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Haptic Robotization of the Human Body by Data-Driven Vibrotactile Feedback

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Abstract

The worlds envisioned in 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 transmitting a robot's haptic vibration to the user's arm. The vibrotactile stimulus was recorded using the actuation of a real robot and modeled using linear predictive coding. 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, haptics, robotization, vibrotactile feedback

1 Introduction

In addition to the many industrial robots that support our daily lives, there are 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, and perhaps even wish that we could become like these robotic heroes, if only for a short time. The question naturally arises: What would it feel like to be a robot? While we are seldom conscious of the activities of our biological muscles or tendons, a ro-

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botic body would have a definite robotic body sense that would be different from that of humans.

In this study, we focused on the body sense of a robot and simulated robot-like feelings in human joints (**Figure 1**). To create a realistic robot-like body sense, we provided vibrotactile feedback based on recording, modeling, and rendering the vibration of a real robot's actuation. Combined with a conventional visual model and sound effects, our system allowed a user to virtually robotize his or her body visually, aurally, and haptically.

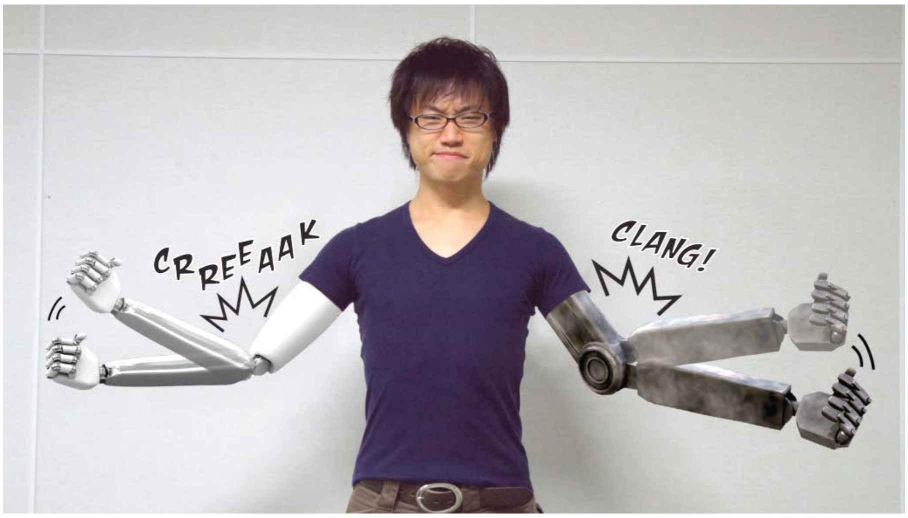


Figure 1. Concept image of virtual robotization of human arms

This paper mainly contributes to the field of computer entertainment technology by presenting a new alternative for achieving an immersive experience in video games. 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. In addition, some previous tactile entertainment systems have enhanced the immersive experience by transmitting vibrotactile feedback to the player's body, synchronized with characters being shot [1] or getting slashed [2].

However, the 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, we can create a more immersive gaming experience for the user. 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.

2 Related Work

2.1 Haptic alteration of objects by vibration recording and rendering

Recording the vibrations resulting from object interaction and rendering the modeled vibrations are often used to alter haptic perception. For instance, the feeling of walking on gravel or snow [3]; plunging a hand into a volume of fluid [4]; tapping on rubber, wood, or aluminum [5-6]; and scraping various surface textures [7] can be realistically simulated using vibrotactile feedback. Some studies have developed haptic recording and rendering systems with simple setups that make it possible to share a haptic experience [8-9]. 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 presenting haptic properties that are different than those of the human body.

2.2 Ego-vibration noise of robot actuation

A robot's own internal motors and gears inevitably generate high-frequency vibrations, which are called ego-vibrations. These ego-vibrations cause a crucial problem in some robotic applications by deteriorating the acceleration and sound signals. Thus, much research has dealt with noise subtraction to improve the sensing skills of robots [10-11].

