International Journal of Social Robotics
https://doi.org/10.1007/s12369-018-0495-2

Softness, Warmth, and Responsiveness Improve Robot Hugs

Alexis E. Block[1,2,3] · **Katherine J. Kuchenbecker**[1,2,3]

Accepted: 5 October 2018

Abstract
Hugs are one of the first forms of contact and affection humans experience. Due to their prevalence and health benefits, roboticists are naturally interested in having robots one day hug humans as seamlessly as humans hug other humans. This project's purpose is to evaluate human responses to different robot physical characteristics and hugging behaviors. Specifically, we aim to test the hypothesis that a soft, warm, touch-sensitive PR2 humanoid robot can provide humans with satisfying hugs by matching both their hugging pressure and their hugging duration. Thirty relatively young and rather technical participants experienced and evaluated twelve hugs with the robot, divided into three randomly ordered trials that focused on physical robot characteristics (single factor, three levels) and nine randomly ordered trials with low, medium, and high hug pressure and duration (two factors, three levels each). Analysis of the results showed that people significantly prefer soft, warm hugs over hard, cold hugs. Furthermore, users prefer hugs that physically squeeze them and release immediately when they are ready for the hug to end. Taking part in the experiment also significantly increased positive user opinions of robots and robot use.

Keywords Physical human–robot interaction · Social robotics · System evaluation

1 Introduction

Hugging another person gives each participant social support, relieves stress, lowers blood pressure, and increases oxytocin levels [7]. With the health benefits and prevalence of hugs in daily human interactions, it is natural that roboticists have tried to artificially create this gesture. A major challenge of mechanizing hugs is the safety and comfort of the human during this intimate exchange. Researchers, therefore, have taken many different approaches, as summarized in Sect. 2.

One related non-robotic approach is the creation of inflatable or weighted vests and jackets to help calm children with sensory processing disorder, children with attention deficit hyperactivity disorder, and individuals with autism spectrum disorder [37]. Deep touch pressure, the kind received from hugging or firmly touching, has been shown to relieve anxiety for people with these disorders [19]. Because they require a loud pump and air flow, inflatable garments are often obtrusive and conspicuous. Inflatable or pressurized vests can also be activated remotely by a parent or instructor at any time [12]. In this instance, the child may not understand the cause of the hug. Additionally, weighted vests must constantly be removed to alleviate the pressure and then replaced. A similar invention called the "Squeeze Machine" applies lateral deep touch pressure by squeezing a user between two foam panels [15]. Patients on the autism spectrum, non-autistic college students, and animals all experienced similar calming effects. The Squeeze Machine is operated by the user, who can control the applied pressure and duration of the encounter, gradually building up over time as he or she becomes more comfortable. While these artificial hug recreations lack the primary component of a second partner, they do address the importance of physical touch.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s12369-018-0495-2) contains supplementary material, which is available to authorized users.

✉ Alexis E. Block
alexis@is.mpg.de

Katherine J. Kuchenbecker
kjk@is.mpg.de

1 Haptics Group, GRASP Laboratory, University of Pennsylvania, Philadelphia, USA

2 Haptic Intelligence Department, Max Planck Institute for Intelligent Systems, Stuttgart, Germany

3 Max Planck ETH Center for Learning Systems, Zurich, Switzerland

Published online: 25 October 2018

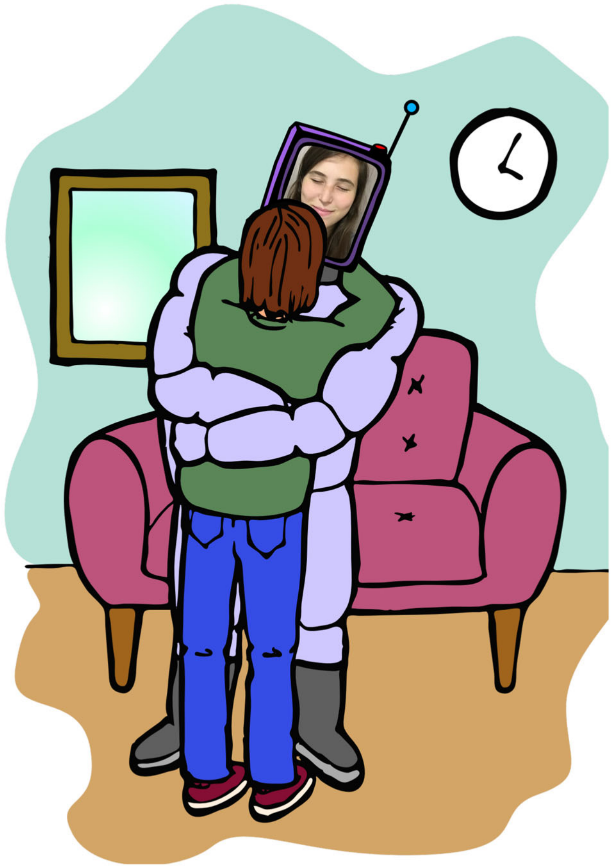

Fig. 1 An artistic rendering of the end goal of this project: a social humanoid robot that can capably hug humans in everyday settings. The screen shows a video message from the person who sent a customized hug to the human participant. Further discussion of the situation depicted in this image can be found in Sect. 9

Physical properties of objects strongly affect how contact interactions are perceived. Harlow and Zimmermann's [16] work with infant Rhesus monkeys strongly influenced this project. When given the choice of which surrogate mother they preferred, a wire mother who fed them, or a cloth mother who did not, overwhelmingly the infants chose the cloth mother. A similar phenomenon can be observed in human children, who prefer to sleep with plush comfort objects or blankets because of the emotional attachment they develop to the experience of softness [22]. These studies inspired our interest in robot softness.

Another comforting physical property that often accompanies softness is warmth. Williams and Bargh [40] ran a set of experiments on this topic; in Study 1 subjects briefly held a cup of warm or iced coffee and were then asked to judge a target person's personality. Participants who held the warm cup of coffee associated warmer personality traits (generous, caring, etc.) to the target person than their cold coffee counterparts. Note that replication of the results of Study 2, which measured a person's subsequent tendency toward prosocial behavior, was not upheld by Lynott et al. [21]. To the best of our knowledge, researchers have have not had difficulty replicating the Study 1 finding that humans associate social warmth with warm physical contact. Indeed, Lakoff and Johnson [20] have suggested that these two experiences go hand in hand: because we receive them simultaneously so often as children, when we experience physical warmth (a warm hug or being wrapped in a blanket), we associate it with feelings of social warmth (love). These non-robotic studies inspired the integration of heat into this experiment.

This research sought to understand the optimal way in which a robot should hug a human, which is a delicate social-physical interaction (Fig. 1). This project builds on previous work in the field of social human–robot interaction (HRI), as discussed in Sect. 2. Section 3 outlines the four hypotheses tested. A description of the robot outfits created, sensors used, and robot programs developed can be read in Sect. 4. Details of the experiment setup and participant breakdown can be found in Sect. 5. Results from the experiment are presented in Sect. 6 and discussed in Sect. 7. Section 8 presents our conclusions, and Sect. 9 addresses several ways in which we hope to expand this work in the future.

2 Related Work

Interactions between humans and robots have intrigued researchers for quite some time. The prior investigations of robots in social-physical contexts detailed below have greatly inspired this project.

2.1 Robot Social Interaction

Improving the sociability of robots has interested many researchers. Most often, robots do not physically interact with people, but rather they use verbal or non-verbal cues to achieve more natural human–robot interactions. In one study about HRI in the wild, Garrell et al. [14] found that more non-contact human–robot interactions occurred when the robot initiated the conversation. People also felt the interaction was more natural when the robot gestured or initiated engagement. Such movements led the human to perceive the robot as having a higher level of intelligence or sociability. From this research, we learn that it is important to have our robot ask for a hug and gesture to the human, to increase the naturalness of the exchange.

In human–human exchanges like conversations, one often attempts to match the level of enthusiasm of their partner [2]. This phenomenon is often referred to as "The Chameleon Effect" [4]. Anzalone et al. [1] replicated this finding with a robot: they programmed a robot to estimate the level of extraversion of their human partner and adapt its personality/behavior to better match that of the human. The humans perceived the robot to have higher social intelligence when it matched their level of extraversion compared to when the robot did not. We somewhat apply this technique to our own research by having conditions that terminate the hug based on user input.

2.2 Robotic Touch

Some researchers focus on the how robots look and behave, but another important area of study is how robots feel. Shiomi et al. [31] were interested in the connection between human–robot physical interaction and human effort. They gave participants a monotonous task to complete either with or without touch interactions from a robot. In cases with touch interactions, the robot held out its hand and asked the participant to hold it. In this case, the contact was initiated by the human, who then moved to hold the robot's hand. The researchers found that when contact occurred, the effort exerted by the human increased, both in terms of the number of actions taken and the length of time they worked. Thus, a hugging robot may be positively perceived and could be used in physical therapy or exercise to encourage human effort.

In contrast to the human-initiated touch described above, Chen et al.'s [5] research featured robot-initiated touch in a clinical setting. While in some cases the robot gave a warning before touching the person, it differs from Shiomi et al.'s experiment because the robot reached to touch the participant, rather than having him/her contact the robot first. In this case, the robot touched a subject's arm to either clean or comfort. Subjects preferred instrumental (cleaning) touch over affective (comforting) touch, which is the same result found between patients and human nurses. The perceived intent of the robot greatly affects the participant's acceptance of the touch. In robot-initiated touch, the authors suggest that any warning prior to contact should be carefully worded. It appears human-initiated contact with a robot is more readily accepted. Taking this preference into account, our experiment features human-initiated contact. The robot first asks the participant for a hug, then the participant must walk to the robot for the hug.

