scientific reports

OPEN

# Semi-autonomous touch method merging robot's autonomous touch and user-operated touch for improving user experience in robot touch

Ryoma Mitsuoka✉, Tomonori Kubota✉, Satoshi Sato & Kohei Ogawa

**The demand for therapeutic robots to alleviate mental health problems is growing. Studies have shown that people's mental health improves when they are touched. Consequently, therapeutic robots are designed to alleviate stress through robot's autonomous touch. However, robot's autonomous touch can sometimes cause discomfort to recipients. This paper proposes a semi-autonomous touch method that merges robot's autonomous touch with user-operated touch to mitigate discomfort while maintaining the sensation of being touched by another person. We conducted an experiment involving 24 participants who were touched on the neck by robots under three conditions: robot's autonomous touch, user-operated touch, and the proposed semi-autonomous touch method condition. Additionally, the study investigated participants' impressions of the robot in each condition. The results showed that semi-autonomous touch condition mitigated discomfort more effectively compared with the robot's autonomous touch method condition. It also enhanced the feeling of being touched by another person entity and suppressed interaction boredom compared with the user-operated touch method condition. Participants reported higher trustworthiness and perceived friendliness in robots utilizing the semi-autonomous touch method compared to those with autonomous touch method condition. These findings indicate that robots featuring the proposed semi-autonomous touch method can provide a comforting experience, leveraging the therapeutic benefits of being touched by another person, and underscore their potential in mental health applications.**

Mental health care is essential for alleviating depression and loneliness[1–5]. Therefore, therapeutic robots have been studied for their potential to relieve people's mental health problems[6–9]. Notably, studies have been shown that using Paro, a therapeutic robot, can relieve stress[10] and pain in users[11], thereby contributing to improved mental health.

Therapeutic robots provide mental health care through the beneficial effects that occur when a person touches the robot[6–11]. However, we believe that mental health care can be further improved by using the effects of therapeutic robots touching a person autonomously, such as stress relief. In this context, "autonomous" means that the robots seem to act autonomously when interacting with the person being touched. The reason that mental health care can be improved using therapeutic robots is grounded in research on human-to-human touch, which has shown significant improvements in mental health from being touched by another person. Specifically, in the medical field, studies have reported that patient are touched by nurses, such as touch, can lower heart rates, a physiological indicator, and relieve state anxiety[12], evidencing a comforting effect[13,14]. Furthermore, this type of interaction allows individuals to receive mental health benefits without needing to actively seek them out. Hence, it is expected that the effects, such as stress relief, will be improved by therapeutic robot's autonomous touch.

Previous research has also explored the impact of a robot's autonomous touch on individuals[15–19]. Willemse et al.[17] found that when a robot touched a participant's shoulder or upper arm, it led to a decrease in the participant's heart rate and an increased sense of familiarity with the robot. However, some studies have

Department of Information and Communication Engineering, Nagoya University, Nagoya, Aichi 464-8603, Japan. ✉email: mitsuoka.ryoma.t5@s.mail.nagoya-u.ac.jp; kubota@nuee.nagoya-u.ac.jp

indicated discomfort with a robot's autonomous touch[20,21]. Hirano et al.[20] reported that male participants felt less comfortable and familiar with robot-initiated touch compared to when they initiated touch with the robot. Therefore, to effectively utilize robots for mental health care through robot's autonomous touch, it is crucial to address and resolve the discomfort associated with such interactions.

The method of touch employed by robots, such as the position and intensity of touch, plays an important role in the discomfort associated with a robot's autonomous touch. Therefore, this paper focuses the robot's touch method. Research on human-to-human touch has identified acceptable body parts for touch[22] and methods for providing a relaxing touch[23]. Other discomfort factors with a robot's autonomous touch include not only the "robot's appearance"[24,25], but also the "relationship with the person who touches"[22] and "previous experience with touch,"[26–29] as established in human-to-human touch studies. However, even with a positive relationship established with the robot, an inappropriate touch method by the robot can still elicit negative reactions from users. Therefore, this paper focuses on refining the touch method of robot.

Discomfort can arise from a robot's autonomous touch if it fails to align with the user's desired touch method. Previous research on robot's autonomous touch has focused on the embrace method[30], robot material[31], and the timing of touch[31], aiming to make the robot more appealing or comfortable for users. Efforts have also been made to adapt human-to-human touch methods to robots[32,33]. However, simply adopting these methods does not guarantee the absence of discomfort in the robot's autonomous touch.

Therefore, we propose a semi-autonomous touch method designed to mitigate discomfort from the robot's autonomous touch while maintaining the sensation of being touched by another person. We define the semi-autonomous touch method merges the robot's autonomous touch (autonomous touch) with user-operated touch (operated touch). Figure 1 shows a conceptual diagram of the semi-autonomous touch method, in which the user partially operates the robot. The robot touches by merging motions generated by an autonomous algorithm with motions directed by the user.

Table 1 shows the advantages and disadvantages of the semi-autonomous touch method compared with the autonomous and user-operated touch methods. We contend that the semi-autonomous touch method capitalizes on the advantages of both autonomous and operated touches.

Herein, we discuss the three perspectives shown in Table 1. First, we will delve into non-uncomfortableness. We consider that the semi-autonomous touch method results in less discomfort for the user compared with autonomous touch method, thereby exhibiting higher non-uncomfortableness than autonomous touch method. Autonomous touch may lead to discomfort, while operated touch tends to be less disconcerting. Operated touch is similar to touching oneself for the user. Since users can control the touch as desired, discomfort is minimized. Moreover, studies have shown that self-touch is perceived as comfortable[34]. Therefore, we believe that the semi-autonomous touch method leverages the strengths of operated touch method to make the user less discomfort than autonomous touch method by merging autonomous and operated touch.

Second, we address the concept of otherness. We consider that the semi-autonomous touch method enhances the sensation of being touched by another person, thus exhibiting higher otherness than that with operated touch method. Although operated touch reduces discomfort, it may not effectively convey the feeling of being touched by someone else. Neuroscience research indicates a clear distinction between self-touch and being touched by another person[35,36], suggesting operated touch does not replicate the sensation of touch by a robot.

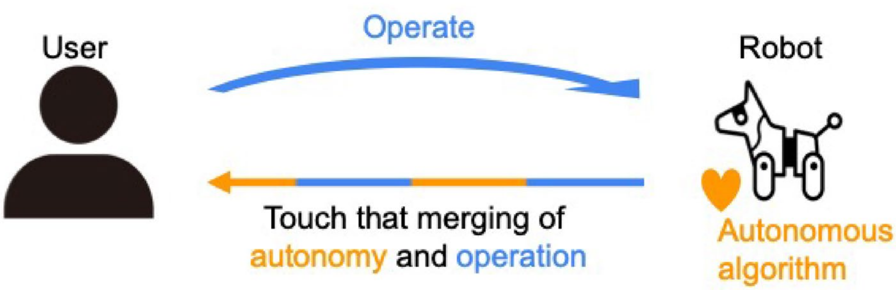


**Figure 1.** Conceptual diagram of semi-autonomous touch method. The user has partial operate the robot. The robot touches the user by merging the motions generated by an autonomous algorithm and motions directed by the user.

| | Operated touch method | Semi-autonomous touch method | Autonomous touch method |
|---|---|---|---|
| Feel less discomfort when touched by the robot (non-uncomfortableness) | Good | Good | Bad |
| Experience a greater sense of being touched by another person (otherness) | Bad | Good | Good |
| Inclined to continue interacting with the robot for a longer period (non-boredom-ness) | Bad | Good | Good |

**Table 1.** Strengths and weaknesses of semi-autonomous touch method, robot's autonomous touch method, and user-operated touch method."Good" indicates that the touch method is considered to satisfy property. "Bad" indicates that the touch method does not satisfy property.

However, autonomous touch, by its nature, makes the user feel that they are being touched by another person. Therefore, we believe that the semi-autonomous touch method enhances the sensation of being touched by another person more effectively than operated touch by merging autonomous and operated touch, thereby leveraging the strengths of autonomous touch.

