International Journal of Social Robotics
https://doi.org/10.1007/s12369-023-01037-6

ORIGINAL RESEARCH

"It Brings the Good Vibes": Exploring Biomorphic Aesthetics in the Design of Soft Personal Robots

Mads Bering Christiansen[1] · Ahmad Rafsanjani[1] · Jonas Jørgensen[1]

Accepted: 1 August 2023

Abstract

The flexible bodies of soft robots provide exciting new possibilities for interaction with humans. In this paper, we propose a novel design paradigm, Soft Biomorphism, for soft robots centered on the idea of amplifying their inherent biomorphic aesthetic qualities and activating these as affordances for human interaction. Following this approach, we developed a set of biomorphic soft robotic prototypes and conducted two studies to understand the effects of biomorphic design aesthetics on people's impressions of these prototypes. Based on qualitative data collected through five workshop sessions, the first exploratory study (n = 10) sought to investigate the envisioned uses and types of interactions that prototypes elicited within the context of personal robots. We found that various uses were considered and that most participants associated the biomorphic aesthetic design with soft robots contributing to emotional and physical well-being. Building on these results, we conducted a second study (n = 32) to investigate if soft robots with enhanced biomorphic qualities are perceived as more appealing and appropriate for physical human–robot interaction aimed at supporting well-being. We did not find any statistically significant preference for biomorphic soft robots. However, we found statistically significant differences in appeal ratings post-interaction for some prototypes, suggesting that physical interaction with soft robots can impact the perceived appeal. Based on our findings, we highlight key issues to bear in mind when considering biomorphic aesthetics in soft personal robot designs and provide tentative design recommendations to combine biomorphic and geometric elements and align visual appearance, tactility, and movement in future robot designs.

Keywords Human–robot interaction · Soft robotics · Biomorphism · Design aesthetics · Personal robots · Well-being

1 Introduction

Soft robots are made of compliant materials with mechanical similarities to soft biological tissue, and their design is often anchored in biomimicry and bioinspiration [1, 2]. Biomimetics proceeds by imitating mechanisms and processes in nature to solve tasks, while bioinspired design seeks to abstract general principles from nature for technological purposes [3, 4]. While these dominating design approaches to soft robotics have succeeded in imbuing soft robots with impressive capabilities, they disregard the aesthetic dimension of robot design. This potentially could be detrimental to achieving practical use of soft robots in human-centered applications, as a robot's aesthetic design demonstrably impacts human–robot interaction (HRI) on multiple levels [5–7]. Moreover, soft robots have a radically different embodiment and appearance than traditional robots, which is plausible to affect, e.g., attributions of sociality, emergent physical interaction, and perceptions of robot agency [8]. Prior work has proposed that soft robots are well-suited for assistive and care robots because they can engage in safe tactile physical interaction [9], are capable of more complex emotion expressions due to their soft materials [10], and, in addition, have a friendlier or more lifelike appearance than traditional robots [11]. The latter is also a highly desirable trait for personal robots that assist or provide entertainment for people in a domestic environment [12, 13]. Although the aesthetic aspects of soft robots have recently been explored in art, design, and architecture (e.g., [14–20]), no prior work

✉ Jonas Jørgensen
jonj@mmmi.sdu.dk

Mads Bering Christiansen
mabc@mmmi.sdu.dk

Ahmad Rafsanjani
ahra@mmmi.sdu.dk

1 SDU Soft Robotics, SDU Biorobotics, University of Southern Denmark, Campusvej 55, DK-5220 Odense M, Denmark

Published online: 02 November 2023

has interrogated what constitutes appropriate aesthetic design criteria for soft personal robots specifically. Prior work has, however, recently called for further study of human perceptions and acceptance of soft robots to enable implementing soft robotics in socially assistive robots [10].

In this article, we introduce the concept of *Soft Biomorphism* to describe formal attributes of soft robotic objects (e.g., their visual appearance, texture, and movements). Soft biomorphism also denotes an alternative design paradigm for soft robotics centered on enhancing their inherent organic aesthetic qualities. In our work, we aim to inductively uncover appropriate contexts and applications for this design aesthetic empirically. I.e., contrary to most work within robotics, wherein the design is derived from the application of the robot, we aim to utilize this specific robot design aesthetic as a driver for discovering matching types of interactions and applications for soft robotics.

