition to remember the reference point for the robot-like feeling evaluation. After that, all four conditions including V+A were conducted in a random order, and the participants answered the two questions. This sequence was repeated three times for each participant.

4.3 Results

Fig. 7 shows the perceived amount of robot-like feeling and reaction force. Whiskers indicate the standard deviation. The robot-like feeling was highest in the V+A+H condition, followed by the V+A, V+H, and V conditions. We performed a one-way analysis of variance (ANOVA) and found significant differences between the feedback conditions ($F(3,24) = 3.35$, $p < 0.001$). A post-hoc comparison using Tukey's HSD method between the feedback conditions showed a significant difference ($p < 0.05$) in all the pairs except V+A vs. V+H. The comparison between V+A and V+H showed a marginally significant difference ($p = 0.07 < 0.10$).

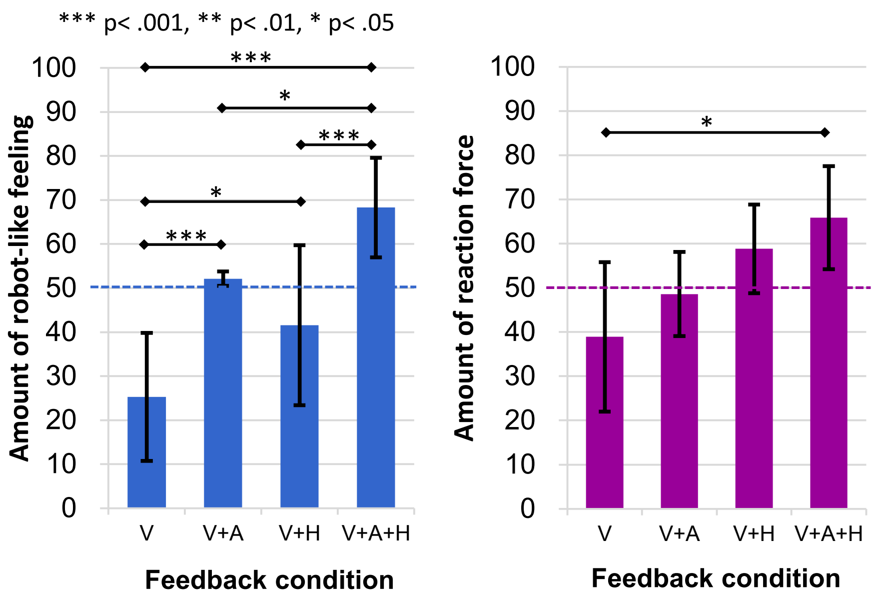

Fig. 7. Mean values of the evaluation of robot-like feeling (left) and reaction force (right).

Participants felt that the reaction force was highest in the V+A+H condition, followed by the V+H, V+A, and V conditions. A one-way ANOVA between feedback conditions showed significant differences ($F(3,24) = 3.34$, $p < 0.05$). A post-hoc test revealed significant differences only between the V and V+A+H conditions ($p < 0.05$).

5 Discussion

5.1 Robot-like feeling

Robot-like feeling was perceived most strongly in the V+A+H condition. This result suggests that the combination of the visual, auditory, and haptic feedback was the most effective in enhancing the robot-like feeling. Simultaneous feedback of auditory and haptic feedback particularly contributed to robot-like feeling, which was supported by the fact that the evaluation of the V+A+H condition was significantly higher than the V+A and V+H conditions, as well as the more traditional V condition.

The evaluation of robot-like feeling in the V+A condition (52.1 points), which we defined as the reference, was close to the actual reference (50 points) and the standard deviation was particularly small. These results imply that the participants could understand the reference position and were able to compare the robot-like feelings between the conditions.

5.2 Reaction force

The highest amount of evaluated reaction force was found in the V+A+H condition. This result suggests that the simultaneous presentation of visual, auditory, and haptic feedback was the most effective way to produce the pseudo force. The result is similar to the evaluation results for the robot-like feeling.

