Robot motion characteristics for embodied interaction with humans using upper arm

Mitsuru JINDAI*, Shunsuke OTA**, Toshiyuki YASUDA* and Tohru SASAKI*

* Faculty of Engineering, University of Toyama
3190, Goifu, Toyama, Toyama, 930-8555, Japan
E-mail: jindai@eng.u-toyama.ac.jp

** Faculty of Computer Science and Systems Engineering, Okayama Prefectural University
111 Kuboki, Soja, Okayama 719-1197, Japan

Received: 21 November 2019; Revised: 30 April 2020; Accepted: 28 July 2020

Abstract
Humans establish embodied interactions, such as bows and handshakes, when they first meet. Through these embodied interactions, it is believed that humans construct a relationship that is emotionally acceptable to each other. In interactions between humans and robots, the same efficiency is expected. There are two types of embodied interactions. The first type is interactions without physical contact, such as those in raising hand greetings and bows. The other type is interactions with physical contact, such as those in handshakes and hugs. Thus, differences are believed to exist between the motion characteristics of robots that are preferred by humans depending on the presence or absence of physical contact. Therefore, in this paper, the differences in motion characteristics of robots that are preferred by humans in their embodied interactions with robots depending on the presence or absence of physical contact are analyzed. First, in a raising hand greeting, which is an embodied interaction without physical contact, the motion characteristics are analyzed. Next, the motion characteristics preferred by humans are identified through sensory evaluations using a raising hand greeting robot system that is developed based on these analyses. Finally, the differences in the preferred motion characteristics with the presence or absence of physical contact are analyzed by comparing the preferred motion characteristics of a raising hand greeting with those of a handshake, which were clarified in a previous study.

Keywords : Human-robot system, Robot interaction, Embodied interaction, Motion characteristics, Motion analysis

1. Introduction

Owing to problems such as population aging and decline in Japan, the working-age population is decreasing gradually. Therefore, in the near future, robots are expected to work in various fields instead of humans, especially in fields involving interaction with humans such as medical welfare and life support. To work in these fields, the robot must first be accepted favorably by humans. Robots must be able to communicate smoothly with humans without giving them a feeling of discomfort.

Humans establish embodied interactions, such as bows and handshakes, when they first meet. Through their embodied interactions, humans can synchronize their embodied rhythms. It is believed that humans construct a relationship that is emotionally acceptable to each other by the synchronization of their embodied rhythms. In interactions between humans and robots, the same efficiency is expected. Robots are accepted psychologically by humans because they provide a feeling of security (Rani, et al., 2007). In particular, researchers have reported that there is a “Midas touch effect” (Crusco, et al., 1984) in interactions involving physical contact between humans and robots (Bevan, et al., 2015). Therefore, it is important for robots to generate embodied interactions with humans.

There are two types of embodied interactions. The first type is interactions without physical contact, such as those in raising hand greetings and bows. The other type is interactions with physical contact, such as those in handshakes and
hugs. Thus, differences are believed to exist between the motion characteristics of robots that are preferred by humans depending on the presence or absence of physical contact.

The embodied interactions between humans and robots have been discussed (Nakagawa, et al., 2012)(Onishi, et al., 2007). Bows and raising hand greetings have been reported as interactions without physical contact(Kanda, et al., 2008)(Zheng, et al., 2014). Handshakes and hugs, as embodied interactions with physical contact, have also been discussed(Avraham, et al., 2012)(Shiomi, et al., 2017)(Jindai, et al., 2018). However, no research has analyzed the differences in motion characteristics that are preferred by humans considering the presence or absence of physical contact. In our previous studies, the motion characteristics that are preferred by humans were clarified for embodied interactions with physical contact, such as handshakes (Ota, et al., 2019)(Jindai, et al., 2011). In particular, a handshake response motion model was proposed based on an analysis of human handshake motions (Jindai, et al., 2008). In this model, the robot generates the response motion of a handshake when the human requests one. Furthermore, the effectiveness of the proposed model was demonstrated via sensory evaluation using a handshake robot system employing the model.

A raising hand greeting, an embodied interaction that uses an arm, is similar to a handshake. However, the raising hand greeting is an embodied interaction without physical contact. Thus, the motion characteristics preferred by humans for raising hand greetings are clarified and compared to those of handshakes, which were clarified in the previous study. As a result, it is possible to analyze the differences in the motion characteristics of robots preferred by humans according to the presence or absence of physical contact.