While Chen et al. found that human-initiated touch is preferred in a clinical setting, Cramer [10] et al. were interested in what touch is preferred in a more relaxed setting. Cramer et al.'s research featured three robot-initiated contacts, one human-initiated contact, and a no contact situation. These researchers found that users preferred when the touch was robot-initiated rather than human-initiated. Users who already had a positive attitude towards robots in general perceived a closer personal connection with the robot. These participants also found robots that interact by touch to be more natural than robots that don't.

The tactile experience of the user is not limited to who or what initiates contact; the physical qualities and visual appearance of that contact also matter. Williams and Bargh's coffee temperature result was confirmed in robotics when Park and Lee [28] altered the skin temperature of a dinosaur robot. They found user perceptions of the sociability of the robot increased with warmth. Nie et al. [27] found similar results when participants watching a horror movie either held hands with a warm robot, held hands with a cold robot, or did not hold hands at all. Participants who experienced physical warmth viewed the robot with increased friendship and trust. Furthermore, using a very mechanical looking robot (RoboSapien) to perform a human-like interaction yielded negative reactions from participants in this experiment. These results led us to cover our mechanical looking robot with fuzzy clothes. The user acceptance and enjoyment benefits of warmth in both Park and Lee's and Nee et al.'s studies led us to examine the impact of robot warmth in our study of robot hugging

2.3 Robot Touch for Social Enjoyment

A common way humans warm up to each other is by interacting physically for social enjoyment, through activities such as high-fives, games, and dancing. Several researchers have focused on the social aspects of physical human–robot interactions by attempting to recreate these common forms of expression. For example, Romano and Kuchenbecker's [30] demonstration with the PR2 included a range of social-physical interactions like high fives, fist bumps, and hugs. Their robot hug was used as a starting point for this research. Fitter and Kuchenbecker [13] studied human–human play in order to program the Baxter robot to play hand-clapping games with humans. Both these projects attempt to recreate a fun human–human interaction with a robot.

Partner dancing is an intimate social-physical interaction that researchers have recreated by replacing one human with a robot. Peng et al. [29] discuss the ways that several groups have looked into cooperative human–robot dance. Pattern Ballroom Dance Robot (PBDR) and its prototype, Ms-DanceR, are two waltzing robots created to bring human–robot collaboration closer than ever [18]. These robots have wheels, rather than legs, to avoid the problem of balancing, as well as a small front base, to allow the human to get close enough to the robot for the required dance embrace. The SpiderCrab robot is a robotic arm that uses improvisational dance to interact with its human partners [38]. Dancers feel that because the robot responds to their spontaneous movements, it behaves as a real human dance partner might. A similar responsive element is integrated into our system, with the human being able to control the duration of the hug. Dance and hugs are two different forms of non-verbal social interactions. The various different approaches show there is a desire for more social interactions between humans and robots.

A blend of social interaction and emotional attachment is seen in Sumioka et al.'s [36] research where users had a 15-min conversation with a remote partner on a cell phone or through a huggable human-shaped device. Users who had the conversation via the hugging device showed a significant reduction in cortisol levels (stress hormone) after the conversations compared to their counterparts who spoke on a mobile phone. This positive physical and psychological result demonstrates the power of interpersonal communication and touch.

2.4 Hugging Robots

Interpersonal touch is so essential and beneficial that many researchers have tried to enable robots to personally connect with humans. DiSalvo et al.'s [11] the Hug is a plush comfort object that works in pairs to provide users "tele-hugs". Its shape mimics a child wrapping his/her limbs around an adult. The Hug plays a melody and its stomach glows to alert the user that its partner is sending a hug. While one user strokes his/her Hug, the Hug with the other user vibrates to match. Throughout the course of voice conservations held with the Hug, it will warm up to a comfortable heat. The Hug lacks the ability to wrap its arms tighter around the human, and it requires a human partner for the user to feel emotional support.

Stiehl et al.'s [35] teddy bear robot, the Huggable, employs a more interactive design. Huggable's temperature, force, and electric field sensors are concealed under a layer of silicone and fur for an enjoyable tactile interface. The robot is small enough to be held in a child's arms, it can detect where and how it is being touched, and it can move its head and arms. With cameras, microphones, and a speaker, it records and engages the person using it, while providing helpful information to a remote caregiver. Huggable has sensitive comfortable skin, but it still falls short of accurately replicating a human hug due to its miniature size and the fact that it cannot measure and reciprocate the pressure with which it is being hugged.

On a similar size scale as the Huggable, Cooney et al. [8] worked with a robot called Sponge Robot. These researchers were interested in using internal inertial sensors, rather than external sensors, to recognize what full-body gestures humans were manipulating the robot to do. By observing humans interacting with Sponge Robot in free play, the researchers categorized the 13 most common interactions, which included hugging. Because of its small size, Sponge Robot, like Huggable, is able to be hugged but is unable to hug the user back. Later, Cooney et al. built on this work using both a hand-held robot, Elfoid, and a life-size robot, Kirin [9]. This later work was focused on discovering typical human touches toward a humanoid robot. The 20 most common touches were categorized into "affectionate," "neutral," and "unaffectionate" categories. Hugging was found to be one of the most frequent affectionate touches humans wanted to express. Again, the robots in these studies did not actively hug the participant back; however, the fact hugging was a common interaction in both studies clearly demonstrates a desire among users to express affection to robots through hugging. These two studies support our belief that a robot that hugs users back would be well received.

Shiomi et al. [32,33] ran two Wizard-of-Oz-style experiments with a large teddy bear robot that was covered with polypropylene cotton and had two elbows powered by easily backdrivable motors (for participant safety). The robot always sits on the floor and introduces itself. One experiment varied whether the robot asked the person for a hug after this introduction. The rest of the interaction was a conversation wherein the robot asked the participant to tell stories about him/herself. Significantly longer interaction times and significantly more personal self-disclosure occurred when participants hugged the robot [33]. In the second experiment, the robot requested a hug from all participants, but it reciprocated the hug (squeezed them back) in only some instances. At the end of the subsequent conversation, the robot asked whether the participant would like to donate to earthquake victims. Shiomi et al. [32] found that subjects whose hugs were reciprocated tended to donate more money than those whose hugs were not, although this trend did not reach statistical significance. Participant acceptance of this robot hug behavior encouraged us to use the design as a model for our own experiment.

Miyashita and Ishiguro [23] used a wheeled inverted pendulum humanoid robot that hugs in a three-step process while maintaining its balance. First, the robot opens its arms. The robot measures the distance between itself and the human by ultrasonic range sensors. When the distance is appropriate, the robot wraps its arms around the person. Finally, the robot opens its arms again. This research does not address how the robot determines when to switch between the second and third steps, thereby deciding the duration of the hug. It also appears the robot uses the human to balance itself, which is potentially uncomfortable for humans. It is made of metal without any soft, cushioned material, so the tactile experience may not be enjoyable for the human.

Recently, Yamane et al. [42] submitted a patent for Disney Enterprises, Inc. to create their own version of a huggable robot. This robot is designed for human interaction, presumably within theme parks. It features a rigid structure with specific elements made of softer material to create a deformable exterior in areas that would contact a human. This robot attempts to match the pressure an external user applies using pressure sensors. The wording of the patent is ambiguous as to whether this robot will be autonomous or tele-operated. The physical appearance of this robot matches that of the character Baymax from the Disney movie "Big

Hero 6". This timely patent application supports the belief that there is great interest in furthering human–robot interaction to include more natural physical exchanges, particularly human–robot hugging.

3 Hypotheses

This hypothesis builds on the aforementioned literature and matches common human social conventions to discover which factors can create a comfortable robotic hug. This project tests the hypothesis that *a soft, warm, touch-sensitive humanoid robot can provide humans with satisfying hugs by matching their hugging pressure and duration.* The first two investigated factors pertain to physical aspects of the robot's body, and the second two relate to how it moves during the hug.

The first factor is softness. Whatever object is hugged should be enjoyable to hug, by deforming somewhat, perhaps similar to human tissue. For this experiment, a layer of foam and fluffy fabric covers the robot, similar to DiSalvo et al.'s [11] the Hug. Another part of what makes a hug enjoyable is the warmth from another human body. We thus heat the exterior of the robot by adding heating elements so it is easily recognized as warmer than ambient temperature.

Next, for a robot to give a good hug, we believe it should reciprocate the amount of pressure the human applies (up to a certain threshold for safety). We calibrate the robot to the size of each user, then vary how tightly it hugs the person. The final factor to a good hug is that it lasts an appropriate duration, which may vary for different people. We use tactile sensors to measure when contact is made and broken, and we terminate the hug before, at, or after the user releases the robot.

We break down this overall hypothesis into four sub-statements to better test their validity:

H1 Subjects will prefer hugging a cold, soft robot rather than a cold, hard robot.
H2 Subjects will prefer hugging a warm, soft robot rather than a cold, soft robot.
H3 Subjects will prefer a robot that hugs with a medium amount of pressure, rather than hugging too loosely or too tightly.
H4 Subjects will prefer a robot that releases them from a hug immediately when they indicate they are ready for the hug to be over, rather than the robot releasing the hug before or after this time.

