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Is a soft robot more "natural"? Exploring the perception of soft robotics in human-robot interaction

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Abstract

Soft robotics technology has been proposed for a number of applications that involve human-robot interaction. It is commonly presumed that soft robots are perceived as more natural, and thus more appealing, than rigid robots, an assumption that has not hitherto been tested or validated. This study investigates human perception of and physical interaction with soft robots as compared with rigid robots. Using a mixed-methods approach, we conducted an observational study to explore whether soft robots are perceived as more natural, and what types of interactions soft robots encourage. In a between-subjects study, participants interacted with a soft robotic tentacle or a rigid robot of a similar shape. The interactions were video recorded, and data was also obtained from questionnaires (N_{video}=123, N_{quest}=94). Despite their drastically different appearances and materials, we found no significant differences in how appealing or natural the robots were rated to be. Appeal was positively associated with perceived naturalness in all cases, however we observed a wide variation in how participants define "natural". Although participants showed no clear preference, qualitative analysis of video data indicates that soft robots and rigid robots elicit different interaction patterns and behaviors. The findings highlight the key role of physical embodiment and materiality in human-robot interaction, and challenge existing assumptions about what makes robots appear natural.

Keywords: human-robot interaction, soft robotics, embodiment, tactile interaction, human factors, naturalness

1. Introduction

Over the past ten years, the field of *soft robotics* has produced a novel class of robots that possess a radically different appearance and aesthetic than traditional robots [1–3]. Soft robots can be defined as systems that are capable of autonomous behavior that are primarily composed of materials with elastic moduli in the range of that of soft biological materials [3]. Because of their pliability, soft robots potentially present fewer dangers to humans, especially for tasks that require close, physical contact. Hence, soft robotics has been claimed to increase the future potential for human-robot interaction (HRI) and enable new applications for robots [3, 4]. While still an emerging field, soft robotic systems have already been implemented in industry for high-speed pick and place tasks [5]. Applications have also been proposed within health care, human assistance, disaster relief and collaborative work. To ensure successful deployment where robots interact closely with humans, more knowledge is, however, needed about how people experience soft robots and how they spontaneously will interact with them. Such knowledge will be crucial for designing interactions with soft robots that are both intuitive and safe.

Because of their visual and functional similarity to biological organisms, soft robots are commonly presumed to be more "natural", and therefore more appealing, than traditional rigid robots. For instance, soft robots are thought to have more natural and fluid movements [6, 7], to "enable soft and natural human-robotics interactions" [7, 8], and to be "capable of soft movements and soft interaction with people"[1]. But at present, there is scant research on how people actually perceive soft robots and if the proposed relation between perceived naturalness and appeal holds.

A central endeavor of HRI research has been to investigate how people perceive social robots and their behavior [9–11]. Physical embodiment has been shown to measurably impact task performance between robots and humans [12–14], while other studies have demonstrated a link between a robot's materiality and the perception of robots as social agents [15–19]. A robot's material design sets the boundaries for interaction and can elicit specific attributions of social agency, even for non-anthropomorphic robots. Moreover, a robot's aesthetic properties (its appearance, movement qualities, tactility etc.) are closely related to its perceived affordances. Physical appearance is repeatedly shown to affect human perception of a robot's capabilities and to influence interaction [20–22]. With few exceptions [23–27], studies on the effects of physical embodiment on HRI have been restricted to conventional robotics technology. To our knowledge, no studies directly comparing human perceptions of silicone-based soft robotics technology and rigid robots have hitherto been conducted.

This exploratory study investigates human perception of and physical interaction with soft robots as compared with mechanical robots. The study was designed with two primary purposes: 1) To investigate the claim that soft robots are more natural and more appealing than conventional robots; and 2) To gain insights into people's perceptions of soft robots and the spontaneous interaction behaviors that soft robots elicit. We carried out an observational study that addresses the following three research questions:

- RQ1: Are soft robots perceived as more natural than traditional rigid robots?
- RQ2: Is there a correlation between how natural and how appealing a robot is perceived to be?
- RQ3: What specific types of interaction behaviors do soft robots elicit? Do these behaviors differ from those elicited by a rigid robot of a similar design?

For the study we used three different robots: two silicone-based soft robotic tentacles and one rigid robot of the same shape and with a similar movement range. We included two soft robots with different aesthetics in order to test whether different soft robots would be assessed differently by users. We chose to focus on people's perceptions of the appearance, movement, and haptic qualities of the robots. By comparing evaluations of and interactions with the soft robots with those of the rigid robot, we set out to understand whether and how materiality determines perceived naturalness and interaction patterns. Finally, we wanted to uncover inconsistencies or incongruences in how people define "natural" in relation to robots, a term that we generally find problematic when assessing people's responses to machines (soft or otherwise). Following previous experiments with social robots in public settings [17, 28, 29], we conducted the study "in the wild", using an open-ended interaction task that would prompt participants to interact freely with the robots.

The main contribution of the study is that it marks a first step towards a holistic understanding of how physical embodiment and materiality shape human-robot interaction with soft robots. Developing such an understanding is crucial in order to design soft robots that can interact or collaborate closely with humans in enjoyable and efficient ways.

2. Methodology

The study uses an observational research design. Observational studies are highly relevant to study HRI, because data are collected as they exist in a naturalistic setting, rather than through the manipulation of variables in controlled experiments [30, 31]. An observational design allows researchers to study how participants intuitively respond to robots in real-life scenarios, which is important for better understanding how specific robots are perceived and what types of interactions they elicit from users. Conducting observational studies is an established method that is used in clinical studies as well as in HRI research [30]. In the present study, we use a mixed methods approach to analyze self-reported data and video recordings; we use statistical analysis combined with qualitative analysis of written answers and transcriptions of video recordings.

2.1 Observational Study Design

We chose a between-subjects design with three conditions in order to measure initial reactions to a specific robot design and to avoid carry-over effects after exposure to another robot. We reasoned that most people had not previously encountered a soft robot, and we wanted to investigate whether the two different soft robot designs would elicit different responses. The choice of a between-subjects design was also motivated by pragmatic considerations: as the trials would take place during public events, it was estimated that a short duration would assure a high number of participants and more reliable self-reporting. Hence, it was preferable that each participant encountered only one robot.

Participants were divided into three groups that encountered one of two silicone-based pneumatically actuated soft robots, or a rigid robot comprised of servo motors. The robots were all constructed specifically for the study (Fig. 1). The two soft robots were of the same type but had different design attributes (color, material, and the rigidity and shape upon inflation). The rigid robot was designed to purposely resemble the two soft robots to act as a baseline for comparison.

We chose to have participants engage in an open-ended interaction without specifying any explicit task, a decision that was meant to focus the participant's attention on the experiential aspects of the interaction, rather than the usefulness or feasibility of the platform.

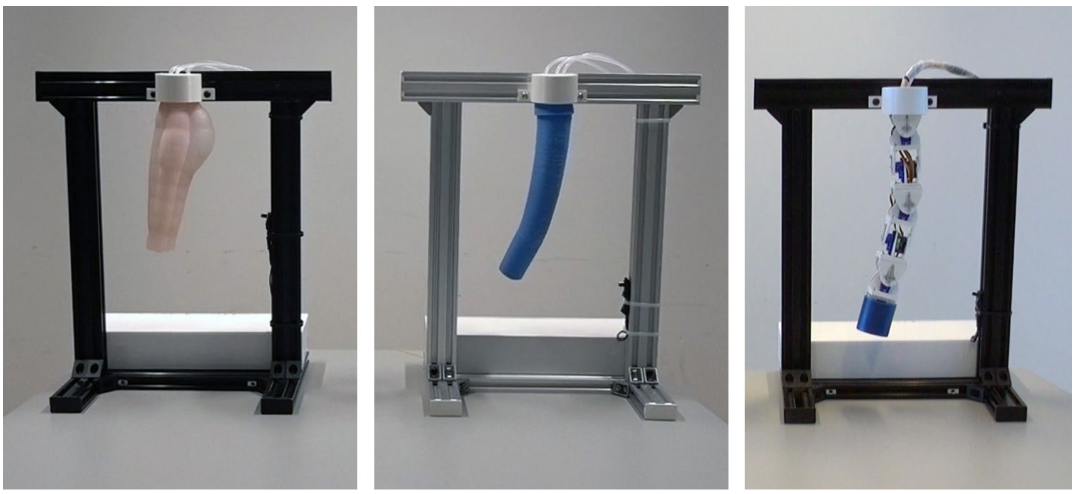

Fig. 1 Study participants interacted with either one out of the two silicone-based, pneumatically actuated soft robots (left and center) or a conventional, rigid robot (right) built specifically for the study. The rigid robot was designed with the same overall shape as the soft robots and programmed with similar movements

2.2 Participants

The study was conducted in accordance with the Danish Code of Conduct for Research Integrity and Danish Data Regulations. Participants were recruited at two public events. During the trial with the soft robots, children under the age of 18 were allowed to enter the premises accompanied by a parent or legal guardian who, in accordance with Danish law, could provide informed consent on their behalf.

A total of 94 non-randomized participants aged 19-70 years (mean age 32.6±11.9) comprising 49 men and 45 women completed the written questionnaire (questionnaires filled out by minors were not included). Fifty-four percent reported no prior interactions with robots. Video data for 123 participants was included for analysis. None of the participants were paid for their participation.

2.3 Materials

We designed a custom soft robotic platform for the study, as no soft robots that would suit the purpose of the study are yet commercially available. We chose a tentacle morphology as it would allow participants to experience the three aesthetic modalities (appearance, movement, reciprocal touch) in focus. Moreover, soft robots of this type are currently being developed for applications that involve close HRI within collaborative robotics (cobots) and assistive robotics (see Fig. 2).