Therefore, in this study, the differences in motion characteristics of robots that are preferred by humans in embodied interactions using upper arms between a human and a robot depending on the presence or absence of physical contact are analyzed. First, the embodied interactions between humans without physical contact, such as raising hand greetings, are analyzed. Next, based on this analysis, a raising hand greeting robot system is developed for generation of raising hand greetings with humans. Then, the motion characteristics of the robot preferred by humans are clarified by sensory evaluations using the developed raising hand greeting robot system. Finally, these motion characteristics are compared with the robot’s motion characteristics preferred by humans in handshake motions, which were clarified in our previous study. The differences in the motion characteristics of robots that are preferred by humans in their embodied interactions with robots depending on the presence or absence of physical contact are then analyzed.

2. Analysis of Raising Hand Greetings Between Humans
2.1. Experiment on Raising Hand Greeting

An experiment was performed to analyze raising hand greetings between humans. In this experiment, the arm motions of research participants were measured using a three-dimensional motion capture system (VICON). Five reflection markers were attached to the research participants at their right hand, right wrist, right elbow, right shoulder, and left shoulder. These positions were measured using 10 cameras. The accuracy of this system is ±1 mm for a sampling rate of 120 Hz.

A scene from the experiment is shown in Fig. 1. In this experiment, the side that will request the raising hand greeting and the side that will respond were predetermined. The research participants stood face-to-face at a distance of 1000 mm. The requesting side began to move his or her hand and voice utterance at an arbitrary time, and the responding side began to move his or her hand and voice utterance according to those of the requesting side. In the raising hand greeting, requesting and responding sides raised their hands to the heights of their faces as shown in Fig. 1.

The experiment was performed for raising hand greetings without and with utterance of a voice greeting. Each pair of research participants performed the raising hand greeting 10 times. The research participants were 30 healthy students (15 pairs) aged between 20 and 24. All of them were right-handed.

All experiments in this study were conducted with the approval of the Ethical Review Committee of the University of Toyama.

2.2. Analysis of Arm Motion

In the raising hand greeting, humans move their hands straight upward on their sagittal planes. The rotation velocity profiles of the elbow and shoulder form a bell-shaped pattern having one peak. The average movement time, average maximum velocity, and average position of the maximum velocity (peak position) are listed in Table 1. The peak position indicates the rate of time until it reaches the maximum velocity to movement time. This implies that the peak position of the elbow and shoulder rotating motions is approximately 50 % . Thus, the rotation velocity profiles of the elbow and shoulder resemble a symmetrical bell-shaped profile. This result indicates that the arm motion is generated by the
2.3. Analysis of Timing of Arm Motion and Voice Utterance

In raising hand greetings between humans, the responding side moves their arms according to the arm motions of the requesting side. Therefore, the timing of the beginning of arm motions is important for smooth embodied interactions. Furthermore, it has been discussed that arm motions preferred by humans are affected by time gaps of beginning of arm motions in embodied interactions using upper arms (Jindai, et al., 2007). The time gap is changed depending on the presence or absence of voice utterances. Thus, in this study, the timings of the beginning of arm motions and the voice utterances were measured. Here, it was assumed that the arm motion begins when the velocity of the right hand exceeded a threshold value which was determined in a preliminary experiment.

2.3.1. Raising Hand Greeting without Voice Utterance

The time gaps between the beginnings of arm motions by both sides during the raising hand greetings without voice utterances were measured. Figure 2 shows a histogram of the measured time gaps. In this figure, the arm motion by the responding side began after that by the requesting side for cases where the time gap is positive. From this result, it can be indicated that most of the responding sides began their arm motion 0.4 s after the arm motions of the requesting sides in raising hand greetings without voice utterance.

2.3.2. Raising Hand Greeting with Voice Utterance

In raising hand greetings with voice utterances, the time gaps between the beginning of the arm motions by both sides and time gaps between the beginning of arm motion and the voice utterance by the responding side were measured.

(1) Time gap of beginning of arm motions

The time gaps between the beginning of the arm motions by both sides were measured. Figure 3 depicts a histogram.
of the measured time gaps. In this figure, a positive time gap indicates that the arm motion by the responding side began after that by the requesting side. It can be observed that the measured time gaps were widely distributed with a peak of 0.6 s. From this result, it can be indicated that most of the response sides begin their arm motion 0.6 s after the arm motion of the requesting side in raising hand greetings with voice utterance. This result indicates that the beginning of arm motion is delayed when the greeting is accompanied by a voice utterance compared to when it is not accompanied by a voice utterance.

![Fig. 3 Time gap between arm motions of request and response sides is illustrated by a histogram. The peak of the histogram is denoted by a red bar.](image)

(2) Time gap between beginning of arm motion and voice utterance

The time gaps between the beginning of arm motion by the requesting sides and voice utterance by the responding sides were measured. Figure 4 shows a histogram of the measured time gaps. A positive time gap indicates that the responding side utters a voice greeting after the beginning of arm motion by the requesting side. From this result, it can be indicated that most of the responding sides utter their voice greetings 1.2 s after the beginning of arm motion of the requesting sides.