4 System Design and Engineering

This project uses a Willow Garage Personal Robot 2 (PR2) to exchange hugs with human users. As seen in Fig. 2, the PR2 has two seven-degree-of-freedom arms and a head mounted to a torso that can move up and down. Although the robot has a large mobile base, it was kept stationary throughout this study to focus on the main hugging interaction, which is delivered with the arms. The PR2 has a hard metal exterior, with cloth covering some of the arm surfaces.

Three different physical conditions were created, as shown in Fig. 3: a Hard-Cold, a Soft-Cold, and a Soft-Warm robot.

- **Hard-Cold:** The robot does not have any additional padding layers.
- **Soft-Cold:** The robot wears layers of foam, cotton, and purple fluffy polyester.
- **Soft-Warm:** This condition is the same as the Soft-Cold condition with the addition of heat. We made a separate, identical purple fluffy polyester layer. The cords were removed from a Sunbeam Quilted Fleece Heated Blanket (model number BSF9GQS-R727-13A00, 218.44 cm $\times$ 228.60 cm $\times$ 1.27 cm). These cords were then sewn into channels between cotton layers to heat the chest and back of the robot. A Thermophore MaxHeat Deep-Heat heating pad (model number: 155, 68.58 cm $\times$ 35.56 cm $\times$ 1.27 cm) was placed on top of the cotton layer and below the polyester layer on the chest of the robot for added warmth. The final warming components were four chemical warming packs, (model number: TT240-AMZ, 6.98 cm $\times$ 8.64 cm $\times$ 1.27 cm) which were placed on both upper arms and forearms of the robot, on top of the foam and beneath the polyester layer.

A Hard-Warm robot was not tested because the heating elements somewhat soften the robot and divulge the thermal experimental variable to users. The robot outfit was designed to be gender neutral to be more universally accepted and to limit the number of experimental variables.

4.1 Tactile Sensors

In order to tell when users made and broke contact with the robot, we needed a haptic sensor. This project uses Chen et al.'s [6] stretchable tactile sensors. This team created a strain-sensing skin by spray-coating latex with an exfoliated graphite piezoresistive sensing paint. To determine the ideal placement location, initial sensor trials were conducted with the sensor mounted on the robot's chest foam. The sensors were placed in series with a 10 kΩ resistor to act as a voltage divider.

For the final experiment, the tactile sensor was moved from the chest to the back for several reasons. First, the

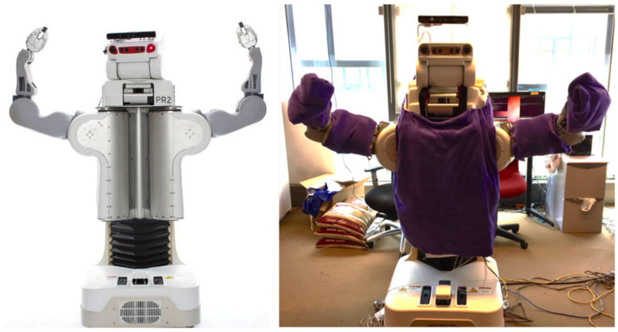

Fig. 2 The left image shows the PR2 in the Hard-Cold condition, and the right image shows the robot in the Soft-Warm condition, wearing the custom-made outfit

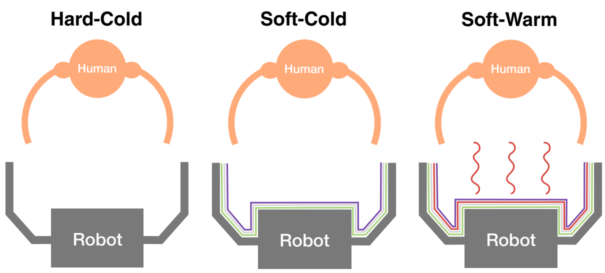

Fig. 3 An overhead view of the three experimental conditions to be tested

base of the PR2 is very large, so a subject had to lean very far towards the robot to make enough contact with the chest-mounted tactile sensor, which some pilot subjects were hesitant to do. Next, the PR2's arms make up the chest area, which rotate as the arms moves. This caused the foam covering the chest area to shift as well. With the foam and sensor pulled between the two arms, it became difficult for a user to make contact with the sensor. Finally, if the robot was hugging in the "too tight" condition and the subject was unable to break contact with the chest sensor, the robot would have no way of knowing when the human wanted to be released from the hug. For these reasons, it was determined that the best location for the sensor would be on the upper back of the robot, where the users' hands would naturally be placed. In this manner, the sensors are able to detect touch through strain that is induced by contact, and had an even stronger signal than the original placement.

To smooth the data, we applied an infinite impulse response low-pass filter. The equation for this filter is as follows:

$$v_{\text{smooth,k}} = w \cdot v_{\text{k}} + (1 - w) \cdot v_{\text{smooth,k}-1} \quad (1)$$

Figure 4 shows the filtered data from the sensor trials using a filter weight w of 0.08, which gives a filter bandwidth of 0.70 Hz. It is important to note that temperature greatly affected the resistance of the sensor, as can be seen by the five unheated trials having higher resistance than the

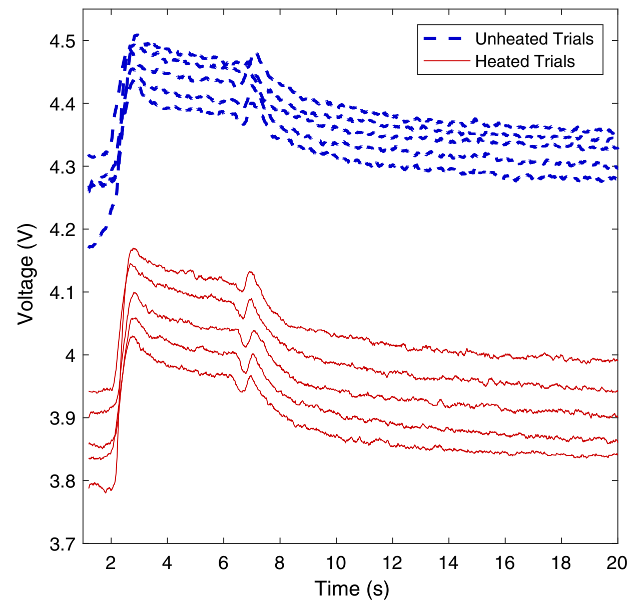

Fig. 4 The filtered data from the unheated and heated tactile sensor trials, with the sensor mounted on the chest

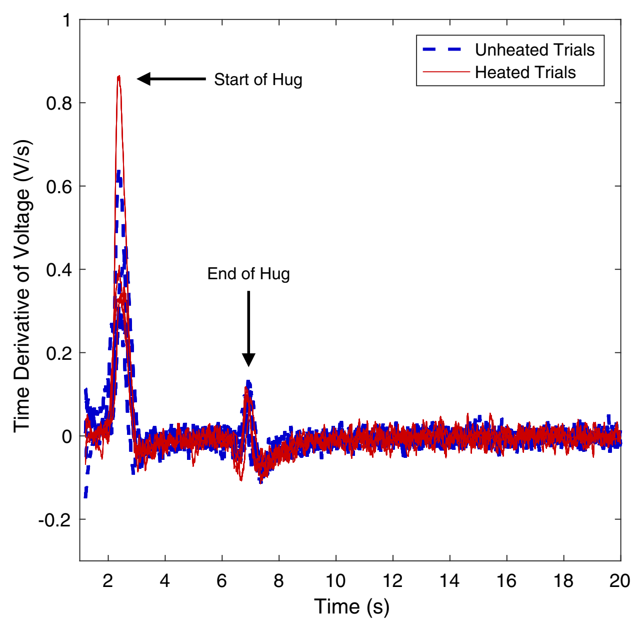

Fig. 5 The derivative of the voltage over time for the tactile sensor trial data, from Fig. 4

five heated trials in Fig. 4. While the magnitude of the heated and unheated trials varied greatly, the overall slope is similar.

Looking at the derivative of the voltage over time collapses all the trials into each other with two defined peaks indicating initiation or conclusion of a hug. Figure 5 shows that the tactile sensor measurements can clearly identify and inform the robot when human contact is made and broken. Using this information, the robot releases the embrace based on the pre-programmed duration with which it is set to hug.

4.2 Robot Program

Starting with the aforementioned demonstration developed by Romano and Kuchenbecker [30], we edited the hug code in several ways to create a more natural hug. An Arduino samples and communicates the tactile sensor data to ROS over serial at 173 Hz, which is then filtered and read into the hug code. Ten different hugs (nine for the behavioral changes, and one used for all three physical changes) were created.

At the start of the experiment, mannequin mode was used to find the joint angles for a comfortable hug based on the participant's body size. These unique joint angles were collected and used for the "just right" hug for each individual.

