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Haptic robotization of the human body by data-driven vibrotactile feedback ☆

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A R T I C L E I N F O

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A B S T R A C T

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.

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 robotic 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 (Fig. 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.

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

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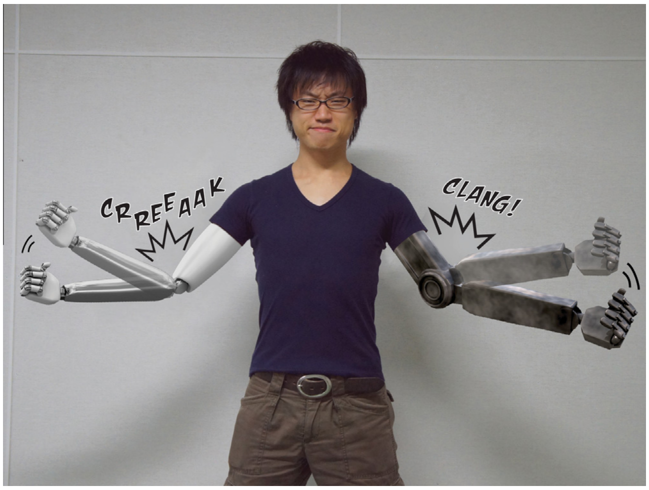


Fig. 1. Concept image of virtual robotization of human arms.

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.

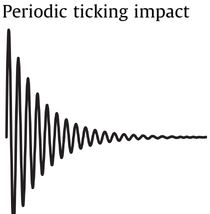
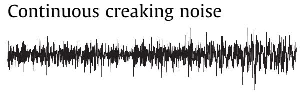
2.3. Difference between "robot-like feeling" and "aluminum-like feeling"

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 Waveform	Periodic ticking impact 	Continuous creaking noise 

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

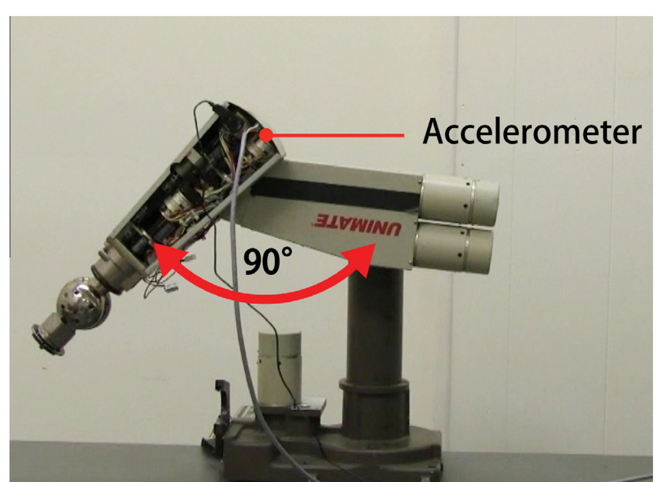


Fig. 2. Recording vibration on robot's elbow joint.