It has been hypothesized that humans are genetically attracted to life and lifelike things [21] and shown that contact with nature can improve human health and well-being [22–25]. Biologically inspired traits are also already used in several product designs, ranging from everything between cars to furniture, for both practical and aesthetic purposes [26–29]. Moreover, lifelike traits can improve the likability of robots [30], and organic robot appearances can help trigger social responses from humans in HRI [31, 32]. It can thus be argued that biomorphic robot designs are beneficial for robots aimed at social HRI. Considering these points, soft biomorphism can plausibly prove a desirable design aesthetic for personal robots that feature soft robotics technology.

The present work consists of a first exploratory phase focused on soft biomorphism and a follow-up study specifically addressing human well-being. Initially, our work did not set out to address well-being and HRI. Instead, its focus was to explore soft biomorphism as a design space and a design principle and its potential for soft personal robots more broadly. However, in our first exploratory study, we found close ties between the soft biomorphic design aesthetic and robot applications related to improving human well-being. These findings led us to further investigate soft biomorphism as a potential design aesthetic for embodied agents for well-being. Through design practice and two studies, the present work thus explores soft biomorphism as a design aesthetic, its potential benefits for soft personal robots, and its appropriateness for robots intended to support well-being. Specifically, the article addresses the following research questions:

RQ1 *How can the organic and lifelike qualities of silicone-based soft robots be amplified through their aesthetic design?*

RQ2 *Which ideas about personal robot applications, interactions, and relations do soft robots with enhanced biomorphic features elicit from potential users?*

RQ3 *Are soft robots with enhanced biomorphic features considered more appealing and more appropriate for applications wherein soft robots are used to support well-being through physical interaction?*

2 Related Work

We position this work within research on robot design and embodiment, personal robots, human interaction with soft robots, and soft robots for human well-being.

2.1 Embodiment in HRI

An indispensable property of robots in real-world environments is their physical embodiment [8]. The design of a robot's body has proved to affect various facets of HRI, such as how users experience, e.g., the social presence of robots [33, 34], their levels of comfort and trust [35, 36], empathy [37], attractiveness [38], and enjoyment [35, 38]. Furthermore, utilizing soft materials in the design of social robot morphologies have been explored for intimate HRI [39], and it has been shown that the inclusion of soft materials increases perceived safety and comfort in close HRI [40]. While one of the most used design approaches for robots is anthropomorphism [41], anthropomorphic robot designs have also been criticized, e.g., because people might wrongfully attribute anthropomorphic robots the same social, intellectual, or emotional capacities as humans, which can lead to a decrease in satisfaction with HRI [42–44]. Moreover, it has been argued that designers lose design freedom and aesthetic control when robots are dominated by anthropomorphic or zoomorphic features, which can lead to suboptimal designs [43].

2.2 Personal robots

Following prior definitions of personal service robots [12, 13], we consider a *personal robot* a robot that operates in a domestic setting, either to help one or more people with practical tasks, provide entertainment, or keep people company. Studies have shown people to have a positive attitude towards living with robots [45–47], and previous research has investigated the effects of robot movement [48, 49], interaction modalities [50, 51], capabilities [52, 53], and robot appearance [54–56] in relation to personal robots. Due to the expected impact of personal robots in future societies, there has been a call for further research on how a robot's physical design and its behavior impact human expectations towards it [13].