Furthermore, in the above analysis, most of the responding sides began their arm motion 0.6 s after the beginning of arm motion of the requesting sides. Thus, it is considered that the number of the response-sides who utter their voice greetings 0.6 s after the beginning of their arm motions is the largest.

![Fig. 4 Time gap between arm motion of request side and voice utterance of response side is illustrated by a histogram. The peak of the histogram is denoted by a red bar.](image)

3. Raising Hand Greeting Robot System

3.1. Construction of Raising Hand Greeting Robot System

A raising hand greeting robot system is developed, as shown in Fig. 5. It is composed of a robot arm, two computers, a speaker, and an accelerometer. The robot arm was designed and fabricated based on an average Japanese male adult (Kouchi, et al., 2000) with four degrees of freedom: shoulder (two axes), elbow, and wrist as shown in Fig. 6. In the raising hand greeting between humans, humans move their hands straight upward on their sagittal planes. Therefore, by using the arm with four degrees of freedom, the robot can generate its arm motion for the raising hand greeting.

The sampling time of the system is 5 ms. The robot can follow the desired position accurately. An accelerometer is strapped onto the wrist of research participants to measure the beginning of the arm motion. A speaker is used to utter the robot’s voice greeting.
3.2. Generation of Arm Motion for Raising Hand Greeting

The result of the analysis of arm motion during the raising hand greeting in the previous section shows that the velocity peak position of the elbow and shoulder rotating motions is approximately 50%. Furthermore, the velocity profiles of the elbow and shoulder rotating motions have smooth changes. The minimum jerk model, which can accurately reproduce the point-to-point motion of human hands (Flash, et al., 1985). In this model, the acceleration changes smoothly, and the velocity pattern has a symmetrical bell-shaped profile that the peak position is 50%, as shown in Fig. 7. Therefore, in order to generate robot’s arm motion for the raising hand greeting, joints of the elbow and shoulder are rotated by angular velocities of the symmetrical bell-shaped profiles which are made by this model. To produce an arm motion similar to that of a human, the movement time, maximum velocity, and initial and target angles are matched to those of humans.

4. Experiment Using Raising Hand Greeting Robot System

In the analysis of raising hand greetings between humans, the time gaps of beginning arm motions and the time gaps between beginning arm motions and voice utterances were widely distributed. Therefore, in consideration of the distributions, experiments in which the time gaps were changed (the analysis by synthesis) were conducted. The aim of the experiments was to determine the most preferred time for beginning the arm motion and voice utterance of the robot when responding to a raising hand greeting from a human in environments with and without voice utterance. Figure 8 depicts the experimental scene. The arm motion of the robot for raising hand greeting was generated based on the analysis of raising hand greetings between humans. Therefore, the robot raised its hand to a height similar to humans as shown in Fig. 8.

In the experiments, the robot generates the response motion of a raising hand greeting when a raising hand greeting is requested by a research participant. Three types of experiments were conducted to determine the preferred timing of
the robot. The first experiment was conducted to determine the beginning time of the robot’s arm motion that is preferred by humans in the raising hand greeting without voice greeting. The second and third experiments were conducted to determine preferred timings in the raising hand greeting with voice greeting. In the second experiment, the beginning time of the robot’s arm motion that is preferred by humans was determined. In the third experiment, the preferred timing of the robot’s voice utterance was determined.

4.1. Beginning of Arm Motion in Case without Voice Utterance

4.1.1. Experimental Method

The analysis result of the raising hand greeting without voice utterance between humans shows that the time gap between the beginning of arm motions by both sides is 0.4 s, as was discussed in the previous section. Therefore, three modes were used based on this result in this experiment. In mode (a), the arm motion of the robot begins simultaneously with the arm motion of the human. In mode (b), the arm motion of the robot begins 0.4 s after the arm motion of the human. The mode is determined based on the result of the analysis of raising hand greetings between humans. In mode (c), the arm motion of the robot begins 0.7 s after the arm motion of the human. In preliminary experiments, the minimum time for many humans to recognize the difference in the robot motion is 0.3 s. Therefore, each mode is shifted 0.3 s or more.