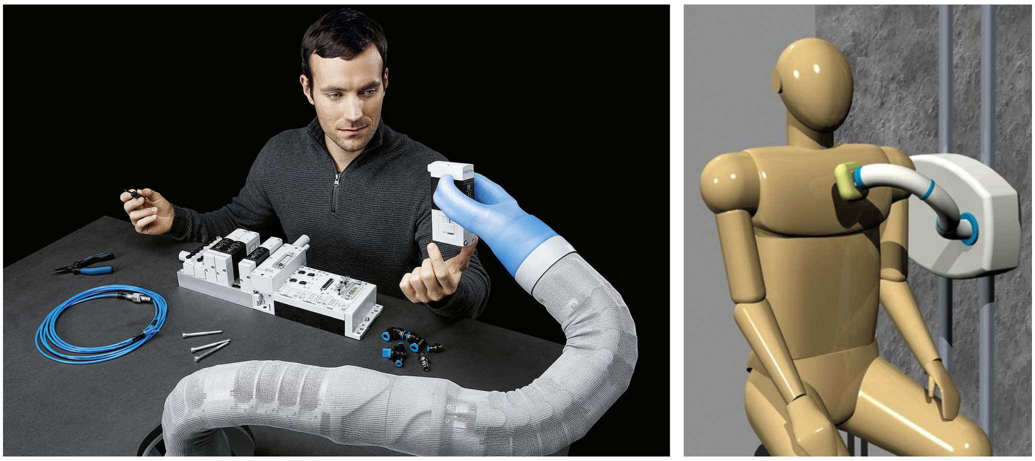

Fig. 2 Examples of soft robots based on tentacle designs developed for scenarios that involve close interaction with humans: the Festo BionicSoftArm cobot (left) and the I-SUPPORT system for assisted bathing (right). Credits: Image of BionicSoftArm ©Festo AG & Co. KG, all rights reserved, used with permission. Illustration of the I-SUPPORT system used with permission from the I-SUPPORT project [32]

2.3.1 Soft robot platform

The soft robotic platform consists of a three-chambered silicone tentacle that is pneumatically actuated (Fig. 3). The tentacle can bend in all directions around its central axis. The tentacle is mounted on a T-slot aluminum frame with mounts that were 3D printed in PLA plastic. The tentacle is supplied with pressurized air via 4/2mm OD/ID silicone tubing. It is actuated with three low noise electrical pumps (MITSUMI R-14 A213). Solenoid valves (Uxcell Fa0520D 6V Normally Closed) are implemented to facilitate the release of air from the chambers. The morphology is controlled by an Arduino Pro Mini microcontroller supplied by an external power supply (6V, 2A). Two H-bridge chips (L292D) drive the valves and pumps. The tentacle is equipped with an infrared (IR) distance sensor (FC-51), which is positioned to the right on the frame (see Fig. 3).

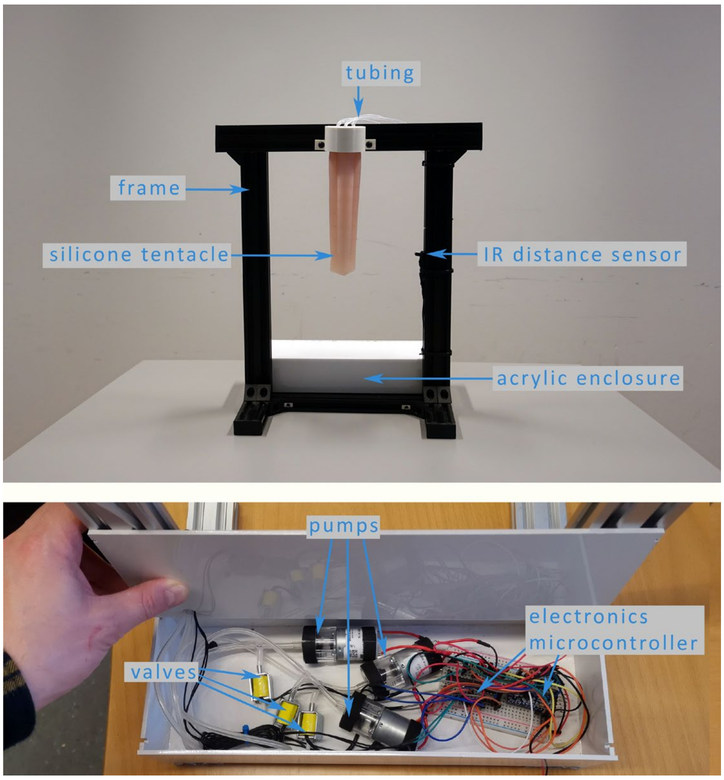

Fig. 3 The platform with the tentacle in its initial position (top). The electronics and pneumatic systems are located inside an acrylic enclosure (bottom)

We built two versions of the soft robotic platform for the study (see Fig. 1 and Fig. 4). The first (hereafter "red robot") incorporates an open source tentacle design [33]. It was cast in uncolored Ecoflex 0030 by using a lost wax casting technique to create the inner compartments. Red jeweler's wax was used for the inner mold parts, which gave the tentacle a pale red hue.

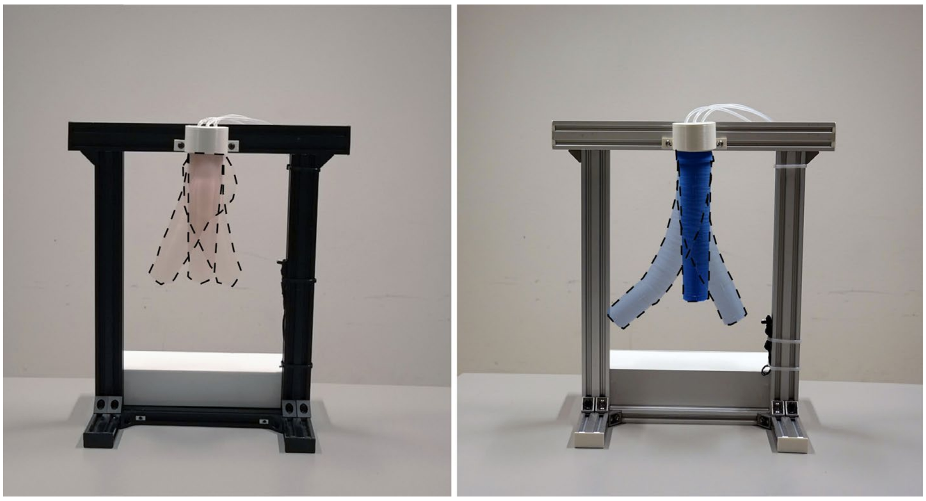
Fig. 4 Overlaid photos showing the movements of the two versions of the soft robotic platform. A dashed outline contour has been added for clarity

The second version (hereafter "blue robot") is equipped with a custom-designed, three-chambered tentacle constructed from Ecoflex 0050. It was wrapped with internal fiber reinforcements (braided fishing line 0.6mm 50kg) before a final layer of silicone was applied. The fiber reinforcements inhibit radial expansion, which constricts the movement so that the tentacle only expands and elongates along its central axis (see Fig. 4). Following fabrication, both tentacles were coated with talc powder to prevent lint and dirt from sticking to the surfaces.

We refer to the two soft robots as the "red robot" and the "blue robot" as convenient shorthands. However, these two robots differ in more ways than just with respect to their color. Taken together, the two soft robots cover different parts of the design space of soft robotics technology. As mentioned above, the tentacle of the red robot is cast in a slightly softer silicone than that used for the blue robot. Moreover, the fiber reinforcements of the tentacle on the blue robot provides a more efficient elongation and sideways movement of the tentacle and creates slight ridges along the tentacle upon inflation. The red robot, by contrast, expands significantly towards the sides, and bulbous bulges emerge on its sides upon inflation, with most pronounced expansion near the tentacle's top. The differences between the two soft robots are most adequately conveyed by the video included under supplementary materials (Online Resource 1).

2.3.2 Rigid robot platform

To establish a baseline for investigating whether soft robots are perceived differently than rigid robots, and whether they elicit different interactions, we constructed a version of the platform where the soft robotic element was replaced with rigid mechanical components (hereafter "rigid robot"). We deemed it important to use a rigid morphology of approximately the same size and shape as the two soft robots and one that was able to realize similar movements.

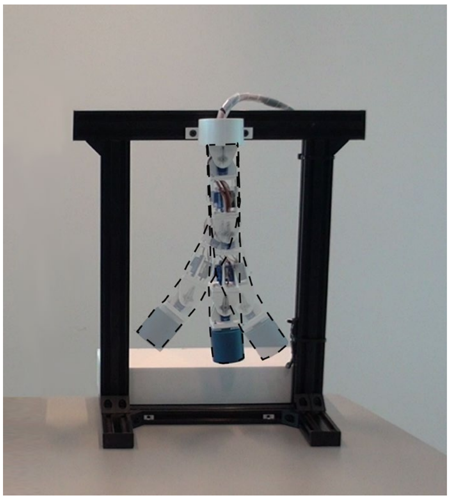

Fig. 5 The rigid version of the platform. A dashed outline contour has been added for clarity

We chose a morphology assembled from five servo motors (TowerPro SG90) and brackets from the Open Source modular system REPY-2.0 [34] that were 3D printed in white PLA (Fig. 5). Two of the servo motors were rotated 90 degrees around the central axis, giving the structure a three-dimensional range of motion similar to that of the soft robots. Many existing rigid robotic platforms have soft end effectors designed for manipulation, therefore a silicone cylinder in a blue color was cast onto the final bracket at the end effector using Ecoflex 0030. The rigid robot is controlled by an Arduino Uno microcontroller equipped with a sensor shield (Sensor Shield V5.0 Upgrade) supplied with external power (4.8V, 2A).

2.3.3 Soft robot behavior

The microcontrollers were programmed from within the Arduino IDE with a code that facilitates two interaction modes:

Mode 1: The user can observe the tentacle move on its own

Mode 2: The user can make the robot move towards their hand by positioning it in front of the IR sensor

Mode 1 is initiated whenever the IR distance sensor does not detect an obstacle within a range of approximately 4 cm. The robot then shifts between six preprogrammed movement sequences – three "breath-like" sequences, where the tentacle inflates and deflates rhythmically, and three "exploration" sequences, where the tentacle inflates to assume different positions within its range of motion. The "breathing" motion is meant to indicate that the robot is active but not currently engaged in a specific task, hence open to interaction. A similar type of rhythmic signaling is already used for this purpose in laptop computers and other equipment with LED lights, and is a nonverbal cue that is both familiar and recognizable to many people. The exploration sequences are designed to showcase the robots' movement dynamics and appearance when inflated.