2.3 Soft robotics and HRI

Only a few studies have investigated various aesthetic designs of soft robots, and the capacities of soft robots for social and physical interaction with humans. Boer and Bewley [57] sought to encourage a broader understanding of possible social robot designs by approaching soft robotics with a focus on their performative qualities and "otherness". Their designs gave rise to ideas of HRI of a playful, negotiable, and curious character. Zheng and Walker [58] investigated soft robotics artifacts focusing on affective HRI and found that their soft robotic artifacts attracted emotional investment due to their "biomorphic quality", kinetic forms, and compliant materials. Budak et al. [59] created a soft robotic "breathing" wall with a biomorphic design aesthetic to explore the potential of human interaction with imitated organic life that challenge the distinctions between organic and synthetic, subject and object. Jørgensen et al. [60] questioned the presumption that soft robots are more "natural" than rigid robots, with findings indicating that both soft and rigid robots can evoke social responses and are ascribed social agency, even if not being designed with distinct zoomorphic or anthropomorphic attributes. Moreover, their findings showed that soft robots appear to invite touching and might be perceived as safer. Klausen et al. [61] and Farhadi et al. [62] explored the possibility of conveying emotions and communicative signals to a user by altering a soft robot's breathing rate, movements and shape, discovering that participants perceived varying levels of arousal and pleasure at different breathing rates.

2.4 Robots and well-being

While numerous studies have explored robots' abilities to support human health and well-being (for systematic reviews, see [63, 64]), only a few have focused more specifically on soft robots within this context. Asadi et al. [65] investigated whether people would synchronize their breathing rhythm with a soft robot by touching it while performing different tasks. Their results suggest that although participants who touched the robot did not synchronize with the robot's movement rhythm, touching a "breathing" soft robot can lead to brain patterns indicative of an increased positive emotional valence. Haynes et al. [66] examined soft robotics as a haptic technology for lessening anxiety by developing a pneumatically actuated huggable interface simulating slow breathing. Through an anxiety-inducing mixed-design experiment, the researchers found that the haptic interface effectively reduced pre-test anxiety in a manner similar to guided meditation. In a qualitative study, Hall et al. [67] explored soft robotics technology in a healthcare setting by developing haptic soft robotic prototypes mimicking attributes of affective human touch intended to reduce procedural anxiety in radiotherapy. Feedback from patients, healthcare professionals, and carers suggest that flexible devices, which can be used on the body and provide pulsation sensations, could be used to reduce procedural anxiety and calm down patients in the given context. Sabinson and Green [68] sought to reduce stress and regulate emotional states in confined spaces through a therapeutic wall-mounted soft robotic surface that initiated different inflation patterns. Comparing their soft robotic prototype with a 2D graphic vector, the researchers found that the participants who followed the exercises led by the soft robotic prototype had significantly lower perceived stress levels, and that the prototype's visual characteristics helped some participants focus and breathe deeper.

2.5 Summary

To summarize, prior work has addressed some of the effects of embodiment on HRI in general and various aspects of personal robot designs, soft robots and HRI, and more specifically, soft robots and well-being. However, research on soft personal robots and their aesthetic design has not yet been conducted. In general, more research is equally needed on the effects of embodiment on HRI and perceived agency with respect to soft robotics specifically, and how their aesthetic design might modulate these [60].

3 Soft Biomorphism

Biomorphism is used as a concept within art, design, and architecture to characterize organic, lifelike, abstract, or curvilinear forms [69] that evoke or refer to living organisms [70]. Similar to [71], we understand "*organic*" to refer to something that consists of or is derived from living matter. Biomorphic forms are thus "nature-centric" or "biologically-shaped" and relate to natural phenomena without being direct representations of them [72], a form of "nature abstracted into new nature" [73].

In the present work, we use *Soft Biomorphism* to characterize the aesthetics of a specific class of soft robot designs that emphasize visual, material, and kinetic resemblance with soft natural organisms. Thus, soft biomorphism encompasses both the object's form as well as its tactility and movement. Drawing on prior descriptions of biomorphic forms [69, 72, 74–76], we take soft biomorphic forms to include curvilinear, sweeping, bulbous, convex, or concave, annular, irregular, rugged, arciform, or asymmetrical forms. The added "soft" in "soft biomorphism" refers to physical softness [2] and not symbolic or figurative softness (e.g., as in a "soft voice"), hence soft biomorphic designs also afford sensations similar to those of touching a living soft-bodied organism. Soft biomorphic movements are taken to be akin to the anatomical movements and dynamic movement patterns of living organisms and can be flowing, and smooth, as well as erratic, or gyrated. Soft biomorphic robot designs may vary in their degree of abstraction or realism with respect to their representations of soft natural organisms in a robot's form, tactility, and movement. While audio can also be included as a factor in soft biomorphism (see, e.g., [14]), the exploration of this aspect lies beyond the scope of this work.