Prior to the experiment, the contents of the experiment and questionnaires were explained to the research participants. Furthermore, they practiced a raising hand greeting with the robot using all modes for a sufficient amount of time. However, the differences between modes were not revealed to them. In the experiment, a paired comparison was performed for all six pairs of mode combinations, and then a seven-point bipolar rating on a scale from -3 (not at all) to 3 (extremely) was determined for the following five items: “Ease of greeting,” “Comfortable velocity,” “Security,” “Politeness,” and “Comfortable vitality.” The research participants used the modes randomly. The research participants were 30 healthy students aged between 20 and 24.

4.1.2. Experimental Results

(1) Paired comparison

Table 2 presents the results of the obtained paired comparison. It lists the number of research participants that preferred the row mode to the column mode. From this table, it is indicated that mode (b) was preferred by the largest number of research participants. Furthermore, the Bradley-Terry model (Bradley, et al., 1952) was fitted to the results for a quantitative analysis using Eq. (1).

\[ P_{ij} = \frac{\pi_i}{\pi_i + \pi_j} \]  
\[ \sum_i \pi_i = \text{Const. (}= \text{Total : 100}) \]

\( \pi_i \) is the intensity of the preference for model \( i \). \( P_{ij} \) is the probability of the judgment that \( i \) is better than \( j \).

Using this model, the results of the paired comparison are expressed by the intensity of preference \( \pi \), as illustrated in Fig. 9. The suitability of the model was validated by the goodness-of-fit and likelihood ratio tests. The figure indicates that mode (b) was rated as the best mode.
### Table 2 Result of paired comparison.

|       | (a) | (b) | (c) | Total |
|-------|-----|-----|-----|-------|
| (a)   | 13  | 31  |     | 44    |
| (b)   | 47  | 50  |     | 97    |
| (c)   | 29  | 10  |     | 39    |

(2) Seven-point bipolar rating

The result of the seven-point bipolar rating is shown in Fig. 10. In the figure, the markers indicate the mean value and the vertical bars indicate the standard deviation for each item. Based on the results of Friedman Test, mode (b) was evaluated as better than modes (a) and (c) with a significant difference of less than 1% on the “Ease of greeting,” “Comfortable velocity,” and “Comfortable vitality” items. These results agree with the result shown in the Bradley-Terry model. Therefore, based on these results, mode (b) is the most preferred mode among the three modes.

This result indicates that many humans prefer the raising hand greeting without voice utterance wherein the robot begins its arm motion 0.4 s after the beginning of the human’s arm motion. This motion characteristic is the same as that between humans.

4.2. Beginning of Arm Motion in Case with Voice Utterance

4.2.1. Experimental Method

To determine the beginning time of the robot’s arm motion that is preferred by many humans, an experiment was conducted on raising hand greetings with voice utterance. The result of the analysis of raising hand greetings with voice utterance between humans shows that the time gap between the beginning of arm motions of both sides is 0.6 s. Therefore, three modes were used based on these results. In mode (a), the arm motion of the robot begins simultaneously with the arm motion of the human. In mode (b), the arm motion of the robot begins 0.3 s after the arm motion of the human. In mode (c), the arm motion of the robot begins 0.6 s after the arm motion of the human. The mode is determined based on the analysis of the results of raising hand greetings between humans. For each mode, the robot utters its voice greeting 0.6 s after the beginning of its arm motion, in accordance with the result of the analysis. The human participants and the robot uttered “Yoroshiku” in Japanese meaning “Hello” in English.

The experiment was conducted with a method similar to that presented in the previous raising hand greeting without voice utterance experiment.

4.2.2. Experimental Results

(1) Paired comparison

Table 3 presents the results of the obtained paired comparison. Figure 11 shows the results fitted into the Bradley-Terry model. It indicates that mode (b) was rated as the best mode.

(2) Seven-point bipolar rating

The result of the seven-point bipolar rating is shown in Fig. 12. In the figure, the markers indicate the mean value and the vertical bars indicate the standard deviation for each item. Based on the results of Friedman Test, mode (b) was evaluated as better than modes (a) and (c) with a significant difference of less than 1% and 5% on the “Ease of occasion this is not a research question, it is a summary of a research paper. The paper discusses the development of a robot for raising hand greetings and compares different modes of the robot’s arm motion. The study includes paired comparison and seven-point bipolar rating methods to evaluate the preferences of humans. Two sections, 4.1 and 4.2, present different approaches to evaluating the robot’s arm motion.