Mode 2 occurs when the IR sensor is triggered by the hand of the participant. The tentacle then deflates and starts moving towards the hand. It moves for approximately 6 seconds before reaching the hand, and after this, it gently presses against the hand for approximately 6 seconds, before returning to its initial starting position.

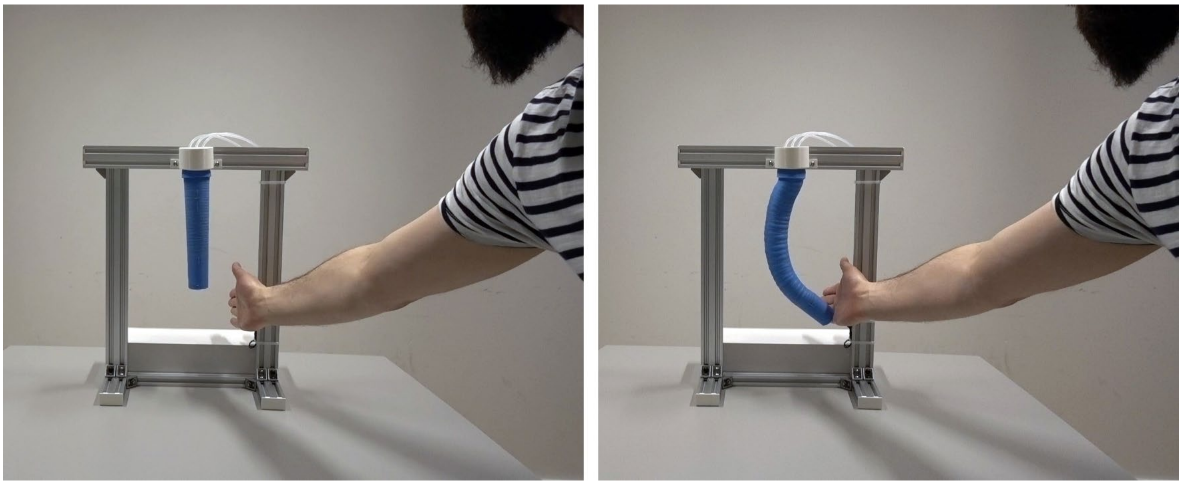

Fig. 6 Activation of the platform with the hand

The two interaction modes approximate semi-autonomous robot behavior that might be useful in real-life scenarios. In such situations, the robot would likely perform some tasks autonomously, but the user would also be able to guide or control its behavior.

The three robots are presented and their behaviors are demonstrated in the video Online Resource 1 under Supplementary Materials.

2.3.4 Rigid robot behavior

The rigid robot was programmed to approximate the movement of the blue soft robot as closely as possible. The Arduino code used for controlling the soft robots was revised so that the preprogrammed movements were accomplished by incrementing the angles of the five servo motors, rather than switching the pumps and valves on and off. This was done by implementing a function that takes the final five servo angles and the duration of the movement to be performed as input. The function then interpolates linearly between the current positions of the servo motors and their destined values. We observed the preprogrammed movements of the blue robot and wrote down all the different positions the tentacle assumes during each "exploration" sequence (e.g. "to the left right in front of the frame", "towards the user, then to the right, ends up near the sensor"). We then experimented with sending different servo values to the rigid robot until we obtained identical positions that were implemented into the code. The movements of the rigid robot were then compared with those of the blue robot, and final adjustments were made. As the “breathing” motion could not be replicated given the rigid morphology, they were replaced with small rocking movements where the string of servo motors moves slightly towards the user and then back to its resting position rhythmically. The same timing was used for all the movements of the rigid robot so that each movement for a given “exploration” sequence, “breathing” movement, and the movement to touch the hand had the same duration as for the two soft robots. We validated the replication of movements by switching the blue robot and the rigid robot on at the same time, and noticing that they performed very similar movements in almost perfect unison (see Fig. 7 and the video under supplementary materials (Online Resource 2)). Furthermore, we ensured that the force delivered from the rigid robot to the hand was as close to that of the blue soft robot by comparing the two and adjusting the rigid robot’s programming.

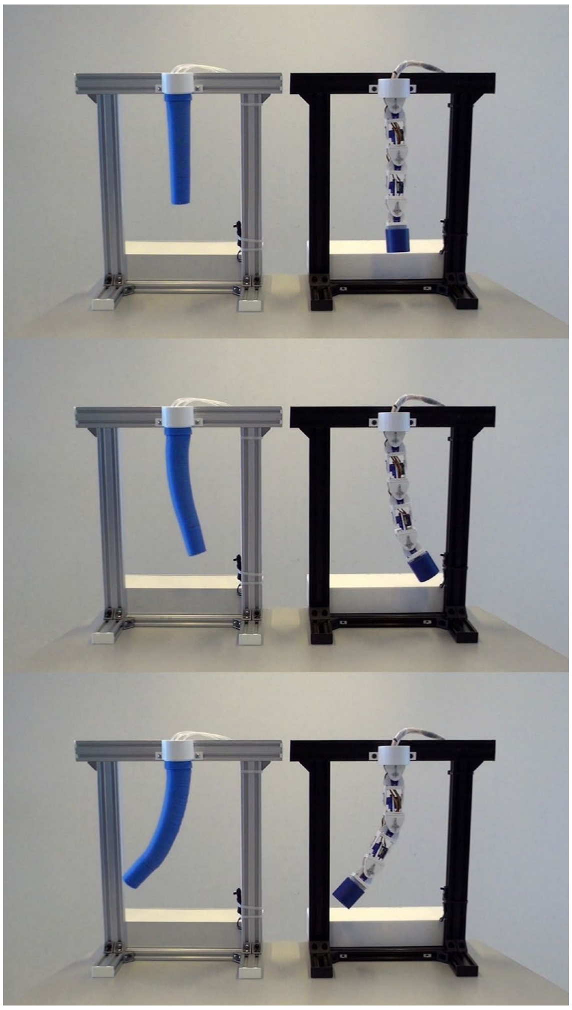

Fig. 7 Still images from video recording of the blue robot and the servo robot switched on simultaneously showing their similar movements. Video available under Supplementary Materials (Online Resource 1)

2.4 Setting

The interaction trials were carried out inside the library of a Danish university. Fig. 8 depicts the setup.

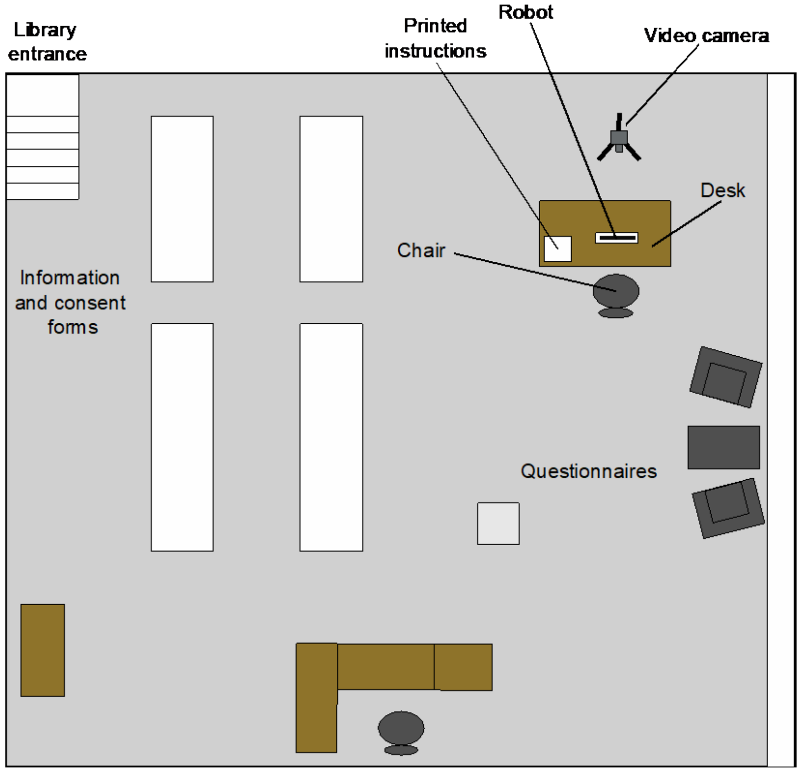

Fig. 8 Diagram of the setting based on the plan drawing of the building and measurements taken of the furnishings in the room

The trials with the red and blue robots took place in the evening outside of normal business hours as part of a citywide public event. During the event other research projects were exhibited at different locations on the university premises. The trial with the rigid robot was conducted during the day at a matchmaking event for college and university students within regular business hours of the library, and the library was frequented by a few non-participant passersby.

The decision to use an “in the wild” setting continues the recent interest within HRI research to conduct user studies outside of laboratories [29, 35–37]. Evaluating interactions in public settings opens up a rich space for observing how people intuitively respond to robots in social contexts. Studies conducted in public settings that capture bystanders and passersby yield insights into people’s perceptions in ways that go beyond the laboratory settings [38]. They are well-suited to reveal how different embodiments yield different interaction patterns, which is useful for understanding how people engage in physical interaction with a specific robot. We reasoned that a social setting would also be more conducive to unstructured dialogue about the robots that would reveal unexpected and nuanced perceptions. Moreover, having participants engage in voluntary, non-purposeful interactions with the robot could lead to freer and more varied interactions, and reveal examples of emergent interactions more relevant to real-world applications.

2.5 Procedure

Participants received information about the study and were given the opportunity to ask questions. They signed a consent form agreeing to be video recorded and, if they chose, to fill out a questionnaire. Participants were guided to one of the three robots. The two main robot interaction modes (see 2.3.3) were described verbally or by means of printed instructions placed beside the robot. Participants were instructed to interact with the robot for as long as they chose. They interacted with the robot individually or in pairs. Each participant interacted with only one robot. The interactions were video recorded with a single HD video camera that was visible to the participants (see Figs. 8 and 9). Following the interaction, participants were asked to complete a questionnaire on a computer or on paper. The entire study took approximately 15-20 minutes to complete.