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

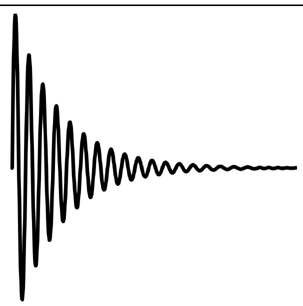
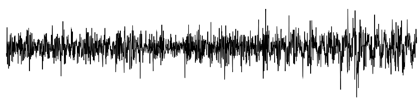
2.3 Difference between “robot-like feeling” and “aluminum-like feeling”

We previously implemented a system that virtually altered the feeling of a material on the body using periodic vibrotactile feedback [12]. We employed a decaying sinusoidal vibration model, which simulated the haptic properties of materials when they collide [5], [13]. The periodic ticking vibrotactile feedback could simulate rubber, wood, and aluminum collisions. We predicted that the aluminum-like impact vibration feedback would evoke a robot-like body sense, but the sensation was just aluminum-like, rather than robotic. In addition, the aluminum-like sensation was felt from outside of the body, as if the user was wearing an exoskeleton suit.

Therefore, we hypothesized that while the aluminum-like feeling is a sensation from the material itself, a robot-like feeling refers to a sensation from the material and structure of a robot, such as motors and gear mechanisms.

This paper focuses on a robot-like “creaking” sensation. The present system involved continuous vibrations captured from real robot actuation, instead of the discrete collision-based vibrations from the prior study (**Table 1**). Furthermore, we combined the vibrotactile feedback with visual and auditory feedback to improve the robotization effect.

Table 1. Novelty of current study

	Previous study	Current study
Feeling	Aluminum body (material)	Robotic body (material + structure)
Vibration	Periodic ticking impact	Continuous creaking noise
Waveform		

2.4 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]. This illusion can be produced by using a vibration of approximately 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 used 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. We believe that applying haptic feedback matched to the appearance and movement of the user’s virtual body may be an effective method to modify the user’s self-body perception. The combination of robot-like visual, sound, and haptic feedback synchronized with the user’s bodily motion should significantly enrich the experience of becoming a robot in fictional world.

3 Haptic Robotization of the Human Arm

Our hypothesis was that presenting robot ego-vibrations to the user’s body in accordance with his or her motion would make the user believe that his or her body had 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 [7], [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 **Figure 2**. After testing some other robots, we chose the PUMA because its simple servomotor and gear mechanism generate 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 meant 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 a 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 entire human haptic perceptual domain.

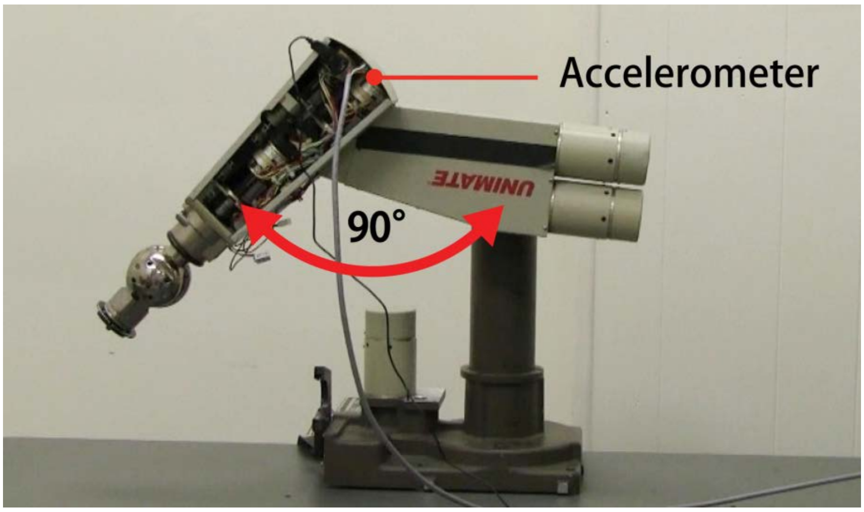


Figure 2. Recording vibration on robot’s elbow joint.

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 the lowfrequency components attributed to the change in the orientation of the robot's forearm. Next, the three acceleration channels were summed to acquire a single wave. We normalized the duration of the acceleration data captured at the various angular velocities by selectively clipping one second of data at approximately 45°, which was the center of the range of motion.

We employed linear predictive coding (LPC) to approximate the spectral density of the raw acceleration data (**Figure 3**). LPC is known to be one of the most powerful speech processing techniques, and it is also used in haptic data modeling [7], [22]. To make a model that approximated 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.).