Decreasing the first angle (shoulder pan) by 0.05 radians, and the fourth angle (elbow flex) by 0.2 radians created the "too tight" hug for the right arm. Increasing these two angles by the same amount created the "too tight" hug for the left arm. The "too loose" hug joint angles were set loose enough so they did not touch any participants; thus they were left standard for all trials, and can be seen below, recorded in radians and rounded to two significant figures.

$$\theta_r = [-0.19, -0.20, -1.25, -1.58, 0.02, -0.49, 0.11]$$
$$\theta_l = [0.17, 0.05, 1.22, -1.35, 1.22, -1.34, -0.83]$$

Even though the robot's arms did not touch any participant, the "too loose" condition can still be considered a hug for several reasons. First, during all hugs, the participant's arms fully encircled and touched the robot. Participants always touched the robot to ensure they would be able to activate the robot's tactile sensor to let it know when to terminate the hug. Therefore, this interaction satisfies the belief that a hug implies touch. Next, the robot's arms moved through the hugging motion and did fully encircle the participant, even though the arms didn't necessarily touch them. The robot was essentially giving the participant an "air hug" in this condition, which is common for people to give each other (for example when a person is sick and you want to comfort them but not get too close or touch so you don't also get sick).

To begin the hug sequence, we added that the robot lifts its arms over the course of 4 s and asks the participant for a hug by saying "Can I have a hug, pleeeease?" After waiting two seconds, the robot then closes its arms for 5 s, using the ROS joint trajectory action, to hug the person according to the pre-assigned condition of pressure to apply. For a too short hug, the robot waits 1 s from when it closes before it releases. Otherwise, the robot continually monitors the derivative of the voltage values until it notices the second spike, with a threshold that was tuned during pilot testing to be 0.2 V/s. For a immediate release hug, it releases immediately when it notices the spike. For a too long hug, the robot releases 5 s after it notices the person releases. After the robot returns to the joint angles associated with the outstretched arms position in which it began (which takes 5 s), the robot drops its arms (which takes 4 s) to mimic a human motion.

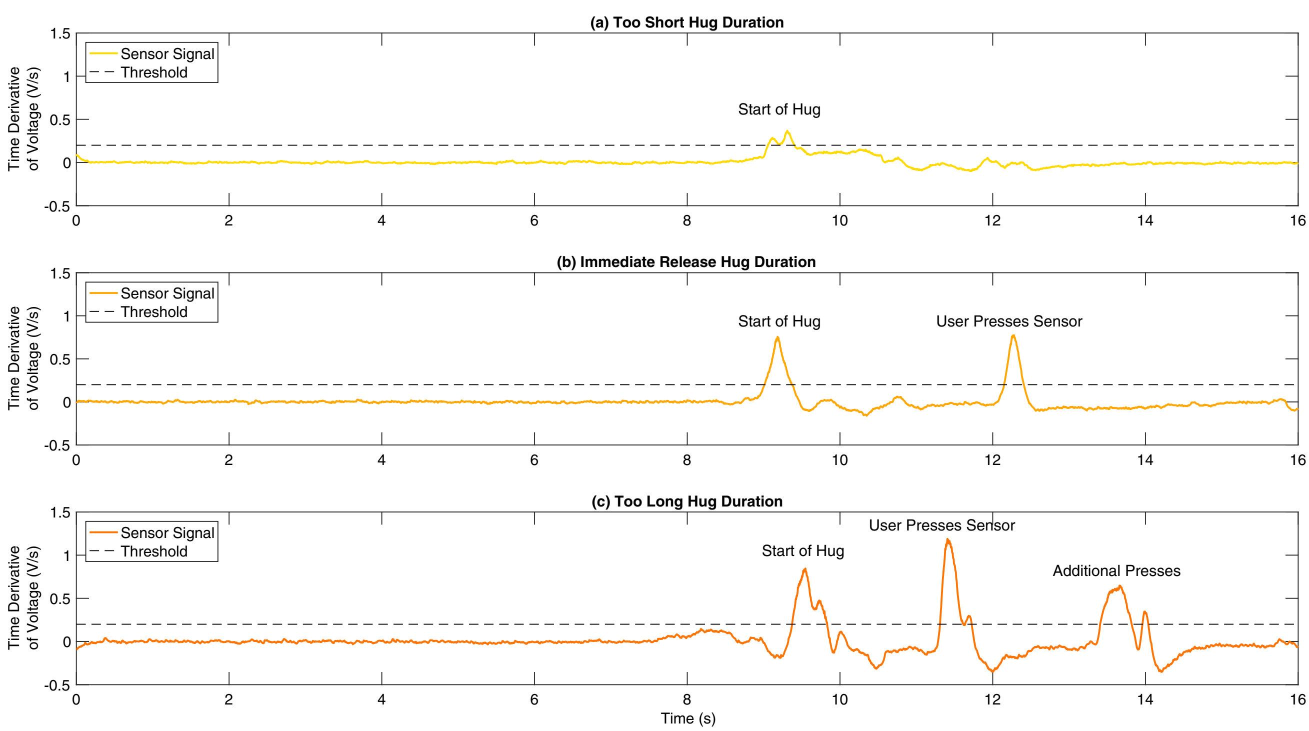

Fig. 6 Tactile sensor data for three randomly selected trials from the experiment. Plot **a** shows a "too short" hug duration trial, plot **b** shows an "immediate release" hug duration trial, and plot **c** shows a "too long" hug duration trial, in which the user worried because the robot wasn't letting go and pressed on the sensor additional times

The success of the experiment relies on the automatic detection of the start and the end of the hug, which is a new component of the system. To verify that this method was reliable, the experimenter monitored the sensor data for every participant for every trial (excluding the Hard-Cold condition, which had no sensor data). No malfunctions were detected. Figure 6 shows the time derivative of the tactile sensor measurements collected during three randomly selected trials to show that automatic detection of the start and end of the hug were reliable. The top plot shows the "too short" hug duration with only one spike at the start of the hug because the robot released before the user was ready to be released. The second plot shows the "immediate release" hug duration with two spikes indicating the start and end of the hug. The bottom plot shows the "too long" hug duration in which the user worried because the robot wasn't letting go and pressed additional times.

5 User Study Methods

All methods for this study were approved by the University of Pennsylvania Institutional Review Board under protocol # 827123. To recruit subjects, the investigator circulated a recruitment email through mailing lists to which our lab has access. Potential subjects read the advertisement and contacted the investigator via email or phone to learn more and possibly schedule an appointment.

5.1 Procedures

A flowchart of the experimental procedure can be found in Fig. 7. After the potential subject arrived at the experiment site, the investigator explained the experiment, using the informed consent form as a guide. The potential subject took several minutes to read over the consent form and ask questions. If he or she still wanted to volunteer, the subject signed the informed consent form. Prior to continuing, the investigator verbally verified that the subject had full use of his or her arms and legs, had no uncorrected vision or hearing impairments, was fluent in English, and was a legal adult. After the subject signed the consent form, the investigator turned on a video camera and began to record the experiment.

Next, the investigator introduced the robot as the personality "HuggieBot" and explained the key features of the Willow Garage PR2, such as the two emergency stops, one located on the back of the robot, the other on a remote control. The investigator introduced the subject to the procedure and explained how the trials work and how the subject should be prepared to move. The subject was taught the involved hug motions in this step. The PR2 was then customized to the size of the subject, while wearing its Soft-Cold outfit. By having the subject stand in front of the robot, the experimenter raised or lowered the body of the PR2 until the subject said the robot's eye cameras were at his/her eye level. Then, the robot was put in mannequin mode and the arms were manually placed in a comfortable hug around the subject. The joint angles for this specific motion were collected.

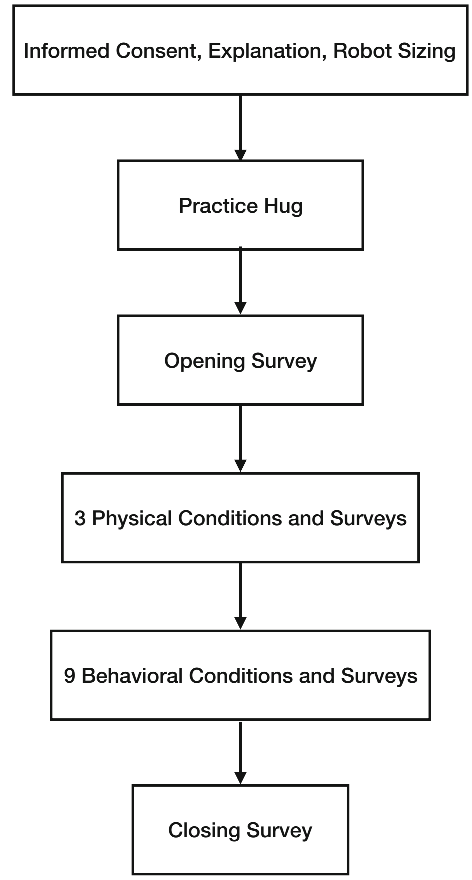

Fig. 7 A flowchart of the experimental procedure

Finally, the subject was reminded of the possibility to terminate the experiment or the robot's movement at any time by verbal request. The investigator then prepared the robot for the first of the three physical attribute trials. While the experimenter was making the necessary changes, the subject was instructed to complete an opening survey based on their initial impressions of the robot. The questionnaire asked the participant to rate how much they agreed with each of the statements listed in Table 1 on a sliding scale from 0 (not at all) to 100 (a great deal). Note that these questions were asked before the user had experienced any active hugs with the robot.