In the visual only (V) condition, the participants evaluated the reaction force as less than 50 points (38.9 points), which indicates that they felt that their arm moved more smoothly than usual. This finding may be attributed to the fact that all participants experienced the V condition after the V+A condition, and felt "liberated" by the disappearance of auditory feedback. We speculated that the participants subconsciously assumed that the reaction force in the V+A condition was the reference point, which is supported by the result that the V+A condition scored around 50 points.

5.3 Relationship between robot-like feeling and reaction force

Fig. 8 shows the plot of all 84 pairs (4 conditions * 3 trials * 7 participants) of the evaluated robot-like feeling (vertical axis) and the evaluated reaction force (horizontal axis). We performed a linear regression analysis on the evaluation data, showing moderate correlation ($R^2 = 0.425$). This result implies that the robot-like feeling might be partially caused by the illusory reaction force.

However, as shown in **Fig. 7**, there was a different tendency between the V+A and V+H condition; the robot-like feeling in V+H condition was lower, while the reaction force was higher. This inconsistency might be attributed to a higher contribution of the auditory cue to the robot-like feeling, and a higher contribution of the vibrotactile cue to the resultant illusory force cues, another haptic sensation.

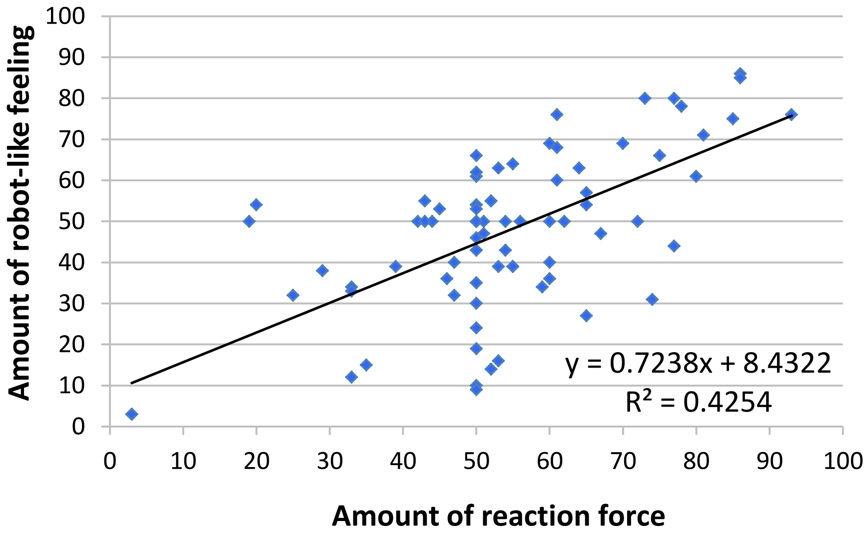

Fig. 8. Relationship between the robot-like feeling and the reaction force.

Realism of robot-like body sense. Three participants commented that they felt creaking in the conditions using haptic feedback (i.e., V+H and V+A+H). This comment implies that the haptic feedback of robot vibration could produce a feeling of creaking friction to some participants. Also, two participants reported that they felt as if the robot arm model on the monitor became their right arm, because the robot model was synchronized with the movement of their real arm. As reported in [20], synchronous movement of the virtual arm and the real arm can facilitate the body-ownership illusion. However, we intend to improve the level of the body-ownership illusion in the future studies. Completely hiding the participant's real arm and overlaying the virtual robot arm would be one promising approach in the facilitation of this illusion.

According to these comments and the evaluation of the robot-like feeling and reaction force, it was confirmed that the integration of robot vibration, creaking sound effects, and the visual robot model synchronized with the user's motion could cause the participant to feel that their body had become robotic.

Realism of auditory feedback. A negative comment, stated by three participants, was that the presented sound was mismatched with the participant's expectation of a robot's sound. In this experiment, the auditory feedback was computed using acceleration data, to which a 1.2 kHz low-pass filter was applied. The lack of high-frequency components might cause an auditory mismatch between the generated sound and the original noise.