The rationale behind proposing soft biomorphism as a design principle is to enable the design of soft robots that appear lifelike yet unfamiliar to facilitate more open-ended and negotiable human–robot relations, that are not modelled on, for instance, the interactions with an animal or a pet. Prior work has argued that robot designs with forms and behaviors open to interpretation may offer increased opportunities for long-term relations between humans and robots because communication can be more varied and engaging over longer time [77]. An advantage of designing robots after animal models instead of choosing an anthropomorphic design is that a robot's limited behavioral, cognitive, or perceptual abilities may be reflected clearer through its appearance [78], thereby supporting the establishment of more appropriate social expectations about the robot [79]. Basing designs on familiar animals, such as domestic pets, however, may also lead to people having expectations about a robot's abilities that cannot be met, potentially resulting in termination of interaction with the robot [78]. It has also been argued that zoomorphic robots designed to be perceived as certain animals are unethical [80], and that robot designs should be based on unfamiliar animals to avoid misconceptions about robot abilities [81]. Thus, where anthropomorphic and zoomorphic robot designs may generate (misleading) expectations about a robot, the abstraction of nature in biomorphic designs can provide familiar cues for intuitive social interactions that may be explained by our inherited inclination towards nature and lifelike things [82]. By eschewing replication of a particular animal or organism, more design freedom is also obtained, while the impression of the robot as a responsive interaction partner can still be conveyed through visual, haptic, and kinetic similarities with natural organisms in general. We believe this can lead to more appropriate robot designs and more interaction possibilities compared to relying on zoomorphic or anthropomorphic designs (e.g., see [77]). In this work we thus explore soft biomorphism as a design principle as well as a design aesthetic and examine which uses and interaction possibilities this design aesthetic suggest to users. In that sense, our work reverses the renowned axiom "*form follows function*" [83], as we instead use aesthetic design as a starting point and a driver for discovering practical functionality and HRI modes. Hence, our approach acknowledges the inherent interdependence of form and function, aiming to explore the ways in which soft biomorphic appearance can influence and inspire function within HRI.

4 Prototypes Designs

The prototypes were developed through design practice with soft robotics and silicone materials. The focus in the aesthetic practice was not to design visually appealing designs but, instead, to make an uncritical investigation of the breadth of soft biomorphism as a design space. Consequently, some of the prototypes may be deemed odd, unappealing, or eccentric, and radically divergent from traditional robots. We chose to include designs that we ourselves found aesthetically pleasing or beautiful as well as those we found off-putting to allow for contrasts and more specific assessments of their various facets to emerge in discussions of them with potential users.

In two consecutive rounds of design experiments aimed at exploring **RQ1**, we first created soft surfaces and then static and dynamic three-dimensional objects. The first round of design experiments focused on ways of manipulating silicone rubber's visual and haptic attributes through texturing and pigmenting. In the second round, both static as well as dynamic prototypes, which could move and change shape by being pneumatically actuated, were explored. An Arduino UNO microcontroller, with a custom motor shield driving three low-noise pumps (MITSUMI R-14 A213) and three solenoid valves (Uxcell Fa0520D 6V NC), was used to simultaneously control the dynamic prototypes. Nine out of a total of 15 soft biomorphic prototypes were selected for inclusion in the studies (see 5 Study 1 and 6 Study 2). The selection was made to capture the variety of the design space, and we additionally chose designs with open and negotiable qualities and identities. The selected prototypes thus feature different *affordances* [84–86] for interaction: flat, smooth surfaces, for instance, may invite touch and stroking, while rounded shapes can encourage holding the objects, and pointy or limb-like shapes can afford grasping. In future work on soft biomorphism, criteria or parameters for choosing representative soft designs could be chosen explicitly, to reduce