**Section 4.1: Experiment without Voice Utterance**

#### Table 2: Result of paired comparison.

|       | (a) | (b) | (c) | Total |
|-------|-----|-----|-----|-------|
| (a)   | 13  | 31  |     | 44    |
| (b)   | 47  | 50  |     | 97    |
| (c)   | 29  | 10  |     | 39    |

**Section 4.2: Experiment with Voice Utterance**

#### Table 3: Result of paired comparison.

|       | (a) | (b) | (c) | Total |
|-------|-----|-----|-----|-------|
| (a)   | 13  | 31  |     | 44    |
| (b)   | 47  | 50  |     | 97    |
| (c)   | 29  | 10  |     | 39    |

**Fig. 9: Result of Bradley-Terry model.**

(2) Seven-point bipolar rating

The result of the seven-point bipolar rating is shown in Fig. 10. In the figure, the markers indicate the mean value and the vertical bars indicate the standard deviation for each item. Based on the results of Friedman Test, mode (b) was evaluated as better than modes (a) and (c) with a significant difference of less than 1% on the “Ease of greeting,” “Comfortable velocity,” and “Comfortable vitality” items. These results agree with the result shown in the Bradley-Terry model. Therefore, based on these results, mode (b) is the most preferred mode among the three modes.

This result indicates that many humans prefer the raising hand greeting without voice utterance wherein the robot begins its arm motion 0.4 s after the beginning of the human’s arm motion. This motion characteristic is the same as that between humans.

**Fig. 10: Result of seven-point bipolar rating.**

(2) Seven-point bipolar rating

The result of the seven-point bipolar rating is shown in Fig. 10. In the figure, the markers indicate the mean value and the vertical bars indicate the standard deviation for each item. Based on the results of Friedman Test, mode (b) was evaluated as better than modes (a) and (c) with a significant difference of less than 1% on the “Ease of greeting,” “Comfortable velocity,” and “Comfortable vitality” items. These results agree with the result shown in the Bradley-Terry model. Therefore, based on these results, mode (b) is the most preferred mode among the three modes.

This result indicates that many humans prefer the raising hand greeting without voice utterance wherein the robot begins its arm motion 0.4 s after the beginning of the human’s arm motion. This motion characteristic is the same as that between humans.

**Fig. 11: Result of Bradley-Terry model.**

4.2. Beginning of Arm Motion in Case with Voice Utterance

4.2.1. Experimental Method

To determine the beginning time of the robot’s arm motion that is preferred by many humans, an experiment was conducted on raising hand greetings with voice utterance. The result of the analysis of raising hand greetings with voice utterance between humans shows that the time gap between the beginning of arm motions of both sides is 0.6 s. Therefore, three modes were used based on these results. In mode (a), the arm motion of the robot begins simultaneously with the arm motion of the human. In mode (b), the arm motion of the robot begins 0.3 s after the arm motion of the human. In mode (c), the arm motion of the robot begins 0.6 s after the arm motion of the human. The mode is determined based on the analysis of the results of raising hand greetings between humans. For each mode, the robot utters its voice greeting 0.6 s after the beginning of its arm motion, in accordance with the result of the analysis. The human participants and the robot uttered “Yoroshiku” in Japanese meaning “Hello” in English.

The experiment was conducted with a method similar to that presented in the previous raising hand greeting without voice utterance experiment.

4.2.2. Experimental Results

(1) Paired comparison

Table 3 presents the results of the obtained paired comparison. Figure 11 shows the results fitted into the Bradley-Terry model. It indicates that mode (b) was rated as the best mode.

(2) Seven-point bipolar rating

The result of the seven-point bipolar rating is shown in Fig. 12. In the figure, the markers indicate the mean value and the vertical bars indicate the standard deviation for each item. Based on the results of Friedman Test, mode (b) was evaluated as better than modes (a) and (c) with a significant difference of less than 1% and 5% on the “Ease of occasion this is not a research question, it is a summary of a research paper. The paper discusses the development of a robot for raising hand greetings and compares different modes of the robot’s arm motion. The study includes paired comparison and seven-point bipolar rating methods to evaluate the preferences of humans. Two sections, 4.1 and 4.2, present different approaches to evaluating the robot’s arm motion.

**Section 4.1: Experiment without Voice Utterance**

#### Table 2: Result of paired comparison.

|       | (a) | (b) | (c) | Total |
|-------|-----|-----|-----|-------|
| (a)   | 13  | 31  |     | 44    |
| (b)   | 47  | 50  |     | 97    |
| (c)   | 29  | 10  |     | 39    |

**Section 4.2: Experiment with Voice Utterance**

#### Table 3: Result of paired comparison.

|       | (a) | (b) | (c) | Total |
|-------|-----|-----|-----|-------|
| (a)   | 13  | 31  |     | 44    |
| (b)   | 47  | 50  |     | 97    |
| (c)   | 29  | 10  |     | 39    |
Table 3 Result of paired comparison.

|    | (a) | (b) | (c) | Total |
|----|-----|-----|-----|-------|
| (a)| 8   | 13  | 21  |       |
| (b)| 52  | 43  | 95  |       |
| (c)| 47  | 17  | 64  |       |

Fig. 11 Result of Bradley-Terry model.