Once all changes were completed, the subject was called out from behind the privacy screen and completed a practice run of the human–robot interaction involved in the experiment. During this practice hug, the robot was in the condition of the subject's first trial. The goal of this practice was to

Table 1 The fifteen survey questions asked in the opening and closing questionaires

Question
I feel understood by the robot
I trust the robot
Robots would be nice to hug
I like the presence of the robot
I think using the robot is a good idea
I am afraid to break something while using the robot
People would be impressed if I had such a robot
I could cooperate with the robot
I think the robot is easy to use
I could do activities with this robot
I feel threatened by the robot
This robot would be useful for me
This robot could help me
This robot could support me
I consider this robot to be a social agent

Table 2 A description of the twelve tested hug conditions, broken into the two parts of the experiment

Physical conditions
Hard-cold
Soft-cold
Soft-warm
Behavioral conditions
Too loose, too short
Too loose, immediate release duration
Too loose, too long
Just right tightness, too short
Just right tightness, immediate release duration
Just right tightness, too long
Too tight, too short
Too tight, immediate release duration
Too tight, too long

ensure correct arm placement to activate the tactile sensor, acclimate the participant to the timing of the hug (from when the robot asked, "Can I have a hug, pleeease?" to when it closed its arms), and to address the worries subjects might have about hugging a robot. Some participants were initially hesitant to hug the robot and missed the first practice hug, so they generally appreciated having multiple chances to get accustomed to it before the start of the experiment. On average, people did 2–3 practice hugs before they felt comfortable beginning the experiment. The twelve tested conditions each participant experienced are listed in Table 2.

A within-subjects study was selected for this experiment for several reasons. First, we were most interested in the differences between the conditions rather than the overall response levels to a robot hug. We also preferred this design for its higher statistical power and the lower number of participants it requires compared to a between-subjects study [41]. An image of a participant hugging the robot in the Soft-Warm condition can be seen in Fig. 8. A sample compilation video of participants hugging the robot during the experiment in various hug conditions is provided as supplementary material.

The three physical trials for the first part of the experiment consisted of the robot in either the Soft-Warm, Soft-Cold, or Hard-Cold condition. In all of these trials, the robot hugged with the "just right" pressure and hugged for a preset duration of 3 s before releasing. After each of these hugs, the subject completed a brief quantitative survey concerning his or her perception of the robot attributes; these survey questions can be found in Table 3. Changing the robot outfit between trials took approximately 5 min. The subject sat at a desk behind a

Fig. 8 A participant hugging the PR2 with its custom Soft-Warm outfit during the experiment

privacy screen and answered the survey questions during this time. Afterwards, the participant read the school newspaper until they were called for the next trial.

The nine behavioral trials for the second phase of the experiment all occurred with the PR2 in the Soft-Warm condition, but with it interacting with the subject in a different way. Here, the robot varied how hard (too loose, just right, too tight) and how long (too short, immediate release, and too long) it hugged the person. Prior to starting the second part of the experiment, participants were taught to press down

Table 3 The survey each participant completed after each hug

Question
Which hug are you evaluating?
This robot behavior seemed (unsafe–safe)
I think the robot is (anti-social–social)
I think the robot is (selfish–caring)
Hugging the robot makes me (unhappy–happy)
Hugging the robot makes me feel (uncomfortable–comforted)

Table 4 The open-ended questions each participant answered at the end of the closing questionaire

Question
What aspects of this activity did you enjoy?
What aspects of this activity were most challenging?
Why would or wouldn't you want to do this activity with a robot?
What other activities would you want to do with this robot?

quickly on the tactile sensor when they wanted to be released from the hug, similarly to how they might pat someone on the back at the end of a hug. Each trial again was followed by the same robot attribute questionnaire (Table 3).

Prior to any experimentation, the investigator developed a randomized order of trials for up to 40 participants, thereby eliminating presentation order effects. The two parts of the experiment were handled separately for randomizing the hug orders. Participants always experienced the three physical conditions first and the nine behavioral conditions afterwards. Therefore, the presentation orders of the hugs were randomized with respect to their category.

At the end of the experiment, the subject completed the brief survey concerning the robot from Table 1, and they answered the four additional open-ended questions that can be seen in Table 4. These subjective measures were used for evaluation because we were interested in user preference, attitude, and opinion.

All slider-type questions in the surveys were based on previous surveys in HRI research and typical Unified Theory of Acceptance and Use of Technology (UTAUT) questionnaires [17,39], and the free-response questions were designed to give the investigators any other information the participant would like to share about the experiment experience. At the end of the entire experiment, the subject then completed a brief demographics questionnaire and was thanked for participating in the study. The investigator answered any questions the participant had and escorted the subject out of the experiment venue.

5.2 Participants

All participants were volunteers recruited from the Penn Engineering community from emails sent out through listservs. We ran two subjects as pilot participants to refine the experimental methods; their data are excluded from analysis because they were not given the same instructions as the later participants. A total of 30 people participated in the study: 14 male, 15 female, and 1 who identifies as "other". Ages of participants ranged from 21 to 54 (M = 26.8, SD = 8.5). 23 participants were engineering students, and 7 were faculty or staff associated with the university. The majority of subjects (25) had a technical education/background, while 5 did not. Subjects also had varied amounts of experience with robots. When asked on a sliding scale from 0 = "novice" to 100 = "expert," many had some experience with robots in general (M = 52.5, SD = 31.2), while fewer had experience with the PR2 specifically (M = 15.8, SD = 26.5).

6 User Study Results

We analyzed five main sources of data to understand how robots should hug: the opening and closing experiment survey, the post-trial survey from the first three trials, the post-trial survey from the last nine trials, verbal comments made by participants during the experiment, and the free-response comments written by subjects at the end of the study.

6.1 Opening and Closing Survey Results

As mentioned earlier, the subject was presented with a set of 15 questions prior to any experimentation. This opening survey was answered by the participant based on initial impressions of the robot after a brief introduction. Following the conclusion of the entire experiment, the subject was asked the same set of 15 questions, which can be found in Table 1. Box plots of the responses to the opening and closing survey questions are shown in Fig. 9. For all analyses we used $\alpha = 0.05$ to determine significance. Using a paired t-test comparison of the opening and closing survey, we found that users felt understood by ($p < 0.005$), trusted ($p < 0.005$), and liked the presence of the robot ($p < 0.005$) significantly more after the experiment. People also found robots to be nicer to hug ($p < 0.005$), easier to use ($p = 0.0087$), and more of a social agent ($p < 0.005$) than they initially anticipated.

Subjects' opinions about whether using the robot was a good idea did not change significantly over the course of the study, nor did their fear of breaking the robot. They also did not feel that people would be significantly more or less impressed if they had a hugging robot after concluding the experiment. Participant beliefs about their ability to coop-

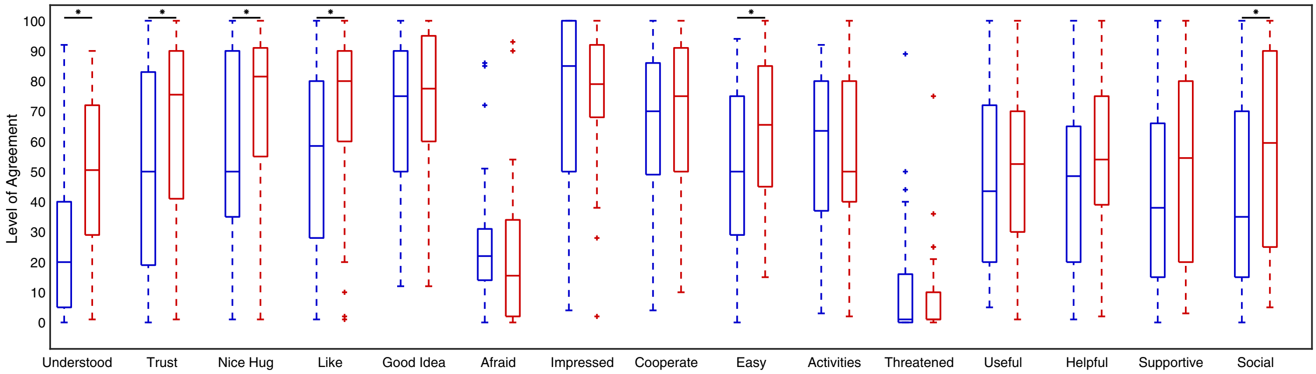

Fig. 9 A comparison of the responses to the opening (blue) and closing (red) surveys. The top and bottom of the box represent the 25th and 75th percentile responses, respectively, while the line in the center of the box represents the median. The lines extending past the boxes show the farthest data point not considered outliers. The + marks indicate outliers. The black lines with stars at the top of the graph indicate where a statistically significant difference was found between the opening and closing survey. (Color figure online)

erate with the robot were not significantly affected by the experiment. The course of the study did not significantly change subject opinions about whether they could do activities with the robot, how threatened they felt by the robot, how useful, how helpful, or how supportive they thought the robot would be.

6.2 Survey Results from Physical Trials

The first three hugs showcased changes in the physical properties of the robot. Box plots of the responses to the five questions participants were asked after each hug can be seen in Fig. 10. The ratings after each trial were analyzed in MATLAB 2017a using a one-way repeated measures analysis of variance (`ranova`). Afterwards, we ran a Tukey posthoc multiple comparison test to determine which conditions were significantly different from each other (`multcompare`). Our data satisfies all the assumptions of a one-way repeated measures ANOVA.