Finally, we address the concept of non-boredomness. We consider that the semi-autonomous touch method fosters a greater desire for prolonged interaction compared with operated touch method, thereby exhibiting higher non-boredomness than operated touch method. One limitation of operated touch is that the robot's movements are predictable, which not only diminishes the feeling of being touched by another person but also makes interactions potentially monotonous for users. This predictability can lead to boredom[37], reducing the beneficial effects of the robot's touch, such as stress relief. In contrast, the unpredictability of autonomous touch keeps the interaction engaging, as evidenced by studies showing participants are willing to engage for longer periods with autonomous touch[19]. We believe that this is attributed to the suppression of boredom, enhancing the desire for continued interaction. Therefore, we believe that the semi-autonomous method leverages the strengths of autonomous touch to make the user suppress interaction boredom more effectively than operated touch method by combining autonomous and operated touch.

In summary, we believe that robots utilizing semi-autonomous touch method can significantly impact users as follows:

1. Increased non-uncomfortableness: Users feel less discomfort when touched by the robot compared to when the autonomous touch method is used.
2. Enhanced otherness: Users experience a greater sense of being touched by someone else compared to when the operated touch method is used.
3. Greater non-boredomness: Users are more inclined to continue interacting with the robot for longer periods compared to when the operated touch method is used.

Robots equipped with semi-autonomous touch method are expected to deliver the above three benefits and relieve user stress.

Although semi-autonomous touch is expected to provide the advantages of autonomous and operated touch, as described earlier, it may only have disadvantages (e.g., user discomfort when touched by the robot, the user feels a sense of self-touching, the user feels monotonous in the interaction). Therefore, to investigate the effectiveness of semi-autonomous touch method, we tested three hypotheses in a laboratory experiment:

H1 Semi-autonomous touch method offers higher non-uncomfortableness compared with autonomous touch method.
H2 Semi-autonomous touch method provides a greater sense of otherness compared with operated touch method.
H3 Semi-autonomous touch method induces greater non-boredomness compared with operated touch method.

The experiment employed a within-subjects design, wherein participants were touched by the robot under three different conditions: autonomous touch method condition (AT), operated touch method condition (OT), and semi-autonomous touch method condition (ST). By comparing the outcomes of ST with those of AT and OT, we aimed to determine whether ST surpasses AT and OT in terms of non-uncomfortableness, otherness, and non-boredomness. In addition, understanding the user's impression of the robot equipped with the semi-autonomous method is crucial for its implementation in therapeutic scenarios. Therefore, we also investigated participants' impressions of the robot, comparing these with impressions from the AT and OT.

The novelties of this study are as follows:

1. Propose a semi-autonomous touch method that merges robot's autonomous touch and user-operated touch.
2. Confirm that the semi-autonomous touch method provides the advantages of autonomous and operated touch and outweighs their disadvantages.

Regarding the first, we propose an interaction in which the user is touched by a user-operated semi-autonomous robot that provides a stress-relieving effect to the user. Previous studies have investigated interactions in which the user touches the robot[6–11] or the robot moves autonomously and touches the user[17]. However, interactions in which the user (operator) can operate the robot and the robot follows the instructions and touches the user have not been studied thus far.

Proposed interaction has not been studied even in the context of semi-autonomous robots. For example, they are being considered for providing directions at train stations[38], advertisements in shopping malls[39], and support for children with autism spectrum condition[40]. However, semi-autonomous robots that aim to touch the user, as considered in this study, have not been developed Proposing this interaction is a novelty of this research.

Techniques for integrating autonomy and operation have been studied in research on semi-autonomous robots; however, it was not the focus of this study. Various technologies to integrate autonomy and operation exist. Beer et al.[41] classified robot autonomy (i.e., the degree of integration of human operation and robot autonomy) into 10 levels. The robot developed in this study corresponds to the sixth highest robot autonomy level, namely "Shared Control with Human Initiative". At this level, the robot autonomously develops goals/plans, and implements actions, and the user can intervene and influence the robot with new goals/plans. We adopted this level of autonomy as we consider it appropriate for integrating the advantages of autonomy and operation.

Regarding the second, we confirmed that the semi-autonomous touch method provides the advantages of autonomous and operated touch. Clarifying the effects of the user-robot interaction on the user (operator) is a novelty of this research.

## Results

In the experiment, we created a scenario where two robots touched the participant's neck with a brush (Fig. 2), simulating a sensation of tickling their necks using robots. This approach was adopted because we believe that this touch was suitable for validating the effectiveness of the semi-autonomous touch method, as it is less susceptible to the ceiling or floor effects, and therefore, suitable for validating the effectiveness of the semi-autonomous touch method.

The experimental setup included three conditions: user-operated touch method condition (OT), robot's autonomous touch method condition (AT), and semi-autonomous touch method condition (ST). In OT, participants operated the brush positions by tilting the joystick of the controller, allowing the robots to touch according to their inputs. In AT, the participant did not operate the controller; instead, the robots autonomously determined the brush positions, enabling autonomous touch. In ST, while the robot autonomously controlled the brush position, participants could operate the reciprocating speed and width of the brush's motion by moving the joystick, providing a sense of both personal operation and autonomous robot movement. The differences in experimental conditions, particularly regarding participant operation and brush movement, are detailed in Table 2.

This study used a within-subjects design, with participants experiencing all three touch conditions. They completed self-reports after each condition and participated in an interview following all conditions. Each robot brush touch lasted 2 min for all conditions, and the order of conditions was counterbalanced. The self-reports and interviews included manipulation check questions, hypotheses, and participant impressions of the robot.

Thirty university students participated in the experiment. Data were obtained from 24 participants (M = 20.58, SD = 2.33, 11 males, 12 females, 1 non-respondent), excluding instances of robot malfunction, experimenter error in robot setup, and non-compliance with instructions by some participants.

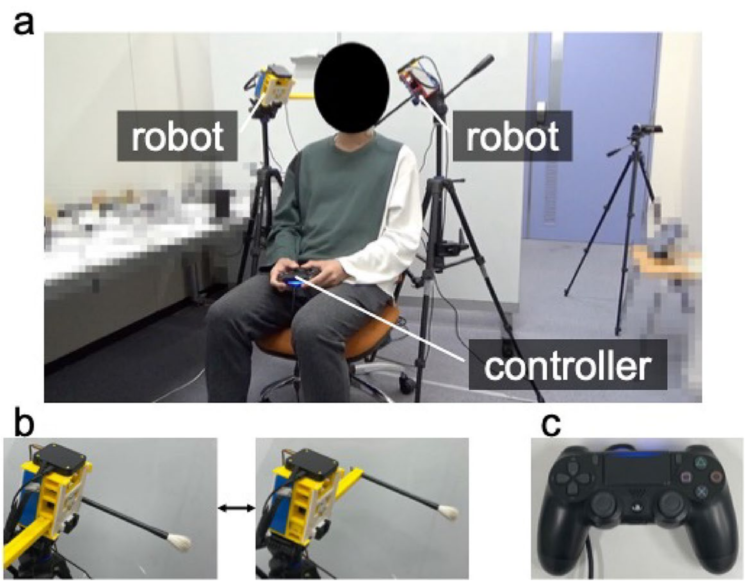


**Figure 2.** Experimental situation. (**a**) Two robots used a brush to touch neck of participant sitting in chair. Robots touched neck for 2 min for each condition. Participant had controller and was able to operate it in OT and ST. Participants experienced all three touch conditions and completed self-report after each condition and interview after all conditions. (**b**) One robot. Each robot held brush and moved it back-and-forth to touch participant's neck. (**c**) Controller.

| | Operated touch method condition (OT) | Semi-autonomous touch method condition (ST) | Autonomous touch method condition (AT) |
|---|---|---|---|
| Operate controller | Do | Do | Do not but hold controller |
| In controlling brush positions, participants controllable range | All | Reciprocating speed and width of the strokes | Uncontrollable |
| In controlling brush positions, robot autonomous algorithm controllable range | Uncontrollable | All (except those operated by the participants) | All |

**Table 2.** Differences in the way robots control brushes in each experimental condition.

## Manipulation check

This section presents the results of the manipulation check conducted to verify whether the three conditions were satisfied. In addition, it explores the likelihood of participant group bias affecting the results of hypothesis H1. The manipulation check confirmed the following criteria, all of which needed to be satisfied for approval:

M1 OT has a higher "sense of self-agency" than AT.
M2 AT has a higher "sense of other-agency" than OT.
M3 ST does not have a lower "sense of self-agency" than AT, and ST does not have a lower "sense of other-agency" than OT.