Fig. 12 Result of seven-point bipolar rating.

4.3. Voice Utterance during Raising Hand Greeting

4.3.1. Experimental Method

An experiment was conducted to determine the timing of the robot’s voice greeting that is preferred by many humans. The results of the analysis of raising hand greetings with voice utterance between humans show that the time gap between the beginning of arm motion of the requesting side and voice utterance by the responding side is 1.2 s. Furthermore, the time gap between the beginning of arm motion and voice utterance by the responding side in interactions between humans is 0.6 s. In addition, from the previous experimental result, many humans prefer a time gap between the beginning of arm motions of both sides of 0.3 s. Therefore, it is considered that humans prefer the uttered voice to begin 0.9 s after beginning of the arm motion by the responding side in the raising hand greeting between a human and a robot.

Three modes were employed based on these results. In mode (a), the robot utters its voice greeting 0.6 s after the beginning of human’s arm motion. In mode (b), the robot utters its voice greeting 0.9 s after the beginning of human’s arm motion. In mode (c), the robot utters its voice greeting 1.2 s after the beginning of human’s arm motion. In this experiment, the robot began its arm motion 0.3 s after the beginning of human’s arm motion.

The experimental conditions remained similar to those of the above-described experiments.

4.3.2. Experimental Results

(1) Paired comparison

Table 4 presents the results of the obtained paired comparison. Figure 13 shows the results fitted into the Bradley-Terry model. It indicates that mode (b) was rated as the best mode.
### Table 4 Result of paired comparison.

|     | (a) | (b) | (c) | Total |
|-----|-----|-----|-----|-------|
| (a) | 21  | 38  | 59  |       |
| (b) | 39  | 47  | 86  |       |
| (c) | 22  | 13  | 35  |       |

#### (2) Seven-point bipolar rating

The result of the seven-point bipolar rating is shown in Fig. 14. In the figure, the markers indicate the mean value and the vertical bars indicate the standard deviation for each item. Based on the results of Friedman Test, mode (b) was evaluated as better than mode (a) with a significant difference of less than 5% on the “Comfortable velocity” item. Furthermore, mode (b) was evaluated as better than mode (c) with a significant difference of less than 5% on the “Ease of greeting” item. These results agree with the result obtained with the Bradley-Terry model and reveal that mode (b) was the most preferred mode between the three modes.

From this result, it is indicated that many humans prefer the raising hand greeting with voice utterance wherein the robot utters its voice greeting 0.9 s after the beginning of the human’s arm motion. This motion characteristic is different from that between humans. The time is shorter than that between humans. However, the time is consistent with that based on the time gap between the beginning of the arm motion and voice utterance by the responding side. Therefore, it is revealed that the timing of voice greeting is related to the beginning of arm motion.

#### 4.4. Consideration of Experimental Results

In the case of raising hand motion without voice utterance, the motion characteristic of the robot that is preferred by humans is when the arm motion of the robot begins 0.4 s after the beginning of the arm motion of the requesting human. This result indicates that the motion characteristics preferred by humans in raising hand greetings in both human-human and human-robot interactions are similar for the environment without voice utterance.

In the case of raising hand motion with voice utterance, the motion characteristic of the robot that is preferred by humans is when the arm motion of the robot begins 0.3 s after the beginning of the arm motion of the requesting side, followed by voice utterance that starts 0.6 s after the beginning of the arm motion of the responding robot. This result indicates that the beginning of the arm motion of a robot preferred by a human is 0.3 s faster than that preferred in human-human interactions in raising hand greetings. Furthermore, this also confirms that the voice utterance begins after the arm motion when responding to a raising hand request.

### 5. Preferred Motion Characteristics of Embodied Interactions

To analyze the difference in motion characteristics depending on the presence or absence of physical contact, the handshake and the raising hand greeting are compared.

#### 5.1. Preferred Motion Characteristics of Handshake

In our previous research, the handshake response motions between humans were analyzed and a handshake response motion model was proposed for handshake robot systems (Jindai, et al., 2008). Furthermore, using a handshake robot
system that employed the proposed model, the motion characteristics preferred by many humans were analyzed. The robot arm of the handshake robot system is the same as that of the robot system in this research. In the handshake motion between a human and the robot, the motion characteristics that are preferred by many humans are as follows.

5.1. Handshake Motion without Voice Utterance

In the handshake response motion without voice utterance, humans prefer a handshake motion wherein the robot arm motion begins 0.1 s after the beginning of the human arm motion.