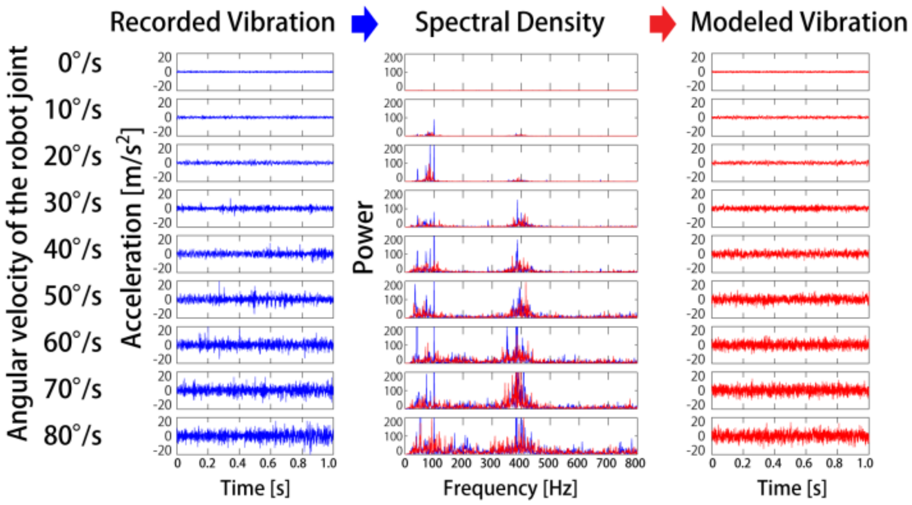


Figure 3. Recorded vibration (left), example of LPC-modeled vibration (right), and overlaid spectral density (center).

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 follows:

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

where *n* is the number of steps (*n* = 0 is substituted), $x(n-k)$ represents the values at the past k steps, $a(k)$ are the LPC coefficients, and *w* is a sample of white Gaussian noise. While the model contains a spectral density similar to that of 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.

3.3 Rendering robot-like feeling

Figure 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 performs 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 an angular velocity within a range of 35–44°/s, the system performs the rendering with the coefficients for 40°/s. Although the LPC coefficients for the rendering switched at a 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 digital to analog (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.). 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. A visual representation of the PUMA 260 robot is displayed and animated synchronously with the user's right forearm motion.

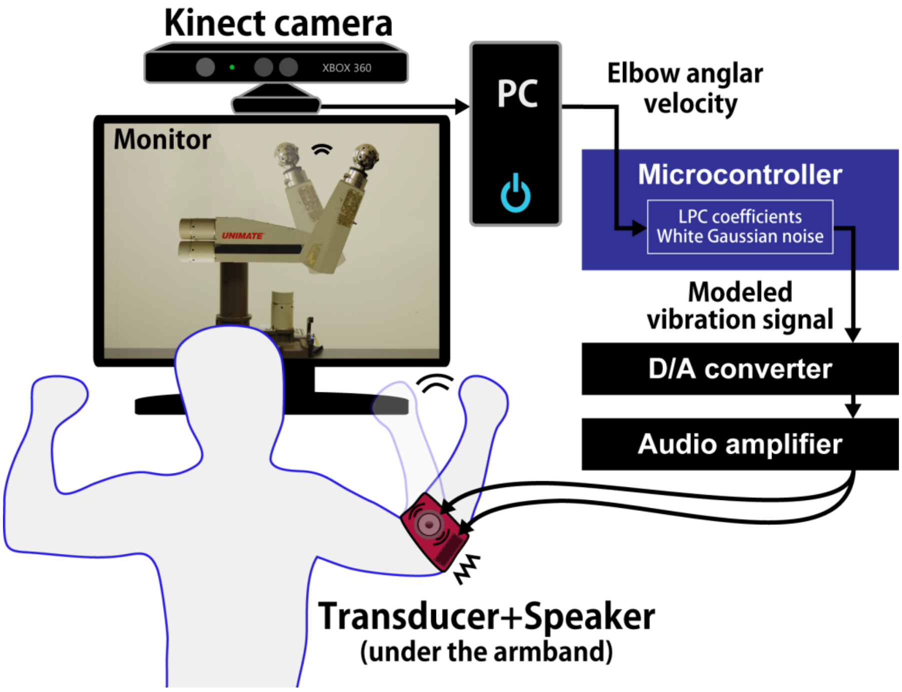


Figure 4. Prototype of virtual robotization system.

3.4 Latency evaluation

We measured the latency from the movement of the user's real arm to the animation of the virtual robot arm. When the real arm movement had an angular speed of approximately 90°/s, the latency was approximately 50 ms. Most of the latency was due to the camera. Because the gap was less than the allowable latency (100–200 ms) 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 (**Figure 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” and “I have motors and gears in my elbow.”