"Sense of self-agency" is defined as the participant's perception of being the initiator of the robot's actions, whereas "sense of other-agency" refers to the perception that the robot is the initiator of the actions.

For M1, OT is a method in which the robot touches according to the participant's operations. M1 was defined because it was necessary for participants to feel that their operations were reflected in OT more than in AT. For M2, AT is a method in which the robot touches autonomously. M2 was defined because it was necessary for participants to feel that the robot's intention was reflected in AT more than in OT. For M3, ST is a method that merges AT and OT. M3 was defined because ST was not established if the participants felt that AT reflected their operations more than ST, and OT reflected the robot's decision more than ST. These three checks allowed us to confirm that the three conditions were set without problems.

We invited participants to answer two questions to verify the success of the manipulation check. The first question focused on the degree of self-agency in the robots' movements (sense of self-agency): "Did you feel that the way the robot moved reflected your operation? (7: yes, 1: no)." The second question addressed the degree of other-agency in the robots' movements (sense of other-agency): "Did you feel the way the robot moved reflected judgment of the robot? (7: yes, 1: no)." Responses were recorded on a 7-point Likert scale.

Figure 3a shows the results for the sense of self-agency. Confirming the non-normal distribution of data, a Wilcoxon signed-rank test with the Holm method indicated that OT was significantly higher than AT, ST was significantly higher than AT, and OT was significantly higher than ST (OT-AT: $Z = 5.295$, $p < 0.001$, Cohen' s $r = 0.764$; ST-AT: $Z = 4.857$, $p < 0.001$, Cohen's $r = 0.701$; OT-ST: $Z = 2.475$, $p = 0.013$, Cohen's $r = 0.357$, all p-values were multiplied by adjusted value).

Figure 3b shows the results for the sense of other-agency. Confirming the non-normal distribution of data, a Wilcoxon signed-rank test with the Holm method revealed that ST was significantly higher than OT, and AT was significantly higher than OT (ST-OT:$Z = 4.790$, $p < 0.001$, Cohen's $r = 0.691$; AT-OT: $Z = 3.393$, $p = 0.001$, Cohen's $r = 0.489$, all p-values were multiplied by adjusted value). However, no significant difference was found between AT and ST (AT-ST: $Z = 1.100$, $p = 0.271$, Cohen's $r = 0.158$, p-value was multiplied by adjusted value).

From the sense of self-agency results, OT was confirmed to more effectively reflect participants' own operations in the robot's actions than AT, indicating the successful fulfillment of M1. Regarding the results for sense of other-agency, AT was perceived by participants as reflecting the robot's intentions in its actions more than OT,

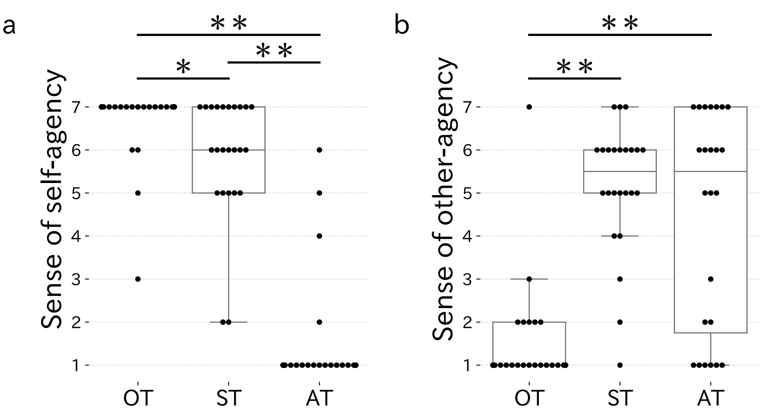


**Figure 3.** Results of sense of self-agency and sense of other-agency. Black dots in figure indicate participants' responses. There were three experimental conditions: operated touch method condition (OT), semi-autonomous touch method condition (ST), and autonomous touch method condition (AT). (**a**) Sense of self-agency. Wilcoxon signed-rank test with Holm method was conducted on responses (significance level: $\alpha = 5\%$). Results showed that OT was significantly higher than AT, ST was significantly higher than AT, and OT was significantly higher than ST (OT-AT: $Z = 5.295$, $p < 0.001$, Cohen's $r = 0.764$; ST-AT: $Z = 4.857$, $p < 0.001$,Cohen's $r = 0.701$; OT-ST: $Z = 2.475$, $p = 0.013$, Cohen's $r = 0.357$, all p-values were multiplied by adjusted value). (**b**) Sense of other-agency. Wilcoxon signed-rank test with Holm method (significance level: $\alpha = 5\%$) was performed on the responses. Results showed that ST was significantly higher than OT and AT was significantly higher than OT (ST-OT: $Z = 4.790$, $p < 0.001$, Cohen's $r = 0.691$; AT-OT: $Z = 3.393$, $p = 0.001$, Cohen's $r = 0.489$, all p-values were multiplied by adjusted value). However, there was no significant difference between AT and ST (AT-ST: $Z = 1.100$, $p = 0.271$, Cohen's $r = 0.158$, p-value was multiplied by adjusted value). (*: $p < 0.05$, **: $p < 0.01$).

thereby confirming the success of M2. From the result for sense of self-agency, ST led participants to feel that their operations were more significantly reflected in the robot's actions compared to AT, and Regarding the result for sense of other-agency, ST was perceived as reflecting the robot's intentions more than OT, indicating that M3 was successful. Therefore, the manipulation check was successful, affirming that the condition settings were appropriate. The median value for ST was 6 for the sense of self-agency and 5.5 for the sense of other-agency, both surpassing the midpoint of the 7-point Likert scale. This indicates that ST was effective in making participants feel that both their own operations and the robot's intentions were being acknowledged.

In the interview, participants' tolerance to tickling stimuli was also explored to ensure that the participant group was unlikely to bias the results of hypothesis H1. Because participant tickle tolerance could influence participants' evaluation of the stimuli, it was possible that biased tickle tolerance would bias the results of the discomfort. Participants were asked, "Do you have a tolerance for ticklish stimuli?" The responses were categorized as "tolerance," "no tolerance," and "neither." Accordingly, 7 out of 24 participants were classified as "tolerance," 13 as "no tolerance," and 4 as "neither." The $\chi^2$ test suggested that the participants formed an unbiased group regarding their tolerance to tickling stimuli. Thus, the influence of an individual's tickle tolerance for the verification of hypothesis H1 was balanced. In addition, our findings provide valuable information on the tickle tolerance of individuals. Further details are provided in the Supplementary Information.

## Verification of hypotheses

In this section, we discuss hypotheses H1, H2, and H3. To determine the support for these hypotheses, participants were asked specific questions. For H1, we posed a question regarding discomfort when touched by the robot (discomfort): "Did you feel discomfort when the robot touched you? (7: yes, 1: no)." For H3, a question was prepared to assess boredom during the robot's touch (boredom): "Did you feel bored by the robot's touch? (7: yes, 1: no)." For H2, since the evaluation content overlapped with the sense of other-agency from the manipulation check, the results of the sense of other-agency were used to verify H2. Responses to these questions were recorded on a 7-point Likert scale.

First, we present the results related to non-uncomfortableness for H1. Figure 4a shows the discomfort results. While not directly related to H1, results for OT are included in Fig. 4a for reference. Confirming the non-normal distribution of data, a Wilcoxon signed-rank test between ST and AT of interest showed that ST significantly reduced discomfort compared to AT ($Z = 2.089$, $p = 0.037$, Cohen's $r = 0.301$).

Next, We then discuss the results related to otherness for H2, shown in Fig. 3b, using the sense of other-agency ratings from the manipulation check. The analysis between ST and OT of interest revealed that ST was significantly higher than OT, indicating that participants felt the robot's movements better reflected user intentions (statistics are shown in Manipulation check section).

Lastly, the results of non-boredomness for H3 are described. Figure 4b shows the boredom results. While not directly pertinent to H3, AT results are also shown in Fig. 4b for reference. Confirming the non-normal distribution of data, a Wilcoxon signed-rank test between ST and OT of interest found that ST was significantly less boring than OT ($Z = 3.325$, $p < 0.001$, Cohen's $r = 0.480$).