5.1.2. Handshake Motion with Voice Utterance

In the handshake response motion with voice utterance, humans prefer a handshake motion wherein the robot arm motion begins 0.2 s after the beginning of the human arm motion. Furthermore, the robot utters its voice greeting simultaneously with the beginning of the human arm motion. Therefore, humans prefer a handshake motion wherein the voice utterance is faster than the beginning of the arm motion.

5.2. Consideration of Preferred Motion Characteristics

Figures 15 and 16 show the timings in cases without and with a voice utterance, respectively. In the case without a voice utterance, when a robot responds to an embodied interaction without a contact such as a raising hand greeting, the motion wherein the robot arm motion begins 0.4 s after the beginning of the human arm motion is preferred by humans. However, when the robot responds to an embodied interaction with a contact such as a handshake, a motion wherein the robot begins its arm motion 0.1 s after the beginning of the human arm motion is preferred by humans.

In addition, in the case with a voice utterance, when a robot responds to a raising hand greeting by a human, the motion wherein the robot begins its arm motion 0.3 s and its voice utterance 0.9 s after the beginning of the human arm motion is preferred by humans. Yamamoto reported that humans prefer the robot’s action to start 0.3 s or more before the robot’s utterance in bow greetings between a human and a robot (Yamamoto, et al., 2004). The bow greeting is an embodied interaction without a physical contact. Therefore, this report agrees with the result of the raised hand greeting between a human and a robot. On the other hand, when a robot responds to a handshake interaction with a human, the motion wherein the robot begins its arm motion 0.2 s after the beginning of the human arm motion is preferred by humans. In particular, humans prefer when the voice utterance of the robot starts before the beginning of its arm motion.

From the above results, it is considered that the motion characteristics preferred by humans change depending on the presence or absence of physical contact when the robot responds to human greeting interactions. In embodied interactions using upper arms, a case with contact tend to begin earlier than a case without contact. Therefore, it is considered that the robot needs to cooperate with the human motion instantaneously for mutual contact in embodied interactions using upper arms.

In addition, in embodied interactions using upper arms with voice greetings, humans prefer the robot’s arm motion to start before the robot’s voice utterance when the robot responds to an interaction without contact (arm motion precedence). However, when a robot responds to an interaction with contact, humans prefer the robot’s voice utterance to start before the beginning of its arm motion (voice utterance precedence). Therefore, it is indicated that the order of the arm motion and the voice utterance should be changed depending on the presence or absence of physical contact in embodied interactions using upper arms.

Furthermore, comparing the embodied interactions between humans with that between a robot and a human, basic
motion characteristics such as the voice utterance precedence or the arm motion precedence are not changed. However, the timings are different. Therefore, for the generation of embodied interactions that are preferred by humans, it is necessary to adjust these timings of the robot according to environments of interactions.

6. Conclusion

This study analyzed the differences in motion characteristics of robots that are preferred by humans in embodied interactions using upper arms between a human and a robot depending on the presence or absence of physical contact. First, in a raising hand greeting between humans, which is an embodied interaction without physical contact, the motion characteristics were analyzed. Then, based on this analysis, the motion characteristics of the robot preferred by humans were clarified by sensory evaluations in this greeting. Finally, in order to clarify the differences in the preferred motion characteristics with the presence or absence of physical contact, these motion characteristics were compared with the robot’s motion characteristics preferred by humans in handshake motions, which is an embodied interaction with physical contact.

From experimental results, this study clarified follows.

- The basic motion characteristics preferred by humans in embodied interactions using upper arms in both human-human and human-robot interactions are similar. However, the time gap of beginning of arm motions which is preferred by humans is shorter for human-robot interactions than human-human interactions in the raising hand greetings with voice greetings. Therefore, for the generation of embodied interactions using upper arms, motion characteristics of the robot can be determined by referring to those of human-human embodied interactions. However, it is necessary to adjust them according to environments of interactions.

- Motion characteristics of robots preferred by humans change depending on the presence or absence of physical contact when the robot responds to human greeting interactions. In embodied interactions using upper arms, responses of robots tend to begin earlier in a case with contact than without contact. Therefore, robots need to cooperate with human motions instantaneously for mutual contact in embodied interactions using upper arms.

- In embodied interactions using upper arms with voice greetings, humans prefer the robot’s arm motion to start before the robot’s voice utterance when the robot responds to an interaction without contact (arm motion precedence). However, when a robot responds to an interaction with contact, humans prefer the robot’s voice utterance to start before the beginning of its arm motion (voice utterance precedence). Therefore, the order of the arm motion and the voice utterance should be changed depending on the presence or absence of physical contact in embodied interactions using upper arms.