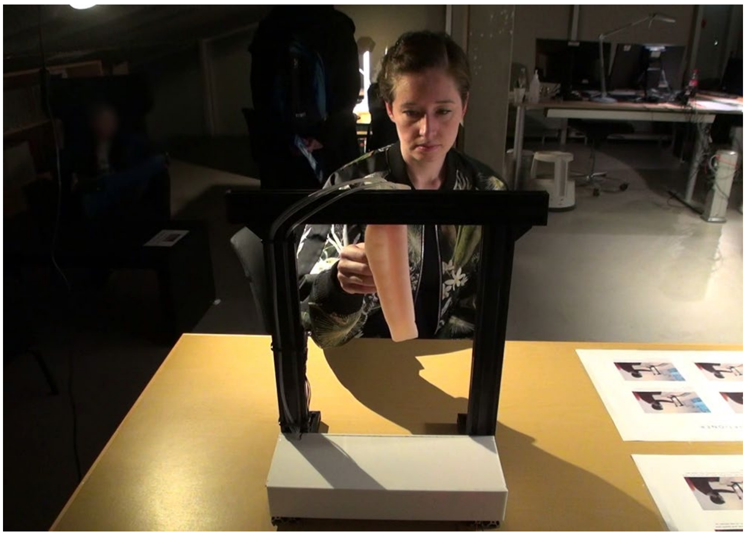

Fig. 9 Participant interacting with the red robot during the trial

2.7 Data collection and analysis

There are several established questionnaires and evaluation tools for studying HRI [10, 39, 40]. Because they refer to conventional rigid robots, we designed a questionnaire that address our specific research questions concerning people's perception of soft robots. The questionnaire contained Likert scale questions (1=Strongly Agree, 5=Strongly Disagree) and open-ended questions where participants could provide short written answers (the Likert scale questions are listed in Table 1 below, the two open-ended questions are stated in 3.2). We asked participants to rate how "natural" and how "appealing" they found the appearance, movements, and touch of the robot. We chose not to provide participants with any definition of "natural" and "appealing" as we wanted participants to respond using their own understanding of the terms. Epistemologically, the decision not to define "natural" and "appealing" is anchored in a contextualist stance, a theoretical position that mediates between the poles of essentialism and constructionism [39]. That is, by not providing definitions we sought to acknowledge that when individuals make meaning of their experiences, e.g. by categorizing something as "natural" or "appealing", the broader cultural context has influence on those meanings, yet the space of possible meanings is also constricted by the material limits of reality. We therefore also asked participants to write down what they understood by the word "natural". For each respondent, the ratings for naturalness of appearance, movements, and touch were added to yield an overall *perceived naturalness* score. Similarly, appeal ratings for appearance, movements, and touch were added to yield an overall *appeal* score.

We used statistical analysis to answer RQ1 and RQ2. RQ3 was answered through qualitative analysis. The study uses statistical analysis to question the substantive claim made by soft roboticists that soft robots are essentially more "natural", by comparing to what extent people agree to apply the word "natural" to the two soft robots and to the rigid robot respectively (while accepting the many different meanings this term encompasses). It should thus be clarified that the argument we present is not that soft robots and rigid robots are substantively equally "natural" in an essentialist sense. Rather, we simply demonstrate that empirically the word "natural" was not more readily applied by people to soft robots than to conventional robots.

2.7.1 Statistical Analysis

We used one-way between-groups analysis of variance (ANOVA), χ^2, or Fisher's exact tests, as appropriate to assess whether age, gender, and mean values of each Likert scale rating differed for the three robots. The same methods and Welch test were used to assess differences between the three robots in quantitative data variables extracted from the video recordings. The assumption of homogeneity was tested with Levene's test of homogeneity for variances that was fulfilled for all questionnaire questions except for question 1 ($p=0.042$), age ($p=0.000$), and interaction time for the video recorded interactions.

ANOVA was conducted to assess differences between the mean values for the primary outcomes for *appeal* and *perceived naturalness* (dependent variables) with *robot* (the robots numbered as 0,1,2) as the independent grouping variable with the significance level set to $p<0.025$ (adjustment for two comparisons).

A regression model was used to test whether *appeal* as a dependent variable was positively associated with *perceived naturalness* and *robot* as independent variables in the following model:

$$appeal = b_0 + b_1 \cdot perceived\ naturalness + b_2 \cdot robot + perceived\ naturalness \cdot robot$$

Adjustments for age, gender, and prior robot interaction experience were done in a secondary analysis.

2.7.2 Thematic Analysis

Video data was analyzed using *thematic analysis*, a qualitative method that is compatible with both essentialist and constructionist research paradigms. Thematic analysis is used to identify, analyze and report patterns (*themes*) within a given data set [41]. Thematic analysis explicates the necessary steps to go from raw data to interpretation and provides specific guidelines for moving through the different phases of a recursive hermeneutic process of analysis. We transcribed all audible verbal utterances in the video recordings verbatim with summaries of the physical actions between participants and robots. If two participants interacted with one of the robots simultaneously, this was counted as two separate interactions. As RQ3 (*What specific types of interaction behaviors do soft robots elicit? Do these behaviors differ from those elicited by a rigid robot of a similar design?*) is exploratory in character, we coded the transcriptions using an inductive approach.

2.8 Hypotheses

Based on our experience discussing soft robots at public and academic events [24, 42–44], we had formed the following hypotheses regarding the outcomes of the exploratory study:

H1: The soft robots would be rated as having a more "natural" appearance than the rigid robot.

> We expected that the appearance of both soft robots would be rated as more "natural" than the rigid robot, as their smooth, continuous surfaces and gradual expansion are reminiscent of living organisms. We also expected that the blue robot, due to its color (rarely found in nature) and slightly more constricted motion would be considered less "natural" than the red robot. We therefore tested if we could reject the null hypothesis that the soft robots would not be rated as having a more "natural" appearance than the rigid robot.

H2: Perceived naturalness and appeal for a soft robot would not be correlated.

We predicted that due to its “fleshy” and “organic” appearance, the red robot would probably be evaluated as having a more “natural” appearance than the blue robot but would not be rated as appealing. We tested if we could reject the null hypothesis that appeal is correlated with perceived naturalness.

H3: Respondents would define the word “natural” with many different meanings.

3.Results

3.1 Quantitative results

Table 1. Mean rankings and standard deviations for the rating questions. Answers were given on a 5-point Likert scale (1=Strongly Agree, 5=Strongly Disagree). Questionnaires from four participants that interacted with the red robot were incomplete. Answers from these have been included and missing answers for specific questions is indicated in the N column that gives the total number of replies for each question.

Question	**Red soft robot (N=47)**	**Blue soft robot (N=23)**	**Rigid robot (N=24)**	**N**	**p-value (ANOVA / χ^2)**
1. *The robot has an appealing appearance*	M: 3.36 SD: 1.05	M: 3.45 SD: 0.74	M: 3.50 SD: 0.83	93	0.82
3. *The robot's movements are appealing*	M: 2.85 SD: 1.00	M: 3.00 SD: 1.04	M: 3.08 SD: 1.10	94	0.65
5. *It is appealing to touch and be touched by the robot*	M: 2.79 SD: 1.20	M: 2.86 SD: 1.11	M: 2.96 SD: 1.00	92	0.83
2. *The robot has a natural appearance*	M: 2.94 SD: 1.09	M: 3.32 SD: 1.00	M: 3.17 SD: 1.24	93	0.38
4. *The robot's movements are natural*	M: 2.89 SD: 1.24	M: 2.41 SD: 0.91	M: 2.88 SD: 1.04	93	0.22
6. *The robot feels natural when I touch it and it touches me*	M: 2.72 SD: 1.08	M: 3.05 SD: 0.81	M: 3.29 SD: 1.08	92	0.08
7. *Appeal* (= 1.+3.+5.)	M: 9.00 SD: 2.70	M: 9.35 SD: 2.58	M: 9.54 SD: 2.36	91	0.68
8. *Perceived naturalness* (= 2.+ 4.+6.)	M: 8.55 SD: 2.69	M: 8.76 SD: 1.92	M: 9.33 SD: 2.63	92	0.47
Age	M: 37.3 SD: 13.2	M: 29.8 SD: 10.4	M: 26.0 SD: 5.09	94	0.00
Gender (female/male)	(22/25)	(10/13)	(13/11)	94	0.75
Prior robot interaction experience (no/yes)	(32/15)	(8/15)	(11/13)	94	0.02

A total of 94 non-randomized participants responded to questionnaires following interactions with one robot: either the red or blue soft robot, or the rigid robot. The results are presented in Table 1, which summarizes the mean values of the responses to the eight survey questions together with demographic data and statistics. The group of participants that interacted with the red robot was significantly older than the other groups (M:37.3 years as compared with 29.8 and 26.0 years). 54% of the participants self-reported no prior interaction experience with robots. There were statistically significant more robot interaction naïve participants in the red robot group compared with the blue robot and the rigid robot groups. The quantitative results respond to RQ1 (*Are soft robots perceived as more natural than traditional rigid robots?*) and RQ2 (*Is there a correlation between how natural and how appealing a robot is perceived to be?*) that are addressed in 3.1.1 and 3.1.2 respectively. The quantitative results are discussed more exhaustively together with the qualitative results under *4. Discussion*.

To confirm the internal consistency of our main data, an internal reliability test was conducted. Cronbach's alpha is commonly used to measure the internal consistency reliability among a group of items that are combined to form a single scale [10]. We obtained Cronbach's alpha values of 0.78 and 0.65 for *appeal* (7) and *perceived naturalness* (8) respectively. The first value is above the standard 0.70 threshold, whereas the second lies just below it. The latter is, however, expectable as Cronbach's alpha is sensitive to the number of items in the scale and increases when more items are included [45]. Hence, when we calculated the mean inter-item correlation, which is a more appropriate measure of internal consistency for scales with less than ten items [45], we obtained a value of 0.38 for perceived naturalness, which lies within the optimal range of 0.2 to 0.4.

3.1.1 RQ1: Are soft robots perceived as more natural than traditional rigid robots?

Results from the survey revealed no statistically significant difference in perceived naturalness for the three robots ($p > 0.05$). We predicted that the two soft robots would be rated as having a more "natural" appearance than the rigid robot (H1), because of their smooth, continuous surfaces and biomorphic bulbous shapes. However, we also did not find any statistically significant difference to support this hypothesis ($p > 0.05$).