Figure 5. Users’ reactions during a 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 by means of questionnaires: visual only (V), visual + auditory (V+A), visual + haptic (V+H), and visual + auditory + haptic (V+A+H).

4.1 Experimental environment

We recruited six males and one female (aged 21–23, right-handed) who had never experienced the system. Since the participants’ experience with real robots may influence the subjective robot-like feeling, we asked each subject whether he or she was familiar with robots like the PUMA260, by showing its picture. All of them answered that they have never seen this kind of robot before.

As shown in **Figure 6**, all the 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 headphone channel only because it was felt that 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 clearly feel the vibrotactile stimuli.

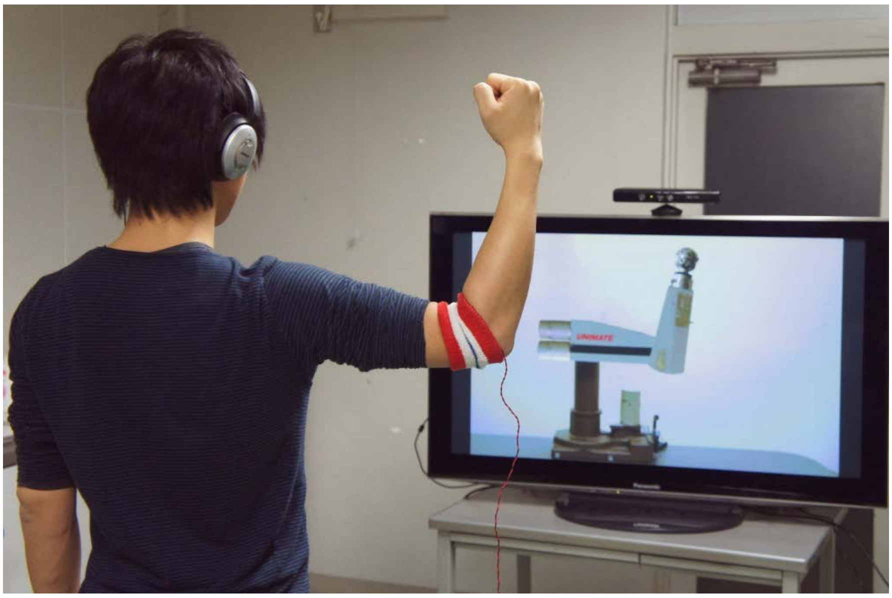


Figure 6. Overview of experiment.

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 s long. After each trial, the participants were asked to answer the following two questions.

(1) 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 robotic at all, 100: totally robotic). Note that we defined the central point (50) as the robot-like feeling in the V+A condition, because the participants had never before experienced a robot-like body sense, and the reference point of the evaluation would differ between participants. Under the other conditions, the participants evaluated the robot-like feeling by comparing with the V+A condition.

(2) How much did you feel a reaction force?

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

4.2 Experimental procedure

First, the participants preliminarily experienced all four conditions once to ensure that 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 of the participants started under the V+A condition, which corresponded to the reference point (50 points) of the robot-like feeling evaluation, and then they experienced the other three conditions in 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 random order, and the participants answered the two questions. This sequence was repeated three times for each participant.

4.3 Results

Figure 7 shows the perceived amounts of robot-like feeling and reaction force. Whiskers indicate the standard deviation. The robot-like feeling was highest under 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 of the feedback conditions using Tukey's HSD method 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 ($p = 0.07 < 0.10$).

Participants felt that the reaction force was the highest under the V+A+H condition, followed by the V+H, V+A, and V conditions. A one-way ANOVA between the 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 ($p < 0.05$).