## Evaluation of robot's impression

In this section, we describe the participants' impressions of the robot, specifically using the semi-autonomous touch method. To gauge the robot's impression, participants were asked to respond to four questions related to trust, friendliness, desire for future interaction (continuity), and preferred touch method. The first question

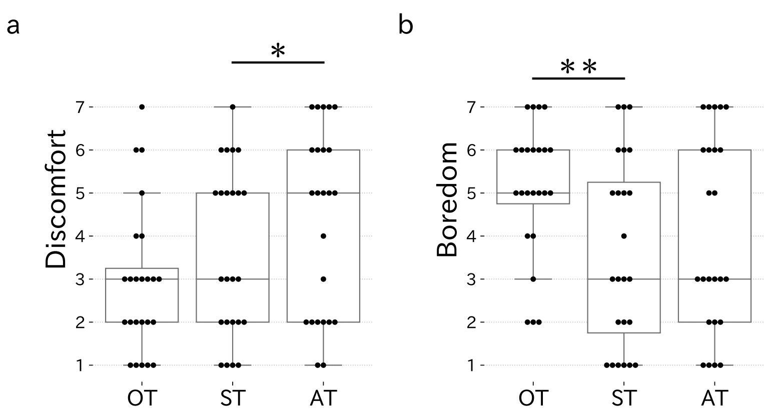


**Figure 4.** Results of discomfort and boredom. Black dots in figure indicate participants' responses. (**a**) Discomfort. Although not related to the H1, results of OT are also shown for reference. Wilcoxon signed-rank test (significance level: $\alpha = 5\%$) was performed only between ST and AT. Results showed that ST was significantly lower than AT ($Z = 2.089$, $p = 0.037$, Cohen's $r = 0.301$). (**b**) Boredom. Although not related to the H3, AT results are shown for reference. Wilcoxon signed-rank test (significance level: $\alpha = 5\%$) was performed only between OT and ST responses. Results showed that ST was significantly lower than OT ($Z = 3.325$, $p < 0.001$, Cohen's $r = 0.480$). (*: $p < 0.05$, **: $p < 0.01$).

assessed the level of trust (trust), asking participants to rate their impression of the robot's trustworthiness on a scale where seven indicated trust and one indicated distrust. The second question inquired about the robot's friendliness (friendliness), asking participants to rate the robot's impression on a scale from 1 (not friendly) to 7 (friendly). This question, along with the one on trust, was prompted by studies reporting changes in trust[31] and friendliness[15,17,20] in perceptions following interactions with the robot. The third question explored participants' willingness for future interactions with the robot (continuity), asking, "Do you want to interact with this robot again? (7: yes, 1: no)." This was aimed at understanding participants' views on robots utilizing semi-autonomous, autonomous, and operated touch methods, as ongoing interaction with a therapeutic robot is beneficial for delivering mental health care. Responses to these three questions were recorded on a 7-point Likert scale. Additionally, the fourth question on to ascertain preferred touch method, participants were asked, "Which condition did you like the most?" during the interview, and they were requested to explain their choices.

Figure 5a shows the results of trust. Confirming the non-normal distribution of data, a Wilcoxon signed-rank test with the Holm method, showed that OT was significantly more trusted than AT, ST was significantly more trusted than AT, and OT was more trusted than ST (OT-AT: $Z = 3.683$, $p < 0.001$, Cohen's $r = 0.532$; AT-ST: $Z = 2.861$, $p = 0.008$, Cohen's $r = 0.413$; OT-ST: $Z = 2.326$, $p = 0.020$, Cohen's $r = 0.336$, all p-values were multiplied by adjusted value).

Next, Fig. 5b shows the friendliness results. Confirming the non-normal distribution of data, a Wilcoxon signed-rank test with the Holm method showed that ST was significantly friendlier than AT ($Z = 2.513$, $p = 0.036$, Cohen's $r = 0.363$, p-value was multiplied by adjusted value). However, there were no significant differences between the OT-AT and ST-OT comparisons (OT-AT: $Z = 0.760$, $p = 0.894$, Cohen's $r = 0.110$; ST-OT: $Z = 0.516$, $p = 0.606$, Cohen's $r = 0.075$, all p-values were multiplied by adjusted value).

Figure 5c shows the continuity results. Confirming the non-normal distribution of data, a Wilcoxon signed-rank test with the Holm method showed no significant differences among the conditions (OT-ST: $Z = 0.578$, $p = 1.000$, Cohen's $r = 0.083$; OT-AT: $Z = 0.248$, $p = 1.000$, Cohen's $r = 0.036$; ST-AT: $Z = 0.231$, $p = 0.817$, Cohen's $r = 0.033$, all p-values were multiplied by adjusted value).

Regarding the preferred touch method, Table 3 shows the participants' preferred touch method. Eight respondents preferred OT, nine preferred ST, and seven preferred AT. A $\chi^2$ test showed no significant preference bias among the conditions ($\chi^2(2) = 0.25$, $p = 0.883$, Cramer's $V = 0.072$).

When asked about the reasons for their preferred method, the most common reason among seven out of eight participants favoring OT was their ability to operate the touch. For AT, the most common reason among four out of seven participants was the autonomy of the robot's touch without user input. The majority of participants preferring ST, seven out of nine, highlighted its combination of both the robot's autonomy and the participant's operation.

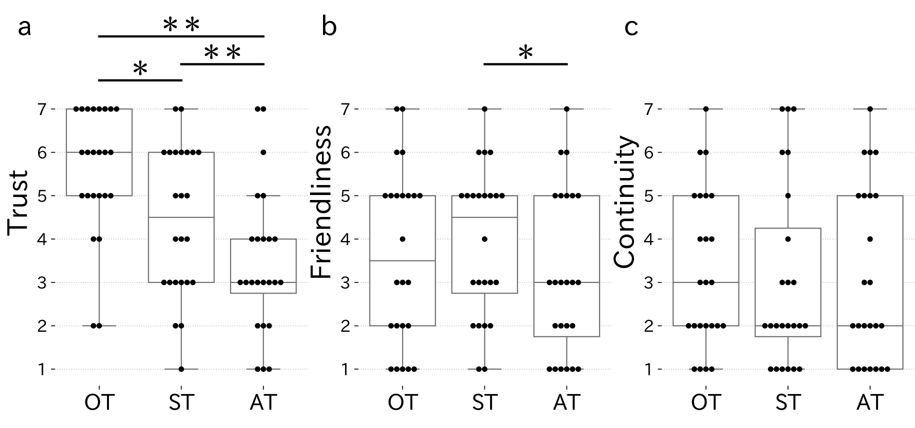


**Figure 5.** Results of trust, friendliness, and continuity. Black dots in figure indicate participants' responses. (**a**) Trust. Wilcoxon signed-rank test with Holm method was performed on the responses. Results show that OT was significantly higher than AT, ST was significantly higher than AT, and OT was significantly higher than ST (OT-AT: $Z = 3.683$, $p < 0.001$, Cohen's $r = 0.532$; AT-ST: $Z = 2.861$, $p = 0.008$, Cohen's $r = 0.413$; OT-ST: $Z = 2.326$, $p = 0.020$, Cohen's $r = 0.336$, all p-values were multiplied by adjusted value). (**b**) Friendliness. Wilcoxon signed-rank test with Holm method was performed on the responses. Results show that ST was significantly higher than AT ($Z = 2.513$, $p = 0.036$, Cohen's $r = 0.363$, p-value was multiplied by adjusted value). However, there was no significant difference between the OT-AT or ST-OT comparisons (OT-AT: $Z = 0.760$, $p = 0.894$, Cohen's $r = 0.110$; ST-OT: $Z = 0.516$, $p = 0.606$, Cohen's $r = 0.075$, all p-values were multiplied by adjusted value). (**c**) Continuity. Wilcoxon signed-rank test with Holm method was performed on the responses. Results show no significant differences between all conditions (OT-ST: $Z = 0.578$, $p = 1.000$, Cohen's $r = 0.083$; OT-AT: $Z = 0.248$, $p = 1.000$, Cohen's $r = 0.036$; ST-AT: $Z = 0.231$, $p = 0.817$, Cohen's $r = 0.033$, all p-values were multiplied by adjusted value). (*: $p < 0.05$, **: $p < 0.01$).

| | Operated touch method condition (OT) | Semi-autonomous touch method condition (ST) | Autonomous touch method condition (AT) |
|---|---|---|---|
| frequency | 8 | 9 | 7 |

**Table 3.** Result for preferred touch method. A $\chi^2$ test (significance level: $\alpha = 5\%$) was performed on responses. Results showed no bias between groups ($\chi^2(2) = 0.25$, $p = 0.883$, Cramer's $V = 0.072$).