3.1.2 RQ2: Is there a correlation between how natural and how appealing a robot is perceived to be?

We predicted that perceived naturalness and appeal would not be correlated for soft robots (H2), citing the red soft robot as a counter example that might be perceived as "natural" but not appealing, due to the potential uncanniness of its flesh-like appearance. Surprisingly, the quantitative results show a significant association between perceived naturalness and appeal ratings for all three robots ($b=0.62$, $F(2,84)=48.33$, $p<0.0001$). The *perceived naturalness*robot* interaction was insignificant ($p=0.60$) indicating that this association did not differ between the three robots. The main effect of *perceived naturalness* remained significant after adjustment for *age*, *gender*, and *prior robot interaction experience* ($p<0.0001$). Data were normally distributed. Preliminary analyses were conducted to ensure no violation of the assumptions of normality and linearity.

3.2 Qualitative analysis of written responses: What do participants understand by "natural"?

To categorize and explore the 90 responses obtained to the question "What do you understand by 'natural'?" (4 participants did not reply to this question), we started by comparing the responses with the six main meanings of the adjective "natural" listed in Oxford Dictionaries (OD) [46]. Of these, only two were applicable to any of the answers provided. The first of these was *Existing in or derived from nature; not made or caused by humankind*. Apart from replies that paraphrased this definition, we included responses that defined natural as being similar to natural organisms, as well as those using "organic" and "biological" as synonyms for natural within this category. The second definition from OD was *In accordance with the nature of, or circumstances surrounding, someone or something*. In this category, we included responses referring to natural as something intuitive, well-known, conventional, or habitual. The remaining entries that did not fit within these two definitions were categorized into three additional categories (see Table 2). These categories were established through an iterative process of semantic interpretation. First, two researchers independently generated a potential category that could contain the highest number of remaining uncategorized items. They then discussed and agreed on which of the categories that would contain the most items and established it as a novel category. This procedure was repeated until all items were categorized. However, 26 entries were not categorized as they were deemed to be too ambiguous. We observed no difference in the distributions within the different definitions of natural based on which robot the participant had interacted with.

Table 2. Categorization of the answers provided to the question 'What do you understand by 'natural'?'

Understanding of 'natural'	Examples	N
'existing in or derived from nature; not made or caused by humankind' (Oxford Dictionaries)'	'Something that is made in a natural process', 'Appears natural, not man-made', 'Something that is reminiscent of what nature has created', 'like a living being (animal)'	28
human-like	'human-like', 'something that is human', 'If a human did it / was it', 'That the movements happen in a natural and 'human' flow.'	14
'in accordance with the nature of, or circumstances surrounding, someone or something' (Oxford Dictionaries)'	'something that is not too different', 'Fits into surrounding context of the setting', 'happens without thinking about it', 'Things that are recognizable from everyday life and you can relate to'	12
opposes 'natural' with 'mechanical', 'robotic', 'artificial', or 'fake'	'Having non-machine or non-mechanical properties. Having non-linear motion' 'Not robotic/artificial', 'Non-artificial' 'That it does not appear mechanical' 'real, not fake'	8
defines 'natural' in relation to appearance, movement, and touch in a robot and answers tautologically	'something that appears natural in relation to movements, sound, shape etc.', 'resembling natural or coordinated movements'	2

3.3 Analysis of video recordings

We analyzed video recordings of the interactions in order to address RQ3 (*What specific types of interaction behaviors do soft robots elicit? Do these behaviors differ from those elicited by a rigid robot of a similar design?*).

We transcribed 62 video recorded interactions with the red robot, 42 interactions with the blue robot, and 25 interactions with the rigid robot. Four transcribed interactions with the red robot were excluded from analysis as it was apparent from the video that the robot was not functioning properly during these interactions (the robot had a ruptured chamber, which was fixed before the remaining interactions). Two transcribed interactions with the blue robot were excluded from analysis as the participants were students that assisted in conducting the study.

Table 3. Quantitative data extracted from video recordings and statistics

	Red soft robot (N=58)	Blue soft robot (N=40)	Rigid robot (N=25)	p-value (ANOVA / χ^2 / Fisher's test)
Interaction type (alone/in pair)	(46/12)	(32/8)	(17/8)	0.47
Interaction time (mins.)	M: 1.22 SD: 0.95	M: 1.37 SD: 1.04	M: 3.54 SD: 1.88	0.00
Participant touched by the robot (no/yes)	(29/29)	(8/32)	(3/22)	0.00
Participant touching the robot (no/yes)	(14/44)	(10/30)	(9/16)	0.51
Participant sitting during interaction (no/yes)	(15/43)	(4/36)	(1/24)	0.03

The interaction times for the rigid robot were statistically significantly longer than for the soft robots (p=0.00 in post hoc tests). We ascribe this in part to a change in the social context: there were markedly fewer people present in the library than at the previous event, and only rarely would a line form behind a participant to prompt them to conclude the interaction. Moreover, we speculate that at the first public event, participants were eager to leave and move on to other exhibits; hence participants interacted with the soft robots for a shorter period. There were statistically significant more participants that stood during the interaction with the red robot than with the blue and the rigid robot.

We coded the transcribed interactions using *thematic analysis* (see 2.7.2) and inductively discovered five main themes of the interaction and discourse: *1. Function/application*, *2. Perspective-taking/attribution of mental states*, *3. Speaking to the robots*, *4. Touch*, and *5. Safety*. Below we describe how the five themes reveal that specific types of interactions where recurrent for the soft robots. We also describe how these differ from the interactions with the rigid robot. Additionally, we offer interpretations of what the interaction behaviors reveal about participants' perceptions of the three robots. Within the first three themes (*1. Function/application*, *2. Perspective-taking/attribution of mental states* and *3. Speaking to the robots*) similarities in the interactions with the soft robots and the rigid robot are dominant. But within the latter two themes (*4. Touch* and *5. Safety*) marked divergences between the interactions with the soft robots and the rigid robot are detectable.

We illustrate the themes with selected excerpts from the transcriptions, in order to provide a nuanced picture of the interactions. In the excerpts, participants are denoted "red-", "blue-" and "rigid-" and a number that gives the order in which they interacted with the robot.

3.3.1. Function/application

Despite deliberately choosing a non-task driven, open-ended interaction, several participants mentioned potential applications for the robot they interacted with. Some also expressed a preference for having a specific function or specified action for the robot defined:

> *It is also like, when you don't know what it can do right?* (red-19)
>
> *What do you think it is supposed to do?* [pause] *I just don't see what function it has* [pause] *I think it would be nice to know what function it fulfils before one has to interact with it* (rigid-9). [rigid-8 interrupts] *You talk about that a lot* (rigid-8). *Yes, but that is what one is thinking right? What it can do?* (rigid-9)

3.3.2 Perspective-taking / attribution of mental states

We found indications that participants treated both the soft robots and the rigid robot as social actors. This is evinced by *perspective-taking*, a psychology term that describes the process by which people try to both perceive and understand a situation from another person's point of view [14]. Evidence of perspective-taking is seen in conversations, for instance when participants attribute the desire to "shake hands", or when the word "groping" is used (albeit jokingly) to describe the robot's actions (see 3.3.4). This suggests that, to some extent, people attribute mental states even to these simple robots and interpret their movements as intentional, which confirms previous work on perception [47] and conventional robots [48]. Further evidence for the perception of the robots as social actors is found in the verbal utterances, where participants imagine the sensory perspective of the robot (perceptual perspective-taking). But also in cognitive perspective-taking, where participants reason about the robot's possible cognitive states, for example what it "wants". The inability to cause the robot to touch a person's hand, for instance, would cause participants to speculate on the robot's social preferences:

> *It doesn't want to touch you* (red-9).
> *Maybe I am gross* [jokingly] (red-8).
> *It thinks you are gross* [while smiling] (red-9)

Cognitive perspective-taking also occurred in relation to other emergent interaction behaviors, for instance when the blue robot incidentally continued touching a participant's hand it was interpreted as a desire of the robot to prolong the touch:

> [The robot touches her hand. It is pressing on the hand and she pulls the hand slowly away, due to friction the tentacle sticks to the hand and bends as she removes the hand] *Oh god!* (blue-23) [both laughing]
> *Very clingy!* (blue-24)

That the non-anthropomorphic and non-zoomorphic robots used in the study evoke significant perspective-taking and attribution of mental states underscores the human propensity for intuitively responding to machines and other artificial systems as social entities [49, 50].

3.3.3 Speaking to the robots

The video data also shows people (N=7) speaking directly to the robots. Direct speech equally confers on the robots a discursive subjectivity: when participants speak directly to the robot it suggests they are relating to it as a social actor, but not necessarily a human one. In some interactions, the rigid robot and the blue robot were instead addressed in a manner similar to how one might speak to a pet:

> [she accidentally bumps her hand into the tentacle, which results in a slap-like gesture:] *Whoops!* [looks at the tentacle:] *I am sorry!* [starts laughing out loud] (red-21)
>
> [while the tentacle pushes on his hand:] *You might as well stop! I am going to stay here!* (red-29)
>
> [looks at the tentacle] *Are you coming over here?* (blue-9)
> *Cooome on…* [rubs the fingers on his one hand together and holds it in front of the robot while smacking his lips, speaks in a high-pitched encouraging voice:] *…Come on…Come on…* [the robot approaches his hand] *Ah, good booy!* (rigid-2)

3.3.4 Touch

Under all three conditions, a majority of participants touched the robot and many were also touched by the robot. For clarity, we treat these two behaviors separately. When the participant actively moves her hand towards the robot up until the point where contact occurs, the behavior is classified as the participant touching the robot. When the hand is held in a fixed position and touch is accomplished by the robot's movement, this is classified as the participant being touched by the robot. 76 percent of the participants that interacted with the red robot actively touched it, for the blue robot the number was 75 percent, and for the rigid robot 64 percent. 50 percent of the participants that interacted with the red robot were touched by the robot, this was the case for 80 percent for the blue robot, and 88 percent for the rigid robot (data available in Table 3). There were statistically significant fewer instances of participants that successfully got the red robot to touch their hand (see Table 3). We attribute this to the robot's slower and less visible movement towards the hand. This prevented many participants from noticing the robot's movement, and they retracted their hand from the sensor before the robot could reach it.