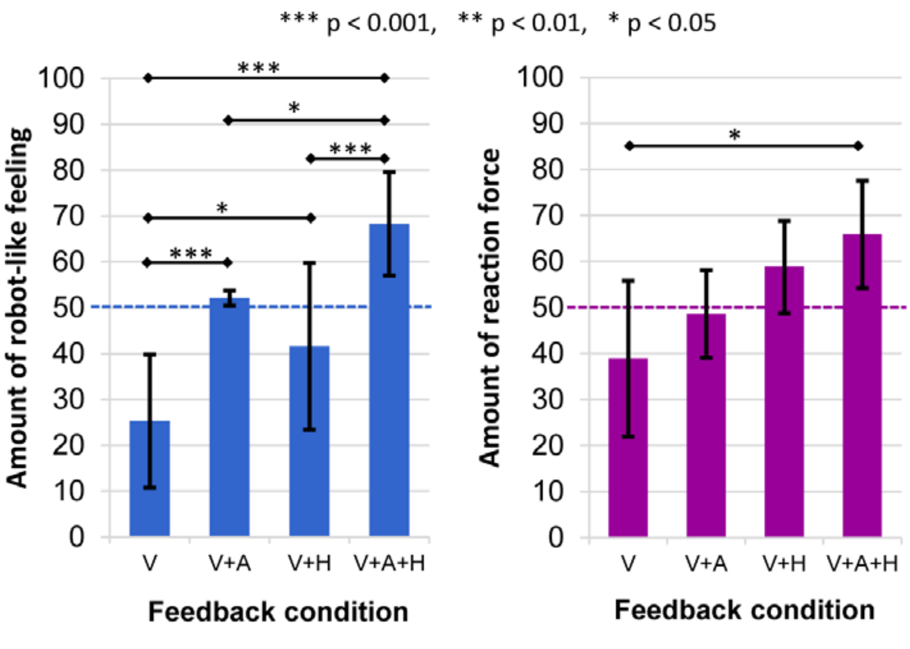


Figure 7. Mean values from evaluation of robot-like feeling (left) and reaction force (right).

5 Discussion

5.1 Robot-like feeling

The strongest robot-like feeling was perceived under 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. The simultaneous auditory and haptic feedback particularly contributed to a robot-like feeling, which was supported by the fact that the evaluation of the V+A+H condition was significantly higher than those for the V+A and V+H conditions, as well as that for the more traditional V condition.

The evaluation of the robot-like feeling under 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.

The results show that auditory feedback alone was also effective at creating a robot-like feeling compared with the visual only (V) condition. As far as we know, auditory feedback that modifies the user's sensation of joint motion is new. There have been many studies on motion-sound mapping, sometimes referred to as sonification or audification, but most of them were for motor learning [24] or auditory sports games [25]. Consumer video games and toys have commonly used sound effects based on human body motion to accentuate the player's gesture (e.g., the sound of slashing a sword when the player swings, the sound of smashing when the player punches). However, the robotic noise feedback in our study modified the player's own joint sense, rather than gestures.

5.2 Reaction force

The highest amount of evaluated reaction force was found under 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. This 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 the 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

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

However, as shown in **Figure 7**, the V+A and V+H conditions had different tendencies: the robot-like feeling was lower under V+H condition, whereas 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, which was another haptic sensation.

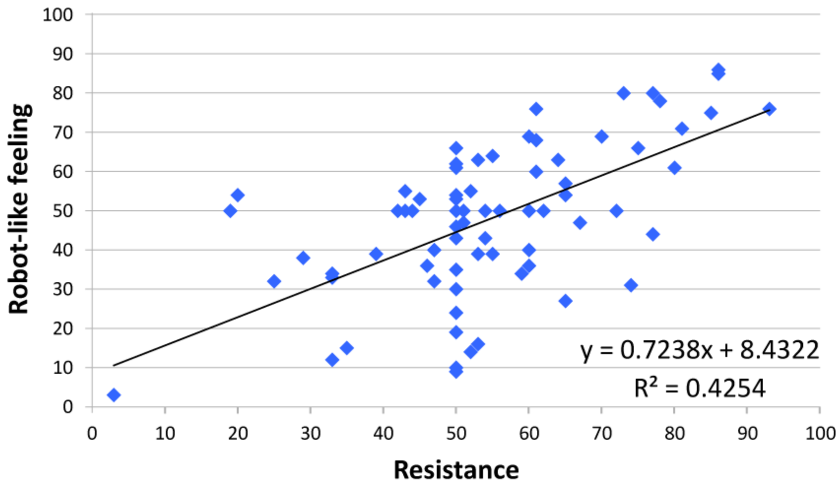


Figure 8. Relationship between robot-like feeling and reaction force.

5.4 Realism of robot-like body sense

Three participants commented that they felt creaking under 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 in some participants. Moreover, 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 movements of a virtual arm and one's real arm can facilitate the body-ownership illusion. However, we intend to improve the level of the body-ownership illusion in future studies. Completely hiding the participant's real arm and overlaying the virtual robot arm would be one promising approach to facilitate this illusion.