Acknowledgments

This work was supported by KAKENHI Grant Number 18K11393 of the Japan Society for the Promotion of Science (JSPS), Japan.

References

Avraham, G., Nisky, I., Fernandes, H. L., Acuna, D. E., Kording, K. P. and Loeh, G. E., Toward Perceiving Robots as Humans: Three Handshake Models Face the Turing-Like Handshake Test, IEEE Transactions on Haptics, Vol.5, No.3 (2012), pp.196-207.

Bevan, C. and Fraser, D. S., Shaking Hands and Cooperation in Tele-present Human-Robot Negotiation, Proceedings of the 10th Annual ACM/IEEE International Conference on Human-Robot Interaction (2015), pp. 247-254.

Bradley, R. A. and Terry, M. E., Rank analysis of incomplete block designs, Biometrika, Vol.39 (1952), pp.324-345.

Crusco, A. H. and Wetzel, C. G., The Midas Touch: The effects of interpersonal touch on restaurant tipping, Personality and Social Psychology Bulletin, Vol.10, No.4 (1984), pp.512-517.

Flash, T. and Hogan, N., The Coordination of Arm Movements: An Experimentally Confirmed Mathematical Model, Journal of Neurosciences, Vol.5, No.7 (1985), pp.1688-1703.

Jindai, M., Ota, S., Yasuda, T. and Sasaki, T., Hug Behavior Response Model for Generation of Hug Behav-
ior with Humans, Journal of Advanced Mechanical Design, Systems, and Manufacturing, Vol.12, No.2 (2018), DOI:10.1299/jamdsm.2018jamdsm0035

Jindai, M. and Watanabe, T., Development of a Handshake Request Motion Model Based on Analysis of Handshake Motion between Humans, Proceedings of the 2011 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (2011), pp.560-565.

Jindai, M., Watanabe, T., Shibata, S. and Yamamoto, T., Development of a Handshake Robot System Based on a Handshake Approaching Motion Model, Journal of Robotics and Mechatronics, Vol.20, No.4 (2008), pp.650-659.

Jindai, M., and Watanabe, T., Development of a Handshake Robot System Based on a Handshake Approaching Motion Model, Proceedings of 2007 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, (2007), DOI:10.1109/AIM.2007.4412423

Kanda, T., Miyashita, T., Osada, T., Haikawa, Y. and Ishiguro, H., Analysis of Humanoid Appearances in Human-Robot Interaction, IEEE Transactions on Robotics, Vol.24, No.3 (2008), pp.725-735.

Kouchi, M., Mochimaru, M., Iwasawa, H. and Mitani, S., Anthropometric Database for Japanese Population, Japanese Industrial Standards Center 1997–98 (AIST,MITI) (2000).

Nakagawa, K., Shiomi, M., Shinozawa, K., Matsumura, R., Ishiguro, H. and Hagita, N., Effect of Robot’s Whispering Behavior on People’s Motivation, International Journal of Social Robotics, Vol.5, No.1 (2012), pp.5-16.

Onishi, M., Luo, Z., Odashima, T., Hirano, S., Tahara, K. and Mukai, T., Generation of Human Care Behaviors by Human-Interactive Robot RI-MAN, Proceedings of 2007 IEEE International Conference on Robotics and Automation (2007), pp.3128-3129.

Ota, S., Jindai, M., Fukuta, T. and Watanabe, T., Small-sized handshake robot system for generation of handshake behavior with active approach to human, Journal of Advanced Mechanical Design, Systems, and Manufacturing, Vol.13, No.2 (2019), DOI:10.1299/jamdsm.2019jamdsm0026

Rani, P., Sarkar, N., and Smith, C. A., Affect-Sensitive Human-Robot Cooperation -Theory and Experiments, Proceedings of the 2003 IEEE International Conference on Robotics & Automation (2003), pp.2382-2387.

Shiomi, M., Nakata, A., Kanbara M. and Hagita, N., A hug from a robot encourages prosocial behavior, Proceedings of The 26th IEEE International Symposium on Robot and Human Interactive Communication (2017), pp.418-423.

Yamamoto, M. and Watanabe, T., Timing control effects of utterance to communicative actions on embodied interaction with a robot, Proceedings of the 13th IEEE International Workshop on Robot and Human Interactive Communication (2004), pp.467-472.

Zheng, Z., Das, S., Young, E., Swanson, A., Warren, Z. and Sarkar, N., Autonomous robot-mediated imitation learning for children with autism, Proceedings of 2014 IEEE International Conference on Robotics and Automation (2014), pp.2707-2712.