## Discussion

In this experiment, we investigated whether participants experienced less discomfort (H1) with the semi-autonomous touch method condition (ST), which merges the robot's autonomous and the user-operated touch, compared with the autonomous touch method condition (AT). Additionally, we examined whether participants felt as though they were being touched by another person (H2) and whether boredom was suppressed (H3) compared with the operated touch method condition (OT). Furthermore, we investigated the participants' impressions of the robots utilizing the three touch methods.

We first address the results of hypothesis testing and impression evaluation, followed by a discussion on deriving design guidelines for creating robots using the semi-autonomous touch method. The section concludes with limitations and summary of our findings.

First, we discuss whether our hypotheses are supported. The results indicated that ST significantly reduced discomfort compared with AT, supporting H1. The effect size, Cohen's $r$, was 0.301, indicating meaningful differences. This reduction in discomfort is attributed to participants' ability to partially operate the robot, integrating the operated touch element of the semi-autonomous method.

Regarding the sense of other-agency, ST significantly enhanced the feeling of being touched by another person compared with OT, supporting H2. With an effect size Cohen's $r$ of 0.691, the semi-autonomous touch method was found to provide a stronger sense of interpersonal touch compared with the operated touch method. This enhancement is likely due to the unpredictable nature of the robot's movements, introduced by the autonomous touch element of the semi-autonomous touch method.

The boredom results showed that the participants were significantly less likely to experience boredom with ST compared with OT, thereby supporting H3. With an effect size of Cohen's $r$ at 0.480, the semi-autonomous touch method is more effective at minimizing boredom compared with the operated touch method. This is attributed to the unpredictable nature of the robot's movements under the semi-autonomous method, enhancing engagement.

Thus, hypotheses H1 to H3 are all supported. The semi-autonomous touch method makes the user less uncomfortable compared with the autonomous touch method, enhances the feeling of being touched by another person compared with the operated touch method, and suppresses interaction boredom more effectively compared with the operated touch method. Thus, the semi-autonomous touch method combines the advantages of both autonomous and operated methods.

We now discuss the participants' impressions of robots utilizing the semi-autonomous touch method. First, the trust results indicated that OT was perceived as significantly more trustworthy compared with AT, ST as more trustworthy compared with AT, and OT as more trustworthy compared with ST. This hierarchy suggests that the participants tended to trust robots in the following order: OT, ST, AT. The effect size Cohen's $r$ was 0.532 for OT-AT, 0.413 for ST-AT, and 0.336 for OT-ST, with meaningful differences. We consider that this was because it was easier for participants to predict robot movements in the order OT, ST, and AT.

Regarding friendliness results, ST made the participants feel significantly friendlier compared with AT, with an effect size of Cohen's $r$ at 0.363, indicating a noticeable difference. We consider that this was because the robots equipped with ST, despite its autonomy, could touch the participants in a way that was less uncomfortable for the participant than the robots using AT.

Summarizing the above two results, ST made participants trust and feel more familiar with the robot compared with AT. Therefore, we believe that the semi-autonomous touch method has the potential to make the robot more preferable to users rather compared with the autonomous touch method.

The continuity results showed no significant differences among the three conditions, indicating that although ST displayed higher non-boredomness compared with OT, it did not show a distinct advantage in continuity over AT or OT. This implies that the semi-autonomous touch method may prolong single-touch interactions more effectively compared with the operated touch method, yet its overall continued use remains comparable to both the autonomous and operated touch methods.

Regarding preferred touch method results, participants were asked to select their favored touch method among the three. The results showed no bias in the participant preference across conditions, with no single method emerging as distinctly favored. Despite fulfilling criteria for non-uncomfortableness, otherness, and non-boredomness, the semi-autonomous touch method did not stand out as the preferred choice.

Based on these results two key considerations emerge for the development of a more preferred robot by users. First, allowing for participant-driven operation timing in the semi-autonomous touch method could enhance its preference. The requirement for participants to operate at least one of the robots in ST, for experimental purposes, was noted; four of seven participants who preferred AT mentioned the lack of required operation as their reason for preference. Modifying the semi-autonomous touch method to allow for more flexible operation timing might increase its preference. Second, alternative methods should be considered to merge autonomous and operated touch are merged. Merging these touch techniques—possibly making it more similar to either the autonomous or operated touch method depending on user preference—may position the semi-autonomous touch method the preferred choice.

In discussing individual differences in evaluating the results of the semi-autonomous touch method, we aimed to obtain design guidelines for future robots using this method, particularly focusing on discomfort and non-boredomness due to potential variability among individuals.

Regarding non-uncomfortableness, although H1 was supported, almost half of the participants (11 out of 24) reported feeling uncomfortable with robot touch in ST. A closer look at participant responses revealed that ten participants rated their discomfort above the midpoint on the scale for both ST and AT. Among these, four participants also reported high discomfort levels in OT, suggesting a general discomfort with neck touch via brushes. By contrast, six participants indicated lower discomfort levels in OT, indicating ST's insufficient mitigation of discomfort for them, whereas OT did not induce similar discomfort. This suggests that incorporating more user-operated elements into semi-autonomous touch method might further mitigate discomfort. The varied responses to the semi-autonomous touch method indicate that customizing elements according to user preferences could enhance comfort levels.

Regarding non-boredomness, despite support for H3, almost half of the participants (10 out of 24) experienced boredom with robot touch in ST. Individual analysis showed that 10 participants felt bored (above the midpoint on the scale) in both ST and OT. Among them, seven also reported high boredom in AT, suggesting a general reluctance toward the brush touch method on their necks. This might stem from the robots' limited stroking area, possibly hindering noticeable differences in the touch methods. Three participants reported lower boredom levels in AT, suggesting that although ST was not effective in preventing boredom for them, AT did not trigger similar feelings. These results imply that adding elements that introduce unpredictability into the robot's movements in ST could further reduce boredom. Reactions to the semi-autonomous touch method varied, with some participants experiencing significant boredom and another person not, adapting the approach to align with user preferences could potentially enhance engagement.

Based on the discussion, our design guideline suggests incorporating features that enable the robot to move in response to user inputs to mitigate discomfort, alongside elements that introduce unpredictability to the robot's movements to mitigate boredom, all tailored to user preferences. However, a trade-off exists: emphasizing user-driven movements may eventually lead to boredom, whereas enhancing unpredictability could increase discomfort. Therefore, it is essential to further explore how to balance these aspects according to individual preferences.

Regarding the limitations of our study, its results are not broadly generalizable. The participant pool was exclusively university students. We believe that people as young as university students could also benefit from therapy robots. In fact, Jeong et al.[42] have studied communication robots that deliver interactive positive psychological and provides other useful skills for college students. Therefore, our findings are at least meaningful to young people. Elderly individuals or those with specific mental health conditions could also benefit from therapy robots. It is possible that the results may differ for elderly individuals or those with specific mental health conditions. Therefore, it is necessary to verify the effectiveness of the semi-autonomous touch method with a broader demographic of participants.

The experimental setup was designed to induce a specific level of discomfort and reluctance to prevent the ceiling and floor effects from obscuring the results. Verifying in varied settings are crucial to gain comprehensive understanding of the semi-autonomous touch method.

In this experiment, we used the touch of brush on the neck as a stimulus, but it is a narrow focus. Touch with other parts of the body, such as the shoulders and head, or other methods of touch employed by robots will be addressed in the future. However, an exhaustive examination of all possible touch points and methods of touch employed by robots is infeasible. Therefore, we will restrict our investigation to the touch points where the user may be touched by a robot and methods of touch the robot may use when semi-autonomous touch is applied. Although only one touch scenario was considered in this study, the results with other scenarios may be similar to the present case if the methods of touch employed by robots satisfy the two criteria described in Experimental situation. For example, touching the thigh of a user in seated position meets the two criteria. Therefore, the findings of this study are expected to be meaningful for a range of touch scenarios.