These comments and the evaluations of the robot-like feeling and reaction force confirmed that the integration of robot vibration, creaking sound effects, and a visual robot representation synchronized with the user's motion could cause the participant to feel that their body had become robotic.

5.5 Mismatch between the user's imagination and perceived feeling

A negative comment made by three participants was that the presented sound did not match 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 have caused an auditory mismatch between the generated sound and the original noise.

To verify this effect, we performed an experiment that recorded a robot's sound using a microphone (Gigaware 60139B, RadioShack Corp.), and the sound was played back 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 did 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 the vibrations. As shown in section 4.1, participants were unfamiliar with the sound of an industrial robot, 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 video of PUMA 260 actuation to allow the participants to know referential experience of a specific robot before the evaluation task. Also, participants should be polled about their experience with fictional robots, as we did for actual robots. Both experiences might affect the subjective robot-like feeling.

In contrast, using the kind of representative robot sound that most people imagine is an alternative idea to generate a convincing robot-like feeling. In science fiction movies or video games, for example, the sound effects representing robot actuation are not at all like real robot actuation sounds.

6 Jointonation: Virtual Reality Robotization System

6.1 VR game application for immersive robotized body experience

We verified that vibrotactile feedback significantly improved a robot-like body sense. However, the prototype system was not very sophisticated, and the robotized body experience seemed to be unattractive.

Therefore, we upgraded the prototype system to a virtual reality (VR) robotization game called Jointonation (**Figure 9**), which used higher quality visual, auditory, and haptic feedback to create a more immersive robotized body experience. The Jointonation system provides vibrotactile feedback to the elbows and knees, visual feedback using a head mounted display (HMD), and a three-dimensional computer graphics (3DCG) robot avatar. By developing attractive and specific applications using our robotization technique, we clarified its contribution to the field of computer entertainment technology.

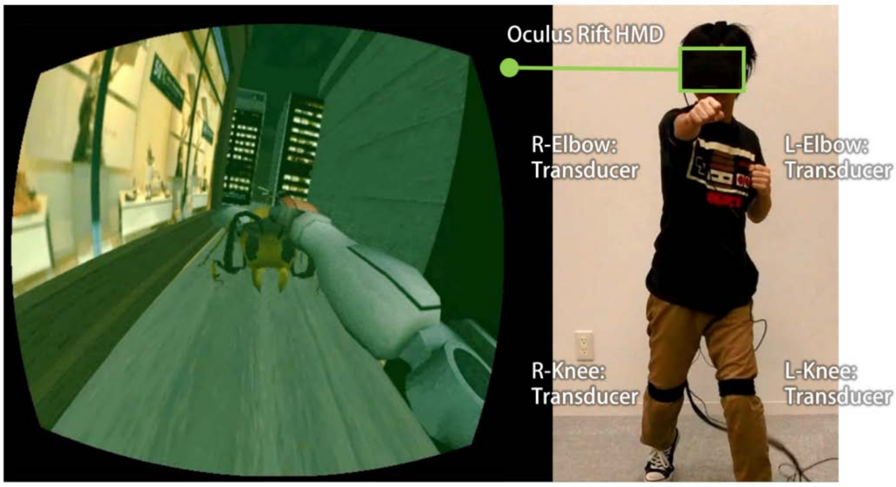


Figure 9. Jointonation: virtual reality robotization system (humanoid robot).
A Kinect camera in front of the player tracks the player's motion. This motion is reflected by the robot avatar's motion in the virtual world, and the robot's first-person view is displayed on the player's HMD.

6.2 Rendering two types of robot-like feelings

We rendered two types of robot-like body senses (**Figure 10**). To create an immersive and convincing robotized body experience, we needed to prepare multiple robot-like feelings, which differed between players, as mentioned in Section 5.3. Many people are more familiar with fictional robots (e.g., SF movies and animes) than real robots. These fictional robots could be divided into two types: human-size robots (humanoids) and giant combat robots. We assumed that these two types of robots are general images of robots. Comparing humanoid and giant robots would make it possible to create a more convincing robotized body experience.

Figure 10. 3D model of human-size robot and giant robot. The 3D models were downloaded from Unity Asset Store (https://www.assetstore.unity3d.com/en/)

6.3 Impact vibration after motion stops

To express a robot's behavior in words, many people would use sounds such as "creak" and "clang." "Creak" would express an annoying noise during robot actuation. This expression corresponds to the frictional vibration during robot actuation that we have proposed. On the other hand, "clang" would represent the impact vibration when the robot's motion stops. Whereas a human's body motion smoothly starts and stops, a robot's motion is very sharp; it starts moving quickly and then quickly stops, which leads a clanging impact vibration. This robot-like motion is represented by the robot dance that is sometimes performed for general entertainment.