To verify this effect, we performed an experiment that recorded robot sound using a microphone (Gigaware 60139B, RadioShack Corp.) and the sound feedback at a refresh rate of 22.05 kHz. However, the participants could not discriminate between the acceleration-based sound and the sound-based sound. Thus, the lack of high-frequency sound does not seem to play an important role in the auditory mismatch feeling.

Another reason for the auditory mismatch feeling might be that we employed an industrial robot to record vibration. The participants were unfamiliar with the sound of an industrial robot; in fact, they had never seen this kind of robot before the experiment, so they could not know how it should sound.

Matching the user's image of the robot-like feeling would be an important future study. One possibility is to show a movie of the PUMA 260 actuation to allow the participants to experience a specific robot sound before the evaluation task. In contrast, the use of a representative robot sound that most people imagine is an alternative idea in generating a convincing robot-like feeling. In science fiction movies, for example, sound effects representing robot actuation are not at all like a real robot actuation sound.

6 Conclusion

This paper presented a method to create a robot-like body sense, aiming for a new entertainment experience as if the human user had actually become a robot. We proposed the vibration recording of real robot actuation, data-driven modeling based on spectral approximation, and vibrotactile rendering to the user's elbow as a function of the elbow angular velocity. We also developed a system that virtually robotized the human arm visually, aurally and haptically by means of integrating a visual robot model that tracks the user's arm motion and produces a creaking sound and vibrotactile feedback. Using this system, we compared four sensory conditions to evaluate the participants' subjective robot-like feeling and perceived reaction force. This experiment revealed that the combination of visual, auditory, and haptic feedback was the most effective in inducing a robot-like feeling. The pseudo reaction force, which might also reflect a robot-like feeling, was generated most strongly with this combination. Additionally, some comments from the participants suggested that our approach can simulate friction of the robot joint.

We intend to upgrade our system to an augmented reality (AR) system using a video see-though head mounted display (HMD) so that the users can see their own body visually changed into that of a robot (**Fig. 9**). A camera mounted on the HMD captures the user's subjective view and tracks markers attached on the arms. The HMD then superimposes virtual robot arms on the user's arms. The AR system will provide an even more immersive experience of the robotized body.

We can alter the user's body to feel like various other objects with a similar setup. We have tested a clicking multimeter dial, a water-spurting garden hose, a groaning vacuum cleaner, and peeling Velcro tape. We have anecdotally observed that vibrotactile stimuli of these materials provides an entertainingly weird body sense, like ticking-dial elbow, water-spurting or air-breathing palm, and Velcro arm.

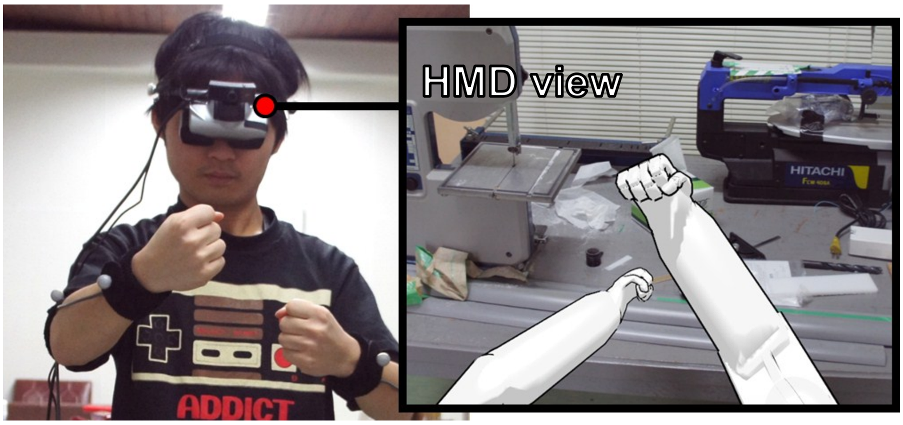

Fig. 9. AR system for virtual robotization of human arms.

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