Touching the robot
A few participants were uncertain about whether they were also allowed to touch the robot, yet the majority of participants did so for all three robots. For the red robot, bystanders would sometimes even touch the robot for a short while, while someone else was interacting with it, which suggests an eagerness to do so. Some participants were intrigued to touch the robot, but also expressed ambivalence:

> *Oh, so I can touch it or?* [pause] *Actually, I don't really know if I want to* [smiles and then laughs] (red-21)

We observed a great variety in how people touched the soft robots. The types of touches ranged from gentle careful caressing, stroking, poking or squeezing to cupping, holding, bending, twisting, blocking, pulling, pushing or slapping the tentacles. Participants varyingly used everything from a single finger to both hands to touch the tentacle. Touches would occur almost anywhere on the surface of the tentacle. The forcefulness with which some participants touched the soft robots caused the red robot to rupture. A substantial portion of the participants (N_{red}=10) also placed their fingers on the bulge at the top of the red robot's tentacle that would form upon inflation. This often occurred while the bulge was starting to inflate with air, or when air was suddenly released.

For the rigid robot, people predominantly touched the soft end effector, only 3 participants (out of the 16 that touched the robot) touched the rigid robot anywhere else. Despite a longer interaction time, we observed far less variety in the touch behaviors for the rigid robot – there was no bending, holding, pulling, twisting, or slapping, and only two participants obstructed its path. Participants used one finger to five fingers, but only one hand. As can be seen in Fig. 12, the soft tentacles were also initially touched at many different points, whereas the rigid robot was primarily touched on the soft end effector.

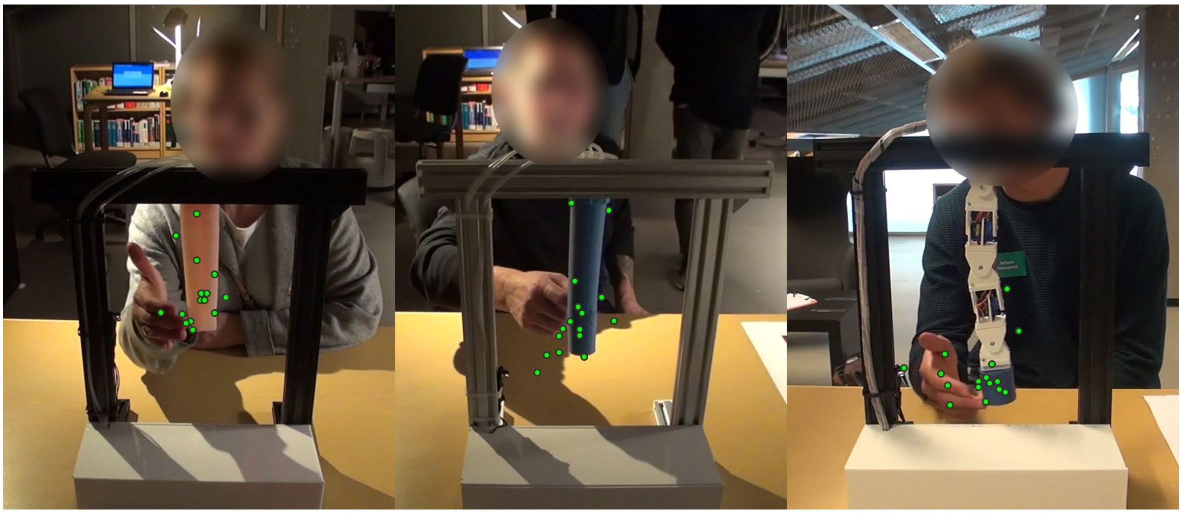

Fig. 12 The point where first touch occurs has been marked with a green dot for the first 16 participants that touched each robot. Dots placed beside the morphology are due to the robot bending while the touch is taking place

A video showing the range of touches from participants to the robots is available under supplementary materials (Online Resource 3).

Being touched by the robot
Several participants interpreted the movement where the robot initiated touch as socially communicative:

Then it actually, sort of, touched [pause] *I wonder if* [pause] *or if it, kind of, wants you to* (rigid-3)
It wants you to shake its hand (rigid-4)
Yes, or like – high five! (rigid-3)

For most participants, being touched by the robot appeared to be a somewhat transgressive yet simultaneously enjoyable experience:

> [The robot is nearing his hand] *It's groping me honey!* [he smiles] [while the robot is moving towards his hand in a high-pitched voice:] *Urghh!* (red-40) [he and bystanders all laugh]

3.3.5 Safety

We observed a marked difference in perceived safety for interactions with the red robot and the rigid robot. Following Bartneck et al. [7], we understand perceived safety to refer to the human user's perception of safety during interaction. This includes the perceived level of danger when interacting with the robot and the level of comfort during the interaction. Perceived safety does not refer directly to any of the indexes suggested for quantitatively measuring safety during physical HRI [50–52], but to the human experience of the interaction.
For the red robot, several participants expressed concern for the safety of the robot:

> *Try to touch it* (red-12 (boy)) [red-13 (boy) touches the tentacle with one finger and then wraps his hand around it near the middle] *No* [red-13's name]*!* (bystander (adult woman))
>
> *Be careful to not over-inflate it – boom!* [laughs] (bystander to red-25))
>
> *You should burst it!* (bystander (girl) to (red-26 (girl)) *Oooh…it does inflate a lot.* (red-26)
>
> *Argh! It's inflating a lot, so take your hand away* (red-45 to red-46). *Will it burst?* (red-45)
> *Oh, I guess it would* (red-46)

Whereas for the rigid robot, participants expressed concern for their own safety. In the quote below for instance, the participant compares the rigid robot to a snake that could potentially harm the person:

> *It is kind of like a snake that comes to you* (rigid-1)
> *Uh-huh...The way it just rolls in* (rigid-2)
> [The robot moves toward rigid-1's hand:] *Then it just comes and it is just like – chu!* [while assembling the fingers of his one hand together and making a gesture with his arm suggesting a snake that attacks] *Then it just strikes – krrr!* (rigid-2) [both smile]

In another instance, the same participant comments on the likelihood that the rigid robot might trap his hand:

> *Then it just pushes…hehe.* (rigid-1)
> *Then your hand is just stuck* [smiles] (rigid-2)

Similarly, while the blue robot and the rigid robot were calibrated to apply approximately the same force to the hand, only the rigid robot caused a participant to suddenly withdraw her hand:

> [When the robot touches her hand:] *Oh, it is kind of pushing me a little* [pulls her hand back and holds it close to her body] (rigid-8) […] [When the robot touches her hand again:] *Now it is actually pushing me a little* [pulls her hand back and holds it close to her body again]

By contrast, a participant instead speculated that the robot is not capable of significant physical force:

> *I don't think it has much force, it bulges out instead* (red-30)

The different reactions regarding perceived safety are noteworthy as they suggest different perceptions for different morphologies.

4.Discussion

The two main goals of this study were:

1) To investigate the claim that soft robots are more natural and more appealing than conventional robots
2) To gain insights into people's perceptions of soft robots and the spontaneous interaction behaviors that soft robots elicit

Below we discuss how our research findings contribute to these ends and what directions for further research and practice they project.

4.1 Moving beyond "natural"

The empirical findings of this study question how applicable and useful the word "natural" is for differentiating soft robots from traditional robots. Despite the conventional assumptions and claims that soft robots are more natural than rigid robots [6–8], no statistically significant difference in scores for overall perceived naturalness was found for the three robots. There were also no statistically significant differences in how natural the appearance, movement, and touch were rated. For this reason, we concluded that the quantitative analysis does not support the hypothesis that soft robots are perceived as more natural than traditional rigid robots. This result challenges prevailing assumptions about people's perceptions of soft robots as compared with conventional robots.

Secondly, we observed a wide range of responses when participants were asked to define the word "natural". This finding further suggests that language and discourse surrounding robot embodiments should be more carefully considered.

With regards to the specific hypotheses, H1 hypothesized that the soft robots would be rated as having a more natural appearance than the rigid robot, which proved not to be the case. A possible explanation for this result could be that the majority of participants responded with the meaning of natural as conventional or habitual in mind. For example, the blue robot might have been considered to have an "unnatural" appearance, as the color is rarely observed in natural organisms, while its softness simultaneously diverges from typical expectations about robots. Similarly, the rigid robot might have been perceived as moving naturally because it moves according to the principles of its mechanical design, which are evident from its appearance.

H2 conjectured that perceived naturalness and appeal would not be correlated, however our results demonstrate a significant relationship between perceived overall naturalness and overall appeal for all three robots. This could indicate that "natural" is used both as a descriptive term and as a term of positive valuation, as has previously been highlighted within discourse analysis [51, 52].

As anticipated by H3, we found that when asked to define the word "natural", participants used a variety of meanings to describe what they meant by the term. Somewhat surprisingly, "human-like" was a prominent descriptor, and it appeared even more frequently than one of the dictionary definitions. This result, however, echoes the tendency to interpret "natural" as meaning "human" when communication is discussed within social robotics research [53]. The two other most frequent meanings included natural as something existing in nature, or not man-made, and natural as familiar or habitual. The great variety in reported usages of the word "natural" further problematizes its use as a descriptor in technical literature that defines soft robots as more "natural". We interpret this result as evidence that the term "natural" is both ambiguous and imprecise, not just from a theoretical linguistic point of view, but also empirically in practice when it is used to describe a soft robot's qualities.

The word "natural" has dominated the discourse on human interaction with computer interfaces [54] social robots [53, 55], and now, soft robots. The results of this study make clear that the term natural is problematic, and we advocate that researchers be cautious of it when articulating claims about soft robotics and HRI. As argued by Hansen and Dalsgaard [54], words are not only descriptive but also formative: language shapes our perception and also our possibilities to act in the world. The words we use to describe robots and HRI matter because they ultimately help shape practice. It is therefore important to look closely at discourse surrounding emerging technologies, not least when considering a new class of robots. The uncritical use of the term "natural" could potentially pre-empt a necessary, nuanced examination of people's perception and appraisal of soft robots and their unique affordances. Hence, we urge researchers to consider how and when they use the term "natural" and consider adopting descriptive language that is less totalizing and ambiguous.