In this experiment, significant differences in discomfort and boredom between conditions were observed during the two-minute-long user-robot interaction. No difference was observed in the overall rate of continued use of the three methods for participants' willingness for future interactions with the robot (continuity). Therefore, this study provides meaningful, but not comprehensive, findings regarding the long-term effect and user acceptance of user-robot interactions. The effects and user acceptance of semi-autonomous touch method should be evaluated over longer durations to develop an effective therapy robot using semi-autonomous touch method.

We investigated whether tickle tolerance affected the results of hypothesis H1. It remained unclear what specific effects the differences in the way each individual felt tickled had on the results. The results of the $\chi^2$test demonstrated that the effect was balanced. However, because the participants' responses were categorized as "tolerance," "no tolerance," and "neither," it was not possible to correlate each individual's tickle tolerance with the discomfort results or discuss in detail the extent to which discomfort was affected. The user's perception of stimuli may impact the development of a therapy robot that is tailored to the user. There are several types of stimulus, and the way they are felt varies from user to user. Therefore, detailed research is required on user perception of the touch that a robot may make when semi-autonomous touch is applied in therapy robots.

This experiment's semi-autonomous touch method represents a combination of the more effective autonomous and operated methods. Exploring alternative integration methods could further mitigate discomfort or increase user preference. Future research should compare and investigate different ways to integrate touch methods to optimize the trade-off between discomfort and user appeal.

In summary, this paper proposed a semi-autonomous touch method designed to mitigate the discomfort associated with robot touch while maintaining the sensation of being touched by another person, with the goal of enhancing the therapeutic effects of robot touch on stress relief. We conducted an experiment to determine whether the semi-autonomous touch method outperforms both autonomous and operated touch in reducing discomfort, enhancing the sense of otherness, and decreasing boredom. In addition, we examined participants' impressions of a robot utilizing the semi-autonomous touch method compared with those employing autonomous and operated touch methods. The results showed that the semi-autonomous touch method made participants feel less uncomfortable compared with the autonomous touch method, thus having a higher degree of non-uncomfortableness compared with the autonomous touch method. In addition, this method made participants feel as though they were being touched by another person more so than with the operated touch method, thereby achieving a higher sense of otherness compared with the operated touch method. Moreover, the semi-autonomous touch method effectively suppressed interaction boredom in comparison to the operated touch method, demonstrating a higher degree of non-boredomness than the operated touch method. These results indicate that the semi-autonomous touch method can make interactions more comfortable, enhance the feeling of being touched by another person, and keep the interaction engaging by merging the robot's autonomous touch with the user-operated touch. In addition, this method fostered greater feeling of trustworthiness and friendliness in users compared to the autonomous touch method. Therefore, by using the method a therapeutic robot, participants are expected to be less uncomfortable with being touched and be able to continue touch-based interaction, while still receiving the benefits of being touched by another person. Moreover, by applying the proposed method to a therapeutic robot, the robot will be more likely be preferred by the user, rather than being equipped with robot's autonomous touch method.

In future, we aim to develop a therapeutic robot featuring the semi-autonomous touch method to verify its superiority in reducing discomfort, enhancing the sense of otherness, and decreasing boredom compared with robots that employ autonomous or operated touch methods. We plan to investigate the robot's effectiveness in providing stress relief and other beneficial touch effects.

As this research develops, it will become possible to develop a robot that provides better care to people and reduces the caregiver's workload. Semi-autonomous touch may also lead to new methods for self-care, such as providing a stress-relieving effect of touch from another person. Semi-autonomous touch method can be incorporated into massage robots, which are already being widely used, to further reduce the user's discomfort from being touched by a robot.

To realize these applications, the stress-relieving effects as well as the effects of long-term use of robots using semi-autonomous touch methodmust be verified. Therefore, we seek to gain precise insights into stress relief through physiological measures and to verify the long-term effects of therapeutic touch in real-world settings through extended field studies.

# Methods

## Experimental situation

This experiment was designed to simulate a scenario where two robots touched and brushed both the left and right sides of participants' necks (Fig. 2), effectively creating a sensation as if the robots were gently tickling their necks. The touch of brushing the neck was employed as the experimental stimulus because it met the following criteria:

1. Ensure participant safety
2. User discomfort when touched by others, but not when touched by oneself.

To validate the discomfort (hypothesis 1), it was necessary that autonomous touch (touched by others) made participants feel sufficiently uncomfortable and operated touch (touched by oneself) made participants feel less uncomfortable. If participants did not feel sufficiently uncomfortable in AT and OT, and similarly did not feel uncomfortable in ST, the ratings would be sufficiently low in all conditions and the differences would be difficult to observe (floor effect). For example, if the discomfort levels are the same between autonomous and operated touch, we cannot differentiate between whether semi-autonomous touch provides the advantages of operated touch or the disadvantages of autonomous touch.

The neck is generally uncomfortable when touched by another person, but not when touched by oneself, thus satisfying the second criterion. Additionally, a brush stroke is less likely to harm the participant, thereby meeting the first criterion. Consequently, stroking the neck with a brush is an appropriate technique to evaluate semi-autonomous touch method.

We established three experimental conditions: (1) operated touch method condition (OT), where the robot's touch was directed by the participant's operations; (2) autonomous touch method condition (AT), where the robot touched the participant without input, acting on its own; and (3) semi-autonomous touch method condition (ST), employing a blend of autonomous and operated touches.

For the experiment, two identical robots were positioned to touch the left and right sides of the participants' necks, as depicted in Fig. 2a. Each robot was fitted with a brush, which, by moving back-and-forth, allowed the robot to stroke the participants' neck. The mechanism that moved the brush utilized a motor (KM-1S-M4625TS) to reel in a fishing line attached to either end of the brush holder, facilitating the brush's back-and-forth motion (Fig. 2b).

We then detail the control algorithms for the OT, AT, and ST, focusing on how the brush's movement was managed. In the OT, the algorithm was designed to ensure participants felt in control of the robots. Specifically, the brush's movement was responsive to the tilt of the joystick of the controller (Fig. 2c) , giving participants the ability to dictate the brush positions.

In AT, the algorithm was designed to give participants the impression of the robot moving autonomously. To achieve this, the brushstrokes were programmed to start or stop autonomously with varying parameters, ensuring that the movements were not monotonous. The robot's brush position was operated based on the following equation:

$$f(t) = A\sin(2\pi ft) + y_0 \tag{1}$$

where $t$ is the elapsed time of the interaction, $A$ is the amplitude, $f$ is the frequency, and $y_0$ is the initial position. The sine function's amplitude and frequency set randomly according to a uniform distribution. The initial position was randomly assigned according to the Lévy distribution, inspired by the finding[43] that such movements mirror the locomotion patterns of various creatures. Parameters were refreshed with an 85% probability each cycle if any parameter lasted for more than 2 s, ensured varied brushstrokes patterns.

In the ST, the design merged participant operation with autonomous robot movement. Specifically, the joystick on the controller allowed participants to adjust the speed and width of the brushstrokes. ST is based on the AT algorithm. ST and AT differ in the settings of the amplitude and frequency. In AT, the amplitude and frequency are set randomly according to a uniform distribution. By contrast, in ST, the amplitude and frequency are set to the amplitude and frequency of the user's joystick operation determined using the fast Fourier transform. Thus, in ST, the user sets the amplitude and frequency, whereas the initial values and their updates are determined using the autonomous algorithm. The criterion for updating the amplitude and frequency was the same as that in AT, that is, the parameters were updated with an 85% probability each cycle if any parameter lasted for more than 2 s. The participants were instructed to operate at least one of the two units, namely the speed and width of the brushstrokes. Thus, ST was realized by merging the autonomous motion of the brush and the motion by user-operation.

Given the robot's touch with participants, incorporating a safety mechanism was deemed important. Accordingly, the PlayStation (PS) button on the robot controller (Fig. 2c) was programmed with an emergency stop function, allowing participants or operators to halt the robot's motion instantly if needed.