A significant difference in the perceived safety of the robot was noticed when the robot was covered in foam (both Soft-Cold and Soft-Warm), compared to when it was not [$F(2, 58) = 5.28$, $p = 0.0078$], with both softer conditions being preferred. There was not a significant difference noticed between the two soft conditions. The statistical significance between the Hard-Cold and Soft-Cold conditions, however, is close to the threshold of significance and so it should be interpreted with caution. There was not a statistically significant difference noticed between any of the three physical conditions for how social or caring the robot was perceived to be. No single physical condition of the robot made participants significantly happier after hugging it. The addition of the foam and heat proved to be crucial components to significantly increase users' comfort during the hug [$F(2, 58) = 3.17$, $p = 0.049$], with the difference noticed between the Hard-Cold and Soft-Warm conditions.

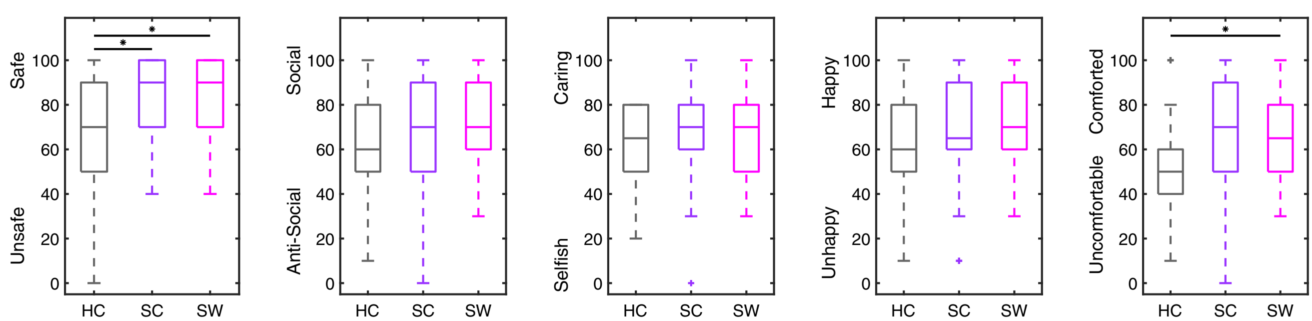

Fig. 10 A comparison of the responses to the survey questions after the first three hugs, changing physical conditions. The grey represents the Hard-Cold condition (HC), the purple color represents the Soft-Cold condition (SC), and the pink color represents the Soft-Warm condition (SW). The top and bottom of the box represent the 25th and 75th percentile responses, respectively, while the line in the center of the box represents the median. The lines extending past the boxes show the farthest data point not considered outliers. The + marks indicate outliers. The black lines with stars at the top of the graph indicate statistically significant differences

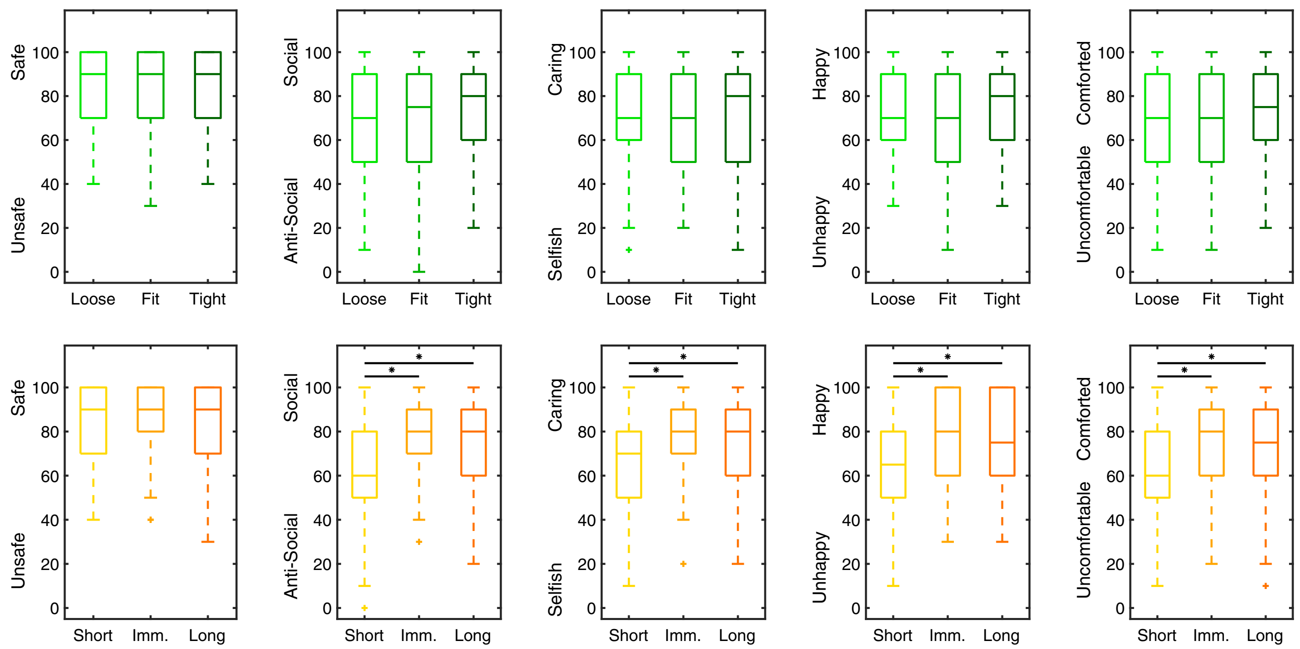

Fig. 11 A comparison of the responses to the survey questions after the last nine hugs, changing behavioral conditions. The top row represents the three levels of the tightness factor (loose, fit, and tight), while the bottom row represents the three levels of the duration factor (short, immediate release, and long). The top and bottom of the box represent the 25th and 75th percentile responses, respectively, while the line in the center of the box represents the median. The lines extending past the boxes show the farthest data point not considered outliers. The + marks indicate outliers. The black lines with stars at the top of the graph indicate statistically significant differences

6.3 Survey Results from Behavioral Trials

The last nine hugs varied the behavior of the robot, changing the pressure applied and the duration of the hug. The ratings after each trial were analyzed using a two-way repeated measures analysis of variance and Tukey posthoc tests, as they were for the first three trials. Our data satisfies all the assumptions of a two-way repeated measures ANOVA. The results from the responses to the five questions after each of these hugs can be seen in Fig. 11, grouped by level for both tightness and duration factors. No significant interaction effect was found between pressure and duration for any of the five questions asked. The perceived safety of the robot behavior did not significantly change across the nine configurations.

Hug duration played a large role in how anti-social or social users perceived the robot to be, with a significant difference noticed between the too-long and too-short hug, as well as between the just-right and too-short hug [$F(2, 58) = 16.057$, $p < 0.005$]. No significant difference was found between the too-long and just-right hugs.

The length of the hug also significantly affected how caring people thought the robot was [$F(2, 58) = 19.492$, $p < 0.005$]. When the robot hugged for too short a time, it was considered more selfish than both the just-right and too-long hug duration, which were thought to be more caring. A significant difference was not noticed between the latter two.

Subjects were least happy when hugging the robot during the too-short hug, and they were significantly happier when it released on cue or held on for 5 s after they pressed the tactile sensor [$F(2, 58) = 8.554$, $p < 0.005$]. There was not a significant difference in the subject's happiness between when the robot released on demand or held on too long. The statistical significance between the too long and too short conditions, however, is close to the threshold of significance and so it should be interpreted with caution.

Finally, the participants felt least comfortable when the robot released them too quickly compared to feeling more comforted when it released when they indicated or when it held on too long [$F(2, 58) = 7.701$, $p < 0.005$]. No difference was found between the last two conditions. The statistical significance between the too long and too short conditions, however, is close to the threshold of significance and so it should be interpreted with caution. No significant differences were found across hug tightness levels.

6.4 Verbal Comments During Experiment

Another form of data came from verbal comments from participants during the experiment, which were transcribed from the video by an investigator. Five subjects (16.7%) commented positively about the softness and warmth of the robot, in comments like “the stomach padding is really nice” and “OOH it’s warm!” Three participants (10.0%) responded negatively about the shorter hugs: a common phrase was “did I miss it?” The rest of the participants did not make unprompted verbal comments about the robot. When asked if they were ready for their next hug during the Hard-Cold trial, four subjects (13.3%) said something like, “no, because it doesn’t look very comfortable,” and they asked if they had to hug the robot in this condition. A final common negative comment, made by 26 participants (86.7%), was asking “is it working?” or “it’s not letting go” during one or more of the intentionally too long hugs. Another common comment made by seven subjects (23.2%) before the last trial was disappointment when they realized the experiment was over; one participant (3.3%) said “aw man, last one?” At other points in the study, three people (10.0%) told the experimenter “I like a good, tight hug,” while two participants (6.7%) explicitly mentioned their preference of the just right tightness, immediate release duration hug by saying things like “that was the best one yet,” or “excellent.”

6.5 Free-Response Questions

The last source of data came from the final comments at the end of the closing survey. When discussing the aspects of the experiment they enjoyed, seventeen people (56.7%) said the hugs in general, eight people (26.7%) mentioned the foam added for softness, and seven people (23.3%) specifically said the warmth improved the enjoyment of the activity. Additionally, eight people (26.7%) discussed the fact that the activity included a robot made it more enjoyable. Four people (13.3%) mentioned that hugging the robot improved their mood, and three (10.0%) noted how much they appreciated the politeness of the robot asking for a hug.