4.2 Similarities and key differences in perception and interactions

We found indications that all three robots were perceived as social actors, rather than simple technological tools (3.3.2, 3.3.3, and 3.3.4), despite the fact that they had no other capacity for communication than movement and were not designed with explicitly zoomorphic or anthropomorphic features. This finding suggests that even simple soft robotic systems can evoke social responses. We find this aspect of ascribed social agency worthy of further study, among other things because it would appear to problematize ethical guidelines recently put forth that recommend modeling human interaction with soft robots on human tool use rather than social interaction [56].

While participants did not rate the robots significantly different (3.1), it is evident from the video recordings that the soft and the rigid robots prompted considerably different interaction patterns and perceptions (3.3.4 and 3.3.5). From our analysis of the interactions, it is possible to identify two main take-aways that appear especially relevant for future soft robot designs to take into account.

4.2.1 Soft materials encourage touch

People were bolder when manipulating and physically exploring the soft robots than the rigid robot. Participants gripped and handled the entire surface area of the soft robots, even to the point of unintentionally damaging one robot. For the rigid robot, the touch that occurred was also almost exclusively (81% of participants) restricted to the soft end effector. We believe that these interaction patterns are important to consider for robot designers, as they connect directly to safety and reliability. Our findings suggest that soft silicone material invites touch in a way that rigid materials do not. From a design perspective, we therefore propose that only parts of a robot that can be touched should be made out of soft silicone: if the entire morphology is made of soft materials, as with the red and blue robots, people might feel safe (or perhaps even expected) to touch all parts of it.

That the soft robots were exposed to more forceful handling also suggests that for robots intended for close physical interaction with humans, durability is tantamount. Users are not familiar with soft robotics technology in the same way as with mechatronics and conventional robots, and we found that some people are under the false impression that a soft morphology can withstand almost anything. The timidity or caution that people show for conventional robots does not seem to carry over to robots made of soft materials. For close physical interaction scenarios, this can potentially pose problems for both the robot and also the person.

There are different plausible explanations for why touching occurs more intensively in interactions with the soft robots than the rigid robot, and why some people even started to touch the robots while other participants were interacting with them. One reason could be that people are unfamiliar with the technology and the material; hence, there is a strong desire or need to explore it tactilely to gain experiential knowledge about it, whereas rigid mechatronics are more well-known and users are well-aware that they can break from a too forceful handling. Research in psychology also provides possible explanations for this divergence in physical interaction. Harlow's historical experiments showed the innate preference of infant rhesus monkeys for soft, terry cloth-clad artificial mothers over bare mesh wire ones [57]. Moreover, the findings demonstrate the importance of soft body contact for subsequent psychological development, a finding that Harlow implied would most likely also apply to humans. Additionally, the psychological phenomenon known as *dimorphous expressions* [58] might also be relevant for soft robots: in the study researchers found that when presented with an image of something cute that produced positive emotions, people also experienced stronger aggressive expressions, such as wanting to pinch a baby's cheeks. Dimorphous expressions explain why people make both caring and aggressive gestures towards appealing stimuli: a soft body that is pleasing to touch could inadvertently also prompt aggressive touching or excessive force. This might explain why the soft robots prompted more brazen and rough interaction behaviors.

4.2.2 Soft robots might be perceived as more safe than rigid robots, but they are not inherently safer

That concern for human safety is only mentioned in interactions with the rigid robot suggests that soft robots could be perceived as more safe to interact with than similar shaped robots made of rigid materials, a finding that is consistent with a previous HRI experiment where rigid robots were covered with soft foam [59]. This might make it easier for users to accept soft robots than rigid robots as partners for collaborative tasks. On the other hand, our empirical tests showed that a soft robot body prompted more excessive force and handling, even to the point of breaking one robot during the trial. One might say that the soft design did not adequately communicate its physical limitations, and some people grossly overestimated its durability. Soft elastic materials might thus make people feel comfortable taking bigger risks in their physical interactions, but this is not advisable for all scenarios as it could lead to an overestimation of safety and underestimation of the risk of physical harm, which also depends on the context of use. Just as the design and materiality of conventional robots conveys important information about affordances, safety, and risk, so should the aesthetic design of soft robots accurately communicate these properties within a specific setting.

5. Conclusions

This study highlights the problematic character of the term "natural" when evaluating soft robotics technology. Within the emerging field of soft robotics, it has been a foregone assumption that soft bodies are more "natural" and therefore more appealing. The study did not support this claim: we found no statistically significant differences in appeal and naturalness ratings overall nor for the appearance, movements, and haptic qualities of the three robots individually. We did, however, find a correlation between overall perceived naturalness and overall appeal ratings for all three robots. We also found that robots made from soft and from rigid materials elicited very different interaction behaviors. From written questionnaires and video recordings of interactions, we found that the term "natural" is problematic and does not sufficiently reference perceptions and interaction in a meaningful way. For these reasons, we conclude that "natural" is an imprecise, and possibly even unproductive, term for evaluating soft robotics and HRI – while soft robots might be inspired by natural organisms and biology, evaluation frameworks would do well to leave out questions of "natural."

The study further reveals that nuanced, mixed methods approaches are needed to investigate how physical embodiment and materiality impact human interaction with soft robots. Good evaluation frameworks for soft robots result both from developing a more precise language to describe user perceptions and interactions, but equally from developing research methodologies that can adequately reflect and highlight the unique characteristics of the interactions with soft robots that emerge in practice. Our positive findings represent preliminary but important first steps in researching how soft robots and traditional robots might be said to differ with respect to HRI. They indicate that touch and perceived safety are potential aspects that might differentiate interaction with soft robots from interaction with traditional robots.

6. Limitations and further work

This study has problematized the notion that soft robots are more "natural" than traditional robots and has identified possible differences in how people interact with soft and traditional robots. The study, however, also has some limitations. One weakness is that participants were only asked to rate the robots in an open-ended, non-specific context. In order for the ratings to be transferable to specific applications/use-cases, the study would ideally account for the fact that specific embodiments and a specific aesthetic might be preferential for specific purposes. That is, a robot that is associated with safety and precision might be preferred for e.g. a health care context, but this consideration need not apply for e.g. an educational robot (cf. 3.3.1). Moreover, the lack of a specific task or goal in the interaction may have contributed to the perception of the robots as more subject-like. Another limitation is that the data reflects first impressions and interaction behaviors that might change or fade over time, as people learn to adapt to the robots. However, the findings give indications of how people perceive and interact with silicone-based soft robots upon the initial encounter, which is important to subsequent acceptance and adoption of a novel technology [60].

Context is also an issue to take into account in relation to the recruitment procedure and the execution of the two trials. Participants were recruited at public events on a university campus at an educational institution that focuses on information technology, and this might have biased the results. However, from the age range of participants (19-70 years) as well as the high proportion of human-robot interaction naïve participants (54%), it seems reasonable to assume that many participants were neither students nor faculty. The two trials were also conducted over two days: the trial with the soft robots took place in the evening as a part of a citywide event, while the trial with the rigid robot was conducted during the day at a matchmaking event for college and university students.

Another limitation of the study is the questionnaire, which we constructed in order to be able to address the specific research questions that motivated this study. Further work is needed to ensure the validity and reliability of this subjective self-reporting tool.

Based on statistical analysis, we concluded that our data could not support that soft robots are perceived as more natural than rigid robots. We did, however, observe lower mean scores, indicating a higher level of agreement, for the overall naturalness rating of the soft robots compared with the rigid robot. Hence, the inability of the results to support this hypothesis could be due to the study being statistically underpowered and hence unable to detect marginal differences.

Finally, this study is only a single case study where we used one specific type of soft robot. In order to determine differences in people's perception of and intuitive interactions with soft robots and traditional robots, further studies are needed. Moreover, the found differences should be replicated in studies with a higher number of participants to strengthen generalizability.

Supplementary materials

Online Resource 1: Video showing the three robots
(Also available at: https://youtu.be/8hOU0E_oXf0)

Online Resource 2: Video of the blue and the rigid robots' similar movement
(Also available at: https://youtu.be/ZIrrnUN9eiI)

Online Resource 3: Video showing examples of how the robots were touched
(Also available at: https://youtu.be/PbvmYUeNIiU)

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. Pfeifer R, Lungarella M, Iida F (2012) The Challenges Ahead for Bio-inspired "Soft" Robotics. Commun ACM 55:76–87 . https://doi.org/10.1145/2366316.2366335

2. Majidi C (2013) Soft Robotics: A Perspective—Current Trends and Prospects for the Future. Soft Robot 1:5–11 . https://doi.org/10.1089/soro.2013.0001

3. Rus D, Tolley MT (2015) Design, fabrication and control of soft robots. Nature 521:467–475 . https://doi.org/10.1038/nature14543

4. Verl A, Albu-Schäffer A, Brock O, Raatz A (2015) Soft Robotics: Transferring Theory to Application. Springer-Verlag, Berlin Heidelberg

5. Soft Robotics Inc. (n.d.) Customers Using Soft Robotics. In: Soft Robot. https://www.softroboticsinc.com/in-use. Accessed 11 Mar 2019

6. Zitzewitz J von, Boesch PM, Wolf P, Riener R (2013) Quantifying the Human Likeness of a Humanoid Robot. Int J Soc Robot 5:263–276 . https://doi.org/10.1007/s12369-012-0177-4

7. Rossiter J, Hauser H (2016) Soft Robotics - The Next Industrial Revolution? [Industrial Activities]. IEEE Robot Autom Mag 23:17–20 . https://doi.org/10.1109/MRA.2016.2588018

8. Laschi C, Mazzolai B, Cianchetti M (2016) Soft robotics: Technologies and systems pushing the boundaries of robot abilities. Sci Robot 1:eaah3690 . https://doi.org/10.1126/scirobotics.aah3690

9. Fong T, Nourbakhsh I, Dautenhahn K (2003) A survey of socially interactive robots. Robot Auton Syst 42:143–166

10. Bartneck C, Kulić D, Croft E, Zoghbi S (2009) Measurement Instruments for the Anthropomorphism, Animacy, Likeability, Perceived Intelligence, and Perceived Safety of Robots. Int J Soc Robot 1:71–81 . https://doi.org/10.1007/s12369-008-0001-3