To create a more realistic robotized body experience, the Jointonation system provide two types of vibrotactile feedback, not only creaking frictional vibration during joint rotation but also clanging impact vibration after the robot motion stops.

6.4 Implementation

In this section we show the updates from the prototype system.

6.4.1 Visual: Viewing VR world created by game engine through 3D-HMD

In the Jointonation system, we developed a VR environment using a professional game engine (Unity, Unity Technologies) and created a humanoid robot and a giant robot as the player's avatars in the VR world. The player was equipped with a HMD (Oculus Rift, Oculus VR, 110° field of view, 1280 × 800 pixel resolution, 3D vision with parallel method) that showed the first-person viewpoint of the robot avatar. The Oculus Rift HMD supports stereovision using a pair of lenses. Each player used the HMD without glasses and chose a pair of lenses suitable for their eyesight. The robot avatar moved synchronously with the player's whole body motion and head orientation, which were captured by a Kinect camera and the HMD's internal head tracking modules (i.e., three-axis accelerometers, gyroscopes, and magnetometers). Eventually, the player felt as if their body had become the robot in the virtual world (**Fig. 11**).

6.4.2 Auditory: Reality-based sound effect

In the prototype system, we used vibration data captured with an accelerometer to generate a robot-like noise. However, the realism of the auditory feedback was insufficient even when we used sound data recorded with a microphone, as discussed in Section 5.3. A data-driven approach for auditory feedback may not be effective at improving the robot-like feeling.

Hence, we employed a reality-based approach, which is the opposite concept to the data-driven approach. We used artificially created robotic sound effects: a creaking noise during robot actuation and clanging impact sound after the motion stopped. These sounds were generated from stereo speakers behind the players. To make the players understand that the sounds were caused by the actuation of their elbows and knees, we designed the 3D position of the sound source so that the players recognized that the sound was coming from their elbows and knees. The sound for the giant robot was created by lowering the pitch of the sound for the humanoid.

6.4.3 Haptic: Creaking frictional vibration and clanging impact vibration

The acceleration data for the clanging impact vibration were captured from the real robot actuation, along with the creaking frictional vibration. We found that the recorded acceleration data, which were shown in Section 3.2, included approximately 0.3 s of transient impact vibration after the robot rotation stopped. We picked out this 0.3 s of impact vibration and rendered it when the user's motion stopped. For the impact vibration, we used the raw acceleration data without modeling because the instantaneous impact vibration did not cause an unnatural haptic sensation, which was caused by repeating a vibration data series.

The acceleration data captured from the real PUMA260 robot were used for the haptic rendering of the humanoid robot. For the giant robot, we used the same data with a 300-Hz low-pass filter to represent a heavier and bigger sensation, because the resonance frequency of an object naturally becomes lower when the object becomes heavier.

6.4.4 Game design

First, the player stands in front of the Kinect camera at a distance of approximately 2.0 m. Next, bands equipped with vibrotactile actuators are placed on the player's elbows and knees, and a belt bag with the HMD control box goes around their waist. Finally, the player wears the Oculus Rift HMD. **Figure 11** shows the game flow of Jointonation. The game starts from a synchronization with the humanoid robot (**Figure 11a**). The player attacks the monsters (flying bees and crawling spiders) by punching and stomping (**Figure 11b**). We did not employ projectile weapons such as guns or missiles because we wanted to allow the player's joints to move and provide the robot-like body sense, which was the main contribution of this study. The flying bees approaching the player's head induced punching, and the crawling spiders induced stomping.

When the player beats the initial set of monsters, a giant red dragon descends from the night sky (**Figure 11c**). To beat the dragon, the player jumps and gets into a giant robot. The player's jump motion is recognized using the Kinect camera by tracking the position of their center of gravity. After the player is synchronized with the giant robot, the system renders giant-robot-like vibrations and sounds so that the player recognizes that they have a bigger and heavier body (**Figure 11d**). In addition, we designed the game field to be an urban area with high-rise buildings so that the player could recognize how big/small they were in comparison with the buildings and dragon.