## Participants

Thirty university students from Nagoya University were recruited for the experiment, with data ultimately obtained from 24 participants (aged 18–26 yr, mean age: 20.58 yr, standard deviation: 2.33 yr). Exclusions were made in cases of robot malfunction, experimenter setup errors, or non-compliance with instructions by participants. The gender distribution among these 24 participants was 11 males, 12 females, and one person who chose not to disclose their gender. Prior to the experiment, participants underwent safety checks, including inquiries about allergies to the brush material, and signed a consent form. Written consent was also obtained for the use of video and images, with participant faces blurred for privacy. The participants shown in Fig. 2a gave written consent for their faces to be mosaicked for publication. The study received approval from the Ethical Review Board of Nagoya University and was performed in strict accordance with the granted ethical approval. Upon completion of the experiment, participants were compensated with an honorarium of JPY 1500 (approximately US$10).

## Procedure

First, participants were required to sign a consent form after confirming they had no allergies to the brush material and reviewing other safety precautions. To introduce the experiment, we showed the robots and explained that they would touch the participants' necks by moving the brushes back-and-forth. We also mentioned that the robot's touch might tickle or cause a prickling sensation on their necks. Participants were then seated, and the robots were adjusted to their physique to ensure the brush would contact their necks properly. In addition, instructions were provided on how to perform an emergency stop of the robot if necessary, including a demonstration of this feature. During the demonstration, participants were positioned to observe the emergency stop without the brush contacting their neck.

Participants were then asked to experience the touch in all three conditions and complete a self-report after each. The robot's brushes touched the participant's necks for 2 min in each condition, with the sequence of conditions being counterbalanced.

At the start of each condition, we explained the specifics of that condition and the robot operation instructions, ensuring participants understood how the robots would be controlled. Participants received the following instructions for each condition: in OT, "the robots will make touch according to your operation"; in AT, "the robots will make touch according to its own intention"; and in ST, "Basically, the robots will make touch according to its own intention, but you can convey the robots how you want it to touch you and ask it to change the way it touches you." For OT and ST, participants were also informed that they could operate the brush movements using the joystick, as outlined in the Experimental Situation section. They practiced this operation until they grasped the method. Especially in ST, participants practiced until they recognized the delay in participant input affecting the robot's movements. During this practice, they observed the movement of the robot without the brushes making touch with their necks.

As a precaution, participants in OT were instructed to continuously move either the left or right joystick throughout the experiment. This was to prevent the robot from stopping and not making touch with them. Similarly, in ST, participants received identical instructions to ensure constant operation of the robots, avoiding any periods without participant interaction. In the AT, participants were given the controller to maintain consistency in posture across all conditions and to enable emergency stopping of the robot if necessary. However, it was clarified that in AT, the joystick would not operate the robots, and participants were advised not to use the joystick.

Following these guidelines, participants were requested to reassume the initial setup posture, with the brush positioned against their neck, and to maintain this posture during the touch interaction for each condition.

After each condition, participants were to fill out a self-report and, concluding all conditions, participate in an interview. During the self-report and interview phases, participants were permitted to adopt any comfortable posture they preferred.

### Statistical analysis

In analyzing each self-reported item (sense of self-agency, sense of other-agency, discomfort, boredom, trust, friendliness, and continuity), we initially confirmed that the distribution of responses did not exhibit normality in the test of differences between conditions. Upon confirming the non-normal distribution, we conducted a Wilcoxon signed-rank test using the coin package (version 1.4.3)[44,45] in R (version 4.3.0)[46]. For situations requiring multiple comparisons, p-values were adjusted using the Holm method. The significance level for all tests was set at 5 percent. Cohen's $r$[47] value was calculated to determine the effect size.

For hypothesis testing H1 through H3, comparisons were made specifically between relevant conditions:

- H1: AT-ST
- H2: OT-ST
- H3: OT-ST

H1 focused on the discomfort index, and H3 on the boredom index. Since the sense of other-agency for H2 was tested during manipulation checks, no new test was conducted; instead, the previously calculated analysis results were utilized.

Regarding the results of participants' tolerance, responses were categorized as "tolerance," "no tolerance," or "neither," and a $\chi^2$ test was applied to detect any bias in the distribution of these categories. Cramer's $V$ was calculated for the effect size of these results. The results are detailed in the Supplementary Information.

For the preferred touch method, interview responses were tested using a $\chi^2$ test , with Cramer's $V$ calculated for the effect size.

## Data availibility

All data used in the analysis are described in the text and Supplementary Information.

Received: 30 April 2024; Accepted: 18 July 2024
Published online: 26 July 2024

## References

1. Alexopoulos, G. S. Depression in the elderly. *The Lancet* **365**, 1961–1970. https://doi.org/10.1016/S0140-6736(05)66665-2 (2005).
2. Craig, T. K. J. & Boardman, A. P. ABC of mental health: Common mental health problems in primary care. *BMJ* **314**, 1609. https://doi.org/10.1136/bmj.314.7094.1609 (1997).
3. Kroenke, K. & Price, R. K. Symptoms in the community: Prevalence, classification, and psychiatric comorbidity. *Arch. Intern. Med.* **153**, 2474–2480. https://doi.org/10.1001/archinte.1993.00410210102011 (1993).
4. Christiansen, J. *et al.* Associations of loneliness and social isolation with physical and mental health among adolescents and young adults. *Perspect. Public Health* **141**, 226–236. https://doi.org/10.1177/17579139211016077 (2021).
5. Hards, E. *et al.* Loneliness and mental health in children and adolescents with pre-existing mental health problems: A rapid systematic review. *Br. J. Clin. Psychol.* **61**, 313–334. https://doi.org/10.1111/bjc.12331 (2022).
6. Stiehl, W. *et al.* Design of a therapeutic robotic companion for relational, affective touch. In *ROMAN 2005. IEEE International Workshop on Robot and Human Interactive Communication)*, 408–415, (IEEE, Nashville, TN, USA, 2005). https://doi.org/10.1109/ROMAN.2005.1513813 (2005).
7. Sefidgar, Y. S. *et al.* Design and evaluation of a touch-centered calming interaction with a social robot. *IEEE Trans. Affect. Comput.* **7**, 108–121. https://doi.org/10.1109/TAFFC.2015.2457893 (2016).
8. Hayashi, R. & Kato, S. Psychological effects of physical embodiment in artificial pet therapy. *Artif. Life Robot.* **22**, 58–63. https://doi.org/10.1007/s10015-016-0320-7 (2017).
9. Dinesen, B. *et al.* Use of a social robot (LOVOT) for persons with dementia: Exploratory study. *JMIR Rehabil. Assist. Technol.* **9**, e36505. https://doi.org/10.2196/36505 (2022).
10. Wada, K. & Shibata, T. Robot therapy in a care house: Its sociopsychological and physiological effects on the residents. In *Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006*, 3966–3971, https://doi.org/10.1109/ROBOT.2006.1642310 (2006).
11. Geva, N., Uzefovsky, F. & Levy-Tzedek, S. Touching the social robot PARO reduces pain perception and salivary oxytocin levels. *Sci. Rep.* **10**, 9814. https://doi.org/10.1038/s41598-020-66982-y (2020).
12. Weiss, S. J. Effects of differential touch on nervous system arousal of patients recovering from cardiac disease. *Heart Lung* **19**, 474–480 (1990).
13. Pepito, J. A. T., Babate, F. J. G. & Dator, W. L. T. The nurses' touch: An irreplaceable component of caring. *Nursing Open* **10**, 5838–5842. https://doi.org/10.1002/nop2.1860 (2023).
14. Routasalo, P. & Isola, A. The right to touch and be touched. *Nurs. Ethics* **3**, 165–176. https://doi.org/10.1177/096973309600300209 (1996).
15. Yonezawa, T., Yamazoe, H. & Abe, S. Physical contact using haptic and gestural expressions for ubiquitous partner robot. In *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 5680–5685. https://doi.org/10.1109/IROS.2013.6697179 (2013).
16. Shiomi, M., Nakata, A., Kanbara, M. & Hagita, N. A hug from a robot encourages prosocial behavior. In *2017 26th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*, 418–423, https://doi.org/10.1109/ROMAN.2017.8172336 (2017).
17. Willemse, C. J. A. M. & van Erp, J. B. F. Social touch in human–robot interaction: Robot-initiated touches can induce positive responses without extensive prior bonding. *Int. J. Soc. Robot.* **11**, 285–304. https://doi.org/10.1007/s12369-018-0500-9 (2019).
18. Hoffmann, L. & Krämer, N. C. The persuasive power of robot touch. Behavioral and evaluative consequences of non-functional touch from a robot. *PLoS ONE* **16**, e0249554. https://doi.org/10.1371/journal.pone.0249554 (2021).
19. Shiomi, M., Nakata, A., Kanbara, M. & Hagita, N. Robot reciprocation of hugs increases both interacting times and self-disclosures. *Int. J. Soc. Robot.* **13**, 353–361. https://doi.org/10.1007/s12369-020-00644-x (2021).