11. Li H, Cabibihan J-J, Tan YK (2011) Towards an Effective Design of Social Robots. Int J Soc Robot 3:333–335 . https://doi.org/10.1007/s12369-011-0121-z

12. Wainer J, Feil-Seifer DJ, Shell DA, Mataric MJ (2007) Embodiment and human-robot interaction: A task-based perspective. In: RO-MAN 2007-The 16th IEEE International Symposium on Robot and Human Interactive Communication. IEEE, pp 872–877

13. Stollnberger G, Weiss A, Tscheligi M (2013) " The harder it gets" Exploring the interdependency of input modalities and task complexity in human-robot collaboration. In: 2013 IEEE RO-MAN. IEEE, pp 264–269

14. Cha E, Kim Y, Fong T, Mataric MJ (2018) A Survey of Nonverbal Signaling Methods for Non-Humanoid Robots. Found Trends® Robot 6:211–323 . https://doi.org/10.1561/2300000057

15. Suchman L (2007) Human-machine reconfigurations: Plans and situated actions. Cambridge University Press

16. Weiss A, Tscheligi M (2010) Special issue on robots for future societies: evaluating social acceptance and societal impact of robots. Int J Soc Robot 2:345–346

17. Kroos C, Herath DC (2012) Evoking agency: attention model and behavior control in a robotic art installation. Leonardo 45:401–407

18. Alač M (2015) Social robots: Things or agents? AI Soc 1–17 . https://doi.org/10.1007/s00146-015-0631-6

19. Penny S (2016) Robotics and Art, Computationalism and Embodiment. In: Herath D, Kroos C, Stelarc (eds) Robots and Art. Springer, pp 47–65

20. Goetz J, Kiesler S, Powers A (2003) Matching robot appearance and behavior to tasks to improve human-robot cooperation. In: The 12th IEEE International Workshop on Robot and Human Interactive Communication, 2003. Proceedings. ROMAN 2003. Ieee, pp 55–60

21. Bartneck C, Forlizzi J (2004) A design-centred framework for social human-robot interaction. In: RO-MAN 2004. 13th IEEE International Workshop on Robot and Human Interactive Communication (IEEE Catalog No. 04TH8759). IEEE, pp 591–594

22. Walters ML, Koay KL, Syrdal DS, Dautenhahn K, Te Boekhorst R (2009) Preferences and perceptions of robot appearance and embodiment in human-robot interaction trials. In: Procs of New Frontiers in Human-Robot Interaction. SSAISB, pp 136–143

23. Boer L, Bewley H (2018) Reconfiguring the Appearance and Expression of Social Robots by Acknowledging Their Otherness. In: Proceedings of the 2018 Designing Interactive Systems Conference. ACM, New York, NY, USA, pp 667–677

24. Jørgensen J (2018) Appeal and Perceived Naturalness of a Soft Robotic Tentacle. In: Companion of the 2018 ACM/IEEE International Conference on Human-Robot Interaction. ACM, pp 139–140

25. Milthers ADB, Bjerre Hammer A, Jung Johansen J, Jensen LG, Jochum EA, Löchtefeld M (2019) The Helpless Soft Robot - Stimulating Human Collaboration Through Robotic Movement. In: Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems. ACM, New York, NY, USA, p LBW2421:1–LBW2421:6

26. Zheng CY (2018) Affective Touch with Soft Robotic Actuators - A Design Toolkit for Personalised Affective Communication. In: Workshop: Reshaping Touch Communication: An Interdisciplinary Research Agenda, ACM CHI Conference on Human Factors in Computing Systems,Montreal. p 4

27. Zheng CY Soft grippers not only grasp fruits: From affective to psychotropic HRI. 4

28. Silvera-Tawil D, Velonaki M, Rye D (2015) Human-robot interaction with humanoid diamandini using an open experimentation method. In: 2015 24th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN). IEEE, pp 425–430

29. Vlachos E, Jochum E, Demers L-P (2016) The effects of exposure to different social robots on attitudes toward preferences. Interact Stud 17:390–404 . https://doi.org/10.1075/is.17.3.04vla

30. Portney LG, Watkins MP (2009) Foundations of Clinical Research: Applications to Practice, 3rd edition. Prentice Hall, Upper Saddle River, N.J

31. Bartneck C, Belpaeme T, Eyssel F, Kanda T, Keijsers M, Šabanović S (2020) Human-Robot Interaction: An Introduction, 1 edition. Cambridge University Press, Cambridge, United Kingdom ; New York, NY, USA

32. Papageorgiou XS, Tzafestas CS, Vartholomeos PP, Laschi C, Lopez R (2015) Ict-supported bath robots: Design concepts. In: Workshop of the 2015 7th International Conference on Social Robotics: Improving the quality of life in the elderly using robotic assistive technology: benefits, limitations, and challenges. Citeseer

33. Borgatti M (2013) A little background | Silicone Robo-Tentacle | Adafruit Learning System. In: Adafruit.com. https://learn.adafruit.com/silicone-robo-tentacle/a-little-background?embeds=allow. Accessed 11 Mar 2019

34. Estevez D (2013) REPY-2.0 Module by DEF. In: Thingiverse.com. https://www.thingiverse.com/thing:99207. Accessed 11 Mar 2019

35. Sabanovic S, Michalowski MP, Simmons R (2006) Robots in the wild: Observing human-robot social interaction outside the lab. In: Advanced Motion Control, 2006. 9th IEEE International Workshop on. IEEE, pp 596–601

36. Dautenhahn K (2018) Some Brief Thoughts on the Past and Future of Human-Robot Interaction. ACM Trans Hum-Robot Interact 7:4:1–4:3 . https://doi.org/10.1145/3209769

37. Kiesler S, Goodrich MA (2018) The Science of Human-Robot Interaction. ACM Trans Hum-Robot Interact 7:9:1–9:3 . https://doi.org/10.1145/3209701

38. Krummheuer AL (2015) Users, bystanders and agents: Participation roles in human-agent interaction. In: Human-Computer Interaction. Springer, pp 240–247

39. De Ruyter B, Saini P, Markopoulos P, Van Breemen A (2005) Assessing the effects of building social intelligence in a robotic interface for the home. Interact Comput 17:522–541

40. Heerink M, Kröse B, Evers V, Wielinga B (2010) Assessing acceptance of assistive social agent technology by older adults: the almere model. Int J Soc Robot 2:361–375

41. Braun V, Clarke V (2006) Using thematic analysis in psychology. Qual Res Psychol 3:77–101 . https://doi.org/10.1191/1478088706qp063oa

42. Jørgensen J (2017) Leveraging Morphological Computation for Expressive Movement Generation in a Soft Robotic Artwork. In: Proceedings of the 4th International Conference on Movement Computing. ACM, New York, NY, USA, pp 20:1–20:4

43. Jørgensen J (2017) Prolegomena for a Transdisciplinary Investigation into the Materialities of Soft Systems. In: ISEA 2017 Manizales: Bio-Creation and Peace: Proceedings of the 23rd International Symposium on Electronic Art. Department of Visual Design, Universidad de Caldas, and ISEA International, University of Caldas, Manizales, Colombia, pp 153–160

44. Jørgensen J (2018) Interaction with Soft Robotic Tentacles. In: Companion of the 2018 ACM/IEEE International Conference on Human-Robot Interaction. ACM, New York, NY, USA, pp 38–38

45. Briggs SR, Cheek JM (1986) The role of factor analysis in the development and evaluation of personality scales. J Pers 54:106–148 . https://doi.org/10.1111/j.1467-6494.1986.tb00391.x

46. natural | Definition of natural in English by Oxford Dictionaries. In: Oxf. Dictionaries Engl. https://en.oxforddictionaries.com/definition/natural. Accessed 18 Mar 2019

47. Heider F, Simmel M (1944) An Experimental Study of Apparent Behavior. Am J Psychol 57:243–259 . https://doi.org/10.2307/1416950

48. Hoffman G, Ju W (2014) Designing Robots With Movement in Mind. J Hum-Robot Interact 3:89–122 . https://doi.org/10.5898/JHRI.3.1.Hoffman

49. Reeves B, Nass CI (1996) The Media Equation: How People Treat Computers, Television, and New Media Like Real People and Places. Cambridge University Press

50. Ghedini F, Bergamasco M (2010) Robotic creatures: Anthropomorphism and interaction in contemporary art. In: 19th International Symposium in Robot and Human Interactive Communication. IEEE, pp 731–736

51. Barthes R (2009) Mythologies, Revised edition. Vintage Classics, London

52. Foucault M (2001) The Order of Things: Archaeology of the Human Sciences. Routledge, London

53. Sandry E (2015) Re-evaluating the Form and Communication of Social Robots. Int J Soc Robot 7:335–346 . https://doi.org/10.1007/s12369-014-0278-3

54. Hansen LK, Dalsgaard P (2015) Note to Self: Stop Calling Interfaces "Natural." In: Proceedings of The Fifth Decennial Aarhus Conference on Critical Alternatives. Aarhus University Press, pp 65–68

55. Dautenhahn K (2013) Human–robot interaction. In: Lowgren J, Carroll JM, Hassenzahl M, Erickson T (eds) The encyclopedia of human– computer interaction., 2nd ed. The Interaction Design Foundation, Aarhus

56. Arnold T, Scheutz M (2017) The Tactile Ethics of Soft Robotics: Designing Wisely for Human–Robot Interaction. Soft Robot 4:81–87 . https://doi.org/10.1089/soro.2017.0032

57. Harlow HF, Zimmermann RR (1959) Affectional Responses in the Infant Monkey. Science 130:421–432

58. Aragón OR, Clark MS, Dyer RL, Bargh JA (2015) Dimorphous Expressions of Positive Emotion: Displays of Both Care and Aggression in Response to Cute Stimuli. Psychol Sci 26:259–273 . https://doi.org/10.1177/0956797614561044

59. Block AE, Kuchenbecker KJ (2018) Softness, Warmth, and Responsiveness Improve Robot Hugs. Int J Soc Robot. https://doi.org/10.1007/s12369-018-0495-2

60. Eggink W, Snippert J (2017) Future Aesthetics of Technology; context specific theories from design and philosophy of technology. Des J 20:S196–S208 . https://doi.org/10.1080/14606925.2017.1352748

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