When it came to the aspects of the activity that participants found challenging, there were three main themes. Five of the 30 participants (16.7%) said nothing about this experiment was challenging to them. Eleven people (36.7%) mentioned that the physical aspects of the robotic platform were challenging. These challenges included the large size of the robot base and/or head, which made it difficult to hug, as well as the height restriction that made this activity more challenging for taller individuals, as the PR2 could not match their height. A final aspect that twenty-one participants (70.0%) found challenging was getting the robot to release in several trials. Although we did not ask this question after each individual trial, we believe that these comments largely referred to the three trials when the robot was programmed to recognize that the person had indicated they were ready for the robot to release and intentionally waited 5 s before releasing.

When asked why they would or would not want to do this activity, there were three main types of comments. Nineteen people (63.3%) wrote that they were pleasantly surprised by how nice the robot hugs were, and that they would like to do this activity again, making it the most common comment. Next, ten people (33.3%) mentioned that while they did enjoy the activity, they preferred human hugs because they felt that the robot did not understand why the human wanted a hug (their emotional state), and would not react appropriately, e.g., squeeze tighter as they human squeezed tighter, or rub their back when the robot notices they are upset. The last common comment was that five people (16.7%) mentioned they would like to do this activity because they noticed positive improvements in their mood after receiving hugs from the robot.

The final free-response question (what other activities would you like to do with the robot) had five common responses. Ten people (33.3%) mentioned that they would would want to do more hugging activities. These activities included snuggling, cuddling, receiving pats on the back, back rubs, and massages. Within this topic, six people (20.0%) mentioned that they wanted to have a conversation with a robot and have it be able to determine they were feeling sad, and offer to give them a hug to cheer them up. Ten people (33.3%) said they would like to play games with the robot, six mentioned (20.0%) they’d like to give the robot high-fives, six said they’d like to dance with the robot, and six others (20.0%) talked about how they’d like the robot to be able to talk with them, react to a conversation, and tell them stories. The last common thread among responses was that three people (10.0%) mentioned they’d like a robot to assist in daily tasks.

7 Discussion

Our hypothesis was composed of four sub-statements, which were all largely supported by the results. First, H1 hypothesized that subjects would prefer hugging a cold, soft robot to a cold, hard robot. The addition of the foam to soften the robot improved the comfort of subjects during the experiment. Subjects also considered the soft robot to be much safer than a hard robot. Because of these survey results, as well as the multiple positive comments about the inclusion of the foam, and the number of people who displayed a lack of interest in hugging the Hard-Cold robot, we conclude that people prefer hugging a soft robot to a hard robot.

Next, H2 hypothesized that subjects would prefer hugging a warm, soft robot to a cold, soft robot. The results from the experiment confirm this hypothesis. The addition of the heat made the most impact on the perceived safety and how comforting the robot was. For these reasons, as well as the numerous positive comments made about the warmth of the robot, both verbally and in writing, we conclude that people prefer hugging a warm robot to a cold robot.

Third, H3 conjectured subjects would prefer a robot that hugs them with a medium amount of pressure, rather than hugging too loosely or too tightly. Multiple subjects verbally mentioned their preference for "really tight hugs," which may help explain some of the results found. Statistical analysis did not find that hug tightness significantly affected answers to any of the questions we asked. We believe that the three studied hug tightness levels were not different enough to cause any measurable effects in these measures. Our too-tight condition was not set very tight out of concern for the safety of our participants. While we initially set out to test too-loose, just right, and too-tight conditions, we believe we actually tested a very loose condition, a slightly loose condition (where the arms of the robot were lightly touching the participant, but not squeezing), and a just-right condition, which our subjects verbally told us they liked best. We can thus conclude that humans like a robot that slightly squeezes them during a hug, but we cannot evaluate levels of pressure higher than were tested in the experiment.

Finally, H4 hypothesized that subjects would prefer a robot that releases them from a hug immediately when they indicated they were ready for the hug to be over, rather than the robot releasing a hug before or after this time. Statistical analysis proved that hug duration played a significant role in the user's experience. In every question with a significant difference noticed (all except for the first question about safety), the too-short hug was less ideal than either the immediate release or the too-long hug. Negative verbal comments were made to the investigator during the trials regarding both the "too short" and "too long" hugs. The number of written comments where the user mentioned it was difficult to get the robot to release indicate discomfort when the robot did not release exactly when they wanted it to. Together, these results make a compelling argument that our subjects preferred having control over the duration of the hug.

Limitations

While this study was a good starting point, it has its limitations. A clear weakness of the studied approach was the PR2 platform used for this experiment. Because of the intimate nature of this exchange, such a large, bulky robot was a less than ideal choice. It made the encounter uncomfortable for some users and potentially inhibited their enjoyment. This robot's arms also made up its chest, which rotated as it moved its arms. Creating padding that covered the chest area for the entirety of the experiment was therefore difficult. The padding shifted after each hug and had to be repositioned by the experimenter before the next trial. Using a different robotic platform, or developing a new one that is specifically made for such social-physical interactions, would be ideal. Another weakness of this project was that we did not equip the robot to match the pressure the human applied; it hugged with three different levels of constant pressure. Due to the delicate question of the safety of telling a robot to hug a person "too tight," we decided to manually pre-program what would be "just right" and "too tight" for each person. Adding this modification in future studies will make for a better user experience and provide more accurate insights regarding user preferences about hug tightness.

The recruitment procedures may also have unintentionally biased our results toward positive assessments because all participants learned the topic of the experiment from the recruitment materials. Additionally, of the participants we recruited, a majority had a technical background. Once the participants arrived, the practice hugs acclimatized participants to the act of hugging a robot, potentially causing higher overall ratings than would be expected without these practice trials. Our study was then conducted in a clinical manner. It is highly unlikely that someone would hug another person twelve times over the course of 50 min without speaking to them. We would thus like to conduct another study with a more "in the wild" design, in which human–robot hugs occur in a more natural way, similarly to how humans hug each other. Next, the default configurations used in all the physical and behavioral trials could have influenced our results. Having the robot hug in the "just right" pressure and for a pre-set duration of three seconds during all physical trials may have affected our conclusions about softness and warmth. Having the robot hug in the Soft-Warm condition for all the behavioral trials may have affected our conclusions about pressure and duration. Finally, some of the significant results found could be the result of the demand effect, a commonly stated disadvantage of running a within-subjects study [3]. Recent research, however, suggests that even when participants of aware of the study's purpose, they do not appear to assist researchers [25]. We, nevertheless, acknowledge the possibility that by experiencing all tested conditions, participants could guess the research question and either intentionally or unintentionally bias their responses.

8 Conclusions

This project represents an early but important first step in this line of social-physical human–robot interaction research. While robots are being integrated into more tasks with humans, like factory assembly lines and military teams, humans are typically expected to maintain a safe distance outside of the robot's workspace. This project aims to bring humans and robots closer, by completely enclosing a human in a robot's arms in a safe and supportive manner. Before more complicated research can be done, it is important to understand the basics of what makes users most comfortable in this new and potentially scary situation. After the positive initial feedback received from this study, it appears that the HRI community could embrace enabling robots to interact physically with humans in typical social interactions they experience with other humans, namely hugs, high fives, games, and dancing. Another implication of this research is that HRI researchers can work to make robots that provide a more enjoyable tactile experience for their users. Every user preferred hugging the robot when it was covered in the soft, fuzzy outfit.

9 Future Work

There are several areas in which to expand and refine this study in future work. First, we plan to create a new robotic platform that is customized for social-physical interactions with humans, using two Kinova JACO arms. We hope the future system we create can deliver good hugs in a more natural setting, without the need for practice trials.

We are interested in studying the emotional and physical response humans have to hugs as a stress reliever. To improve the quantitative quality of our results, we plan to include objective measures such as heart rate and facial expression in future experiments. By measuring these objective measures, we plan to investigate and compare the responses humans experience when hugging a robot versus hugging another human, an animal (like a pet), and a comfort object.

Next, we aim to enable people to be able to send customized hugs to each other through this new platform, to discover the extent to which personal connections can be reinforced at a distance. Our vision includes an online forum for people to customize the hug they would like to send, including setting the tightness and duration, uploading a video or voice recording, and perhaps adding a rub or pat on the receiver's back. An artistic rendering of what the final stage of this project might look like can be seen in Fig. 1.

The applications for this research are widespread. Immediate uses could be on college campuses to help alleviate student stress or nursing homes to try to bring happiness to the residents. As the research progresses, the platform could be adapted for use in rehabilitation centers or for children with autism. A final area for implementation for this research could be through co-parenting using telepresence robots [26], to enable parents and children to connect in real time when far away.

Acknowledgements Open access funding provided by the Max Planck Society. This work is supported in part by funding from the Max Planck ETH Center for Learning Systems. We thank Elyse Chase for developing the artistic rendering of our project goal (Fig. 1), as well as Elisabeth Smela and Ying Chen for providing us with custom-made sensors for our project. We would also like to thank Joe Romano, whose PR2 props code served as a foundation of this experiment, Siyao (Nick) Hu for his help and expertise working with the PR2, and Naomi Fitter for her help in designing the user study and analysis.

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

Informed Consent Informed consent was obtained from the study participants.