20. Hirano, T. *et al.* How do communication cues change impressions of human–robot touch interaction?. *Int. J. Soc. Robot.* **10**, 21–31. https://doi.org/10.1007/s12369-017-0425-8 (2018).
21. Chen, T. L., King, C.-H., Thomaz, A. L. & Kemp, C. C. Touched by a robot: An investigation of subjective responses to robot-initiated touch. In *Proceedings of the 6th international conference on Human-robot interaction*, 457–464. (ACM, Lausanne Switzerland) https://doi.org/10.1145/1957656.1957818 (2011).
22. Suvilehto, J. T., Glerean, E., Dunbar, R. I. M., Hari, R. & Nummenmaa, L. Topography of social touching depends on emotional bonds between humans. *Proc. Natl. Acad. Sci.* **112**, 13811–13816. https://doi.org/10.1073/pnas.1519231112 (2015).
23. Etzi, R., Carta, C. & Gallace, A. Stroking and tapping the skin: Behavioral and electrodermal effects. *Exp. Brain Res.* **236**, 453–461. https://doi.org/10.1007/s00221-017-5143-9 (2018).
24. Mori, M., MacDorman, K. F. & Kageki, N. The uncanny valley [from the field]. *IEEE Robot. Autom. Mag.* **19**, 98–100. https://doi.org/10.1109/MRA.2012.2192811 (2012).
25. Löffler, D., Dörrenbächer, J. & Hassenzahl, M. The uncanny valley effect in zoomorphic robots: The U-shaped relation between animal likeness and likeability. In *Proceedings of the 2020 ACM/IEEE International Conference on Human–Robot Interaction*, HRI '20, 261–270, (Association for Computing Machinery, New York, NY, USA). https://doi.org/10.1145/3319502.3374788(2020).
26. Fromme, D. K. *et al.* Nonverbal behavior and attitudes toward touch. *J. Nonverbal Behav.* **13**, 3–14. https://doi.org/10.1007/BF01006469 (1989).
27. Jones, S. E. & Brown, B. C. Touch attitudes and behaviors, recollections of early childhood touch, and social self-confidence. *J. Nonverbal Behav.* **20**, 147–163. https://doi.org/10.1007/BF02281953 (1996).
28. Webb, A. & Peck, J. Individual differences in interpersonal touch: On the development, validation, and use of the "comfort with interpersonal touch" (CIT) scale. *J. Consum. Psychol.* **25**, 60–77. https://doi.org/10.1016/j.jcps.2014.07.002 (2015).
29. Maier, A. *et al.* Association of childhood maltreatment with interpersonal distance and social touch preferences in adulthood. *Am. J. Psychiatry* **177**, 37–46. https://doi.org/10.1176/appi.ajp.2019.19020212 (2020).
30. Onishi, Y., Sumioka, H. & Shiomi, M. Moffuly-II: A robot that hugs and rubs heads. *Int. J. Soc. Robot.*https://doi.org/10.1007/s12369-023-01070-5 *(2023).*
31. Block, A. E. & Kuchenbecker, K. J. Softness, warmth, and responsiveness improve robot hugs. *Int. J. Soc. Robot.* **11**, 49–64. https://doi.org/10.1007/s12369-018-0495-2 (2019).
32. Luo, R. C. & Hsieh, K. C. Tapping motion detection incorporate with impedance control of robotics tapotement massage on human tissue. In *2018 IEEE 15th International Workshop on Advanced Motion Control (AMC)*, 160–165. https://doi.org/10.1109/AMC.2019.8371080 (2018).
33. Ishikura, T. *et al.* Pleasant stroke touch on human back by a human and a robot. *Sensors* **23**, 1136. https://doi.org/10.3390/s23031136 (2023).
34. Dreisoerner, A. *et al.* Self-soothing touch and being hugged reduce cortisol responses to stress: A randomized controlled trial on stress, physical touch, and social identity. *Compr. Psychoneuroendocrinol.* **8**, 100091. https://doi.org/10.1016/j.cpnec.2021.100091 (2021).
35. Blakemore, S.-J., Wolpert, D. M. & Frith, C. D. Central cancellation of self-produced tickle sensation. *Nat. Neurosci.* **1**, 635–640. https://doi.org/10.1038/2870 (1998).
36. Blakemore, S.-J., Wolpert, D. M. & Frith, C. D. The cerebellum contributes to somatosensory cortical activity during self-produced tactile stimulation. *NeuroImage* **10**, 448–459. https://doi.org/10.1006/nimg.1999.0478 (1999).
37. Kruk, M., Pawlak, M. & Zawodniak, J. Another look at boredom in language instruction: The role of the predictable and the unexpected. *Stud. Second Lang. Learn. Teach.* **11**, 15–40. https://doi.org/10.14746/ssllt.2021.11.1.2 (2021).
38. Shiomi, M. *et al.* Field trial of a networked robot at a train station. *Int. J. Soc. Robot.* **3**, 27–40. https://doi.org/10.1007/s12369-010-0077-4 (2011).
39. Shiomi, M. *et al.* Recommendation effects of a social robot for advertisement-use context in a shopping mall. *Int. J. Soc. Robot.* **5**, 251–262. https://doi.org/10.1007/s12369-013-0180-4 (2013).
40. Zaraki, A., Wood, L., Robins, B. & Dautenhahn, K. Development of a semi-autonomous robotic system to assist children with autism in developing visual perspective taking skills. In *2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*, 969–976. https://doi.org/10.1109/ROMAN.2018.8525681 (2018).
41. Beer, J. M., Fisk, A. D. & Rogers, W. A. Toward a framework for levels of robot autonomy in human–robot interaction. *J. Hum. Robot Interact.* **3**, 74–99. https://doi.org/10.5898/JHRI.3.2.Beer (2014).
42. Jeong, S. *et al.* Deploying a robotic positive psychology coach to improve college students' psychological well-being. *User Model. User-Adapt. Interact.* **33**, 571–615. https://doi.org/10.1007/s11257-022-09337-8 (2023).
43. Reynolds, A. M. Current status and future directions of Lévy walk research. *Biol. Open* **7**, bio030106. https://doi.org/10.1242/bio.030106 (2018).
44. Hothorn, T., Hornik, K., van de Wiel, M. A. & Zeileis, A. A Lego system for conditional inference. *Am. Stat.* **60**, 257–263. https://doi.org/10.1198/000313006X118430 (2006).
45. Hothorn, T., Hornik, K., van de Wiel, M. A. & Zeileis, A. Implementing a class of permutation tests: The coin package. *J. Stat. Softw.* **28**, 1–23. https://doi.org/10.18637/jss.v028.i08 (2008).
46. R Core Team. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria (2023).
47. Cohen, J. *Statistical Power Analysis for the Behavioral Sciences* 2nd edn. (Routledge, 1988).



## Acknowledgements
This work was supported by JST Moonshot R&D Grant No. JPMJMS2011.


## Author contributions
Conceptualization: R.M., T.K., S.S., K.O.; data curation: R.M.; formal analysis: R.M., T.K., K.O.; funding acquisition: K.O.; investigation: R.M.; methodology: R.M. T.K., S.S., K.O.; project administration: R.M., T.K., K.O.; resources: R.M., T.K., S.S., K.O.; software: R.M.; supervision: T.K., S.S., K.O.; validation: R.M., T.K., K.O.; visualization: R.M., T.K., K.O.; writing-original draft: R.M.; writing-review and editing: R.M., T.K., S.S., K.O.

## Competing Interests
The authors declare no competing interests.

## Additional information
**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1038/s41598-024-67964-0.

**Correspondence** and requests for materials should be addressed to R.M. or T.K.

**Reprints and permissions information** is available at www.nature.com/reprints.

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.