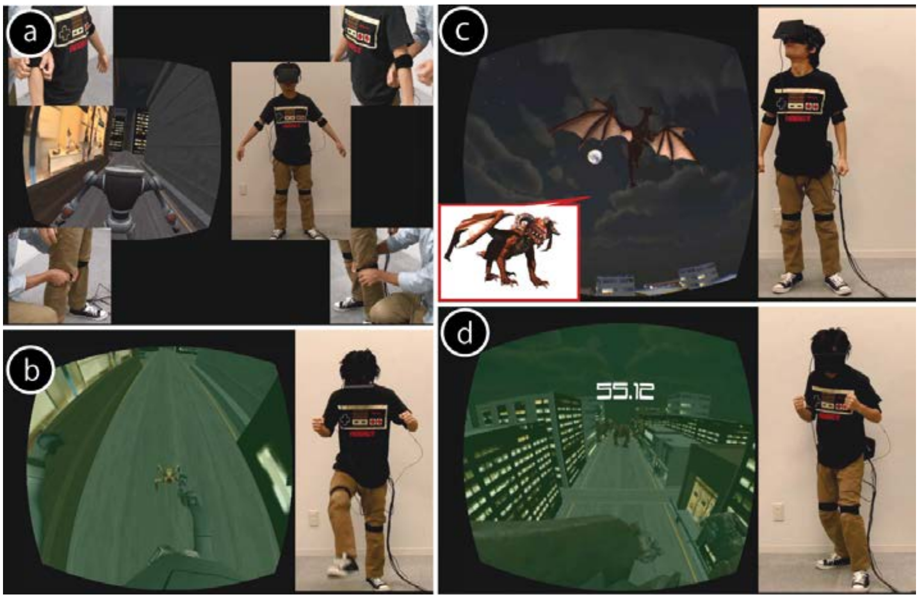


Figure 11. Game flow of Jointonation

6.5 Demonstration

We demonstrated the Jointonation system at two conferences, ACE2013 [26] and SIGGRAPH Asia 2013 [27]. Approximately 300 visitors played our Jointonation demonstration (**Figure 12**). Many visitors played with a serious look, but smiled after the demonstration and made comments such as "I actually became a robot," "My joints are creaking," and "Truly immersive." These behaviors and feedback suggest that the Jointonation system provided the visitors with a highly immersive robotized body experience.

Figure 12. Hands-on demonstration of Jointonation.

There were three noteworthy comments made by visitors.

C1: My body got heavier/bigger when I became the giant robot.

C2: The cables to the elbows and knees hindered my body movement.

C3: I felt that the vibrations were weak.

In relation to C1, we theorize that the characteristics of the giant robot were emphasized by comparing it with the humanoid robot. Some visitors kept their arms outward as if they got fatter when they became the giant robot. This behavior could be explained by the fact that the CG model of the giant robot interrupted the player's lower field of view, causing them to feel that their body had become fatter. We speculate that the Jointonation system could represent the size of the giant robot.

C2 should be solved in future work. Taking up the slack by fitting the cables to the player's body is one possible option to make the demonstration more comfortable. In addition, building a more robust system is important because Jointonation includes heavy physical exercise such as punching and stomping. We will use flexible and movable cables designed for industrial robots to improve the robustness.

A serious problem for the current Jointonation system is shown in C3. We believe that the Jointonation system is very entertaining, but we should refine the system to better present our haptic robotization technique. One of the reasons for the weak vibrotactile perception might be the delay of the Kinect camera processing. The camera's 30-Hz refresh rate seemed to cause an unrecognizable delay, and reduced the realism of the haptic sensations. Using a higher speed tracking system such as a high refresh rate camera or rotary encoder would solve this problem.

7 Conclusion

This paper presented a method to create a robot-like body sense, aiming at a new entertainment experience that makes a human user feel like they have 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's angular velocity.

We developed a prototype that virtually robotized the human arm visually, aurally, and haptically by integrating a visual robot representation that tracked the user's arm motion and produced a creaking vibrotactile feedback and noisy sound. Using this system, we compared four sensory conditions to evaluate each participant's 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 could simulate the friction of the robot joint.

We also developed a virtual reality robotization system called Jointonation that used higher quality visual, auditory, and vibrotactile feedback to create a more realistic and immersive robotized body experience. The Jointonation system provides visual feedback using an HMD and 3DCG robot avatar, auditory feedback based on reality-based sound effects, and vibrotactile feedback to both the elbows and knees. We tested the Jointonation system at two conference demonstrations and reported the player's comments in this paper.

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

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