References

1. Anzalone SM, Varni G, Ivaldi S, Chetouani M (2017) Automated prediction of extraversion during human–humanoid interaction. Int J Soc Robot 9:385–399
2. Bernieri FJ, Rosenthal R (1991) Interpersonal coordination: behavior matching and interactional synchrony. In: Feldman RS, Rime B (eds) Fundamentals of nonverbal behavior. Cambridge University Press, Cambridge, pp 401–432
3. Charness G, Gneezy U, Kuhn MA (2012) Experimental methods between subject and within subject design. J Econ Behav Organ 81:1–8
4. Chartrand TL, Bargh JA (1999) The chameleon effect: the perception-behavior link and social interaction. J Personal Soc Psychol 76(6):893–910
5. Chen TL, King CHA, Thomaz AL, Kemp CC (2014) An investigation of responses to robot-initiated touch in a nursing context. Int J Soc Robot 6:141–161
6. Chen Y, Yu M, Bruck HA, Smela E (2016) Stretchable touch-sensing skin over padding for co-robots. Smart Mater Struct 25(5):1–16
7. Cohen S, Janicki-Deverts D, Turner RB, Doyle WJ (2015) Does hugging provide stress-buffering social support? A study of susceptibility to upper respiratory infection and illness. Assoc Psychol Sci 26(2):135–147
8. Cooney MD, Becker-Asano C, Kanda T, Alissandrakis A, Ishiguro H (2010) Full-body gesture recognition using interial sensors for playful interaction with small humanoid robot. In: IEEE/RSJ international conference on intelligent robots and systems, pp 2276–2282
9. Cooney MD, Nishio S, Ishiguro H (2012) Recognizing affection for a touch-based interaction with a humanoid robot. In: IEEE/RSJ international conference on intelligent robots and systems, pp 1420–1427
10. Cramer H, Kemper N, Amin A, Wielinga B, Evers V (2009) Give me a hug: the effects of touch and autonomy on people's responses to embodied social agents. Comput Anim Virtual Worlds 20:437–445
11. DiSalvo C, Gemperle F, Forlizzi J, Montgomery E (2003) The hug: an exploration of robotic form for intimate communication. In: Proceedings of the IEEE international workshop on robot and human interactive communication, pp 403–408

12. Duvall JC, Dunner LE, Schleif N, Holschuh B (2016) Active "Hugging" vest for deep touch pressure therapy. In: UbiComp/ISWC '16 Adjunct, pp 458–463
13. Fitter NT, Hawkes DT, Kuchenbecker KJ (2016) Rhythmic timing in playful human-robot social motor coordination. In:Social robotics: 8th international conference 2016 proceedings. Lecture notes in artificial intelligence. Springer, Berlin, pp 296–305
14. Garrell A, Villamizar M, Moreno-Noguer F, Sanfeliu A (2017) Teaching robot's proactive behavior using human assistance. Int J Soc Roboti 9:231–249
15. Grandin T (1992) Calming effects of deep touch pressure in patients with autistic disorder, college students, and animals. J Child Adolesc Psychopharmacol 2(1):63–72
16. Harlow HF, Zimmerman RR (1959) Affectional responses in the infant monkey. Science 130(373):421–432
17. Heerink M, Krose B, Evers V, Wielinga B (2009) Measuring acceptance of an assistive social robot: a suggested toolkit. In: IEEE international symposium on robot and human interactive communication (RO-MAN), pp 528–533
18. Kosuge K, Takeda T, Hirata Y, Endo M, Nomura M, Sakai K, Koizumi M, Oconogi T (2008) Patner ballroom dance robot—PBDR. SICE J Control Meas Syst Integr 1(1):74–80
19. Krauss KE (1987) The effects of deep pressure touch on anxiety. Am J Occupat Therapy 41(6):366–373
20. Lakoff G, Johnson M (1999) Philosophy in the flesh: the embodied mind and its challenge to western thought. HarperCollins, New York
21. Lynott D, Corker KS, Wortman J, Connell L, Donnellan MB, Lucas RE, O'Brien K (2014) Replication of experiencing physical warmth promotes interpersonal warmth by Williams and Bargh (2008). Soc Psychol 45(3):216–222
22. Mahalski PA (1981) The incidence of attachment objects and oral habits at bedtime in two longitudinal samples of children aged 1.5–7 years. J Child Psychol Psychiatry 24(2):283–295
23. Miyashita T, Ishiguro H (2003) Human-like natural behavior generation based on involuntary motions for humanoid robots. In: Proceedings of the IEEE humanoids, pp 203–212
24. Mori M (1970) The uncanny valley. Energy 7(4):33–35
25. Mummolo J, Peterson E (2017) Demand effects in survey experiments: an empirical assessment. https://doi.org/10.2139/ssrn2956147
26. Neustaedter C, Yang L (2017) Family communication over distance through telepresence robots. In: ACM CSCW workshop on robots in groups and teams
27. Nie J, Park M, Marin AL, Sundar SS (2012) Can you hold my hand?: physical warmth in human–robot interaction. In: Seventh annual ACM/IEEE international conference on human–robot interaction, ACM, pp 201–202
28. Park E, Lee J (2014) I am a warm robot: the effects of temperature in physical human–robot Interaction. Robotica 32:133–142
29. Peng H, Zhou C, Hu H, Chao F, Li J (2015) Robotic dance in social robotics—a taxonomy. IEEE Trans Hum Mach Syst 45(3):281–293
30. Romano JM, Kuchenbecker KJ (2011) Please touch the robot. Hands-on demonstration. In: Proceedings of the IEEE/RSJ conference on intelligent robots and systems (IROS), San Francisco
31. Shiomi M, Nakagawa K, Shinozawa K, Matsumura R, Ishiguro H, Hagita N (2017a) Does a robot's touch encourage human effort? Int J Soc Robot 9:5–15
32. Shiomi M, Nakata A, Kanbara M, Hagita N (2017b) A hug from a robot encourages prosocial behavior. In: 26th IEEE international symposium on robot and human interactive communication
33. Shiomi M, Nakata A, Kanbara M, Hagita N (2017c) A robot that encourages self-disclosure by hug. In: Springer C (ed) International conference on social robotics, pp 324–333
34. Short E, Hart J, Vu M, Scassellati B (2010) No fair!! An interaction with a cheating robot. In: ACM (ed) 5th ACM/IEEE conference on human–robot interaction, 2010. HRI'10, pp 219–226
35. Stiehl WD, Lieberman J, Breazeal C, Basel L, Cooper R, Knight H, Lalla L, Maymin A, Purchase S (2006) The huggable: a therapeutic robotic companion for relational affective touch. In: Proceeding of the IEEE consumer communications and networking conference, pp 1290–1291
36. Sumioka H, Nakae A, Kanai R, Ishiguro H (2013) Huggable communication medium decreases cortisol levels. Sci Rep 3:3034
37. VandenBerg NL (2001) The use of a weighted vest to increase on-task behavior in children with attention difficulties. Am J Occup Therapy 55(6):621–628
38. Wallis M, Popat S, McKinney J (2010) Embodied conversations: performance and the design of a robotics dancing partner. Des Stud 31(2):99–117
39. Weiss A, Bernhaupt R, Tscheligi M, Wollherr D, Kuhnlenz K, Buss M (2008) A methodological variation for acceptance evaluation of human–robot interaction in public places. In: IEEE international symposium on robot and human interactive communication (RO-MAN), pp 713–718
40. Williams LE, Bargh JA (2008) Experiencing physical warmth promotes interpersonal warmth. Science 322:606–607
41. de Winter JCF, Dodou D (2017) Experimental design in: human subject research for engineers: a practical guide. Springerbriefs in applied sciences and technology. Springer, pp 17–39
42. Yamane K, Kim J, Alspach AN (2017) Soft body robot for physical interaction. US patent application 20,170,095,925

Alexis E. Block is currently a doctoral fellow in the Center for Learning Systems, a joint program between the Max Planck Institute for Intelligent Systems and ETH Zurich. She earned her B.S.E. in Mechanical Engineering and Applied Mechanics and her M.S.E. in Robotics from the University of Pennsylvania in 2016 and 2017, respectively. She was honored with the Penn Alumni Association Student Award of Merit at graduation, an Honorable Mention for the NSF Graduate Research Fellowship, and she is co-chairing HRI Pioneers 2019. Her research blends physical human–robot interaction, social robotics, and haptics.

Katherine J. Kuchenbecker directs the Haptic Intelligence Department at the Max Planck Institute for Intelligent Systems in Stuttgart, Germany. She earned her Ph.D. in Mechanical Engineering at Stanford University in 2006, did postdoctoral research at the Johns Hopkins University, and was an engineering professor at the University of Pennsylvania before she moved to the Max Planck Society in 2017. Her research centers on haptic interfaces, which enable a user to touch virtual and distant objects as though they were real and within reach, as well as haptic sensing systems, which allow robots to physically interact with objects and people. She delivered a TEDYouth talk on haptics in 2012 and has been honored with a 2009 NSF CAREER Award, the 2012 IEEE Robotics and Automation Society Academic Early Career Award, a 2014 Penn Lindback Award for Distinguished Teaching, and various best paper and best demonstration awards. She co-chaired the IEEE Technical Committee on Haptics from 2015 to 2017 and co-chaired the IEEE Haptics Symposium in 2016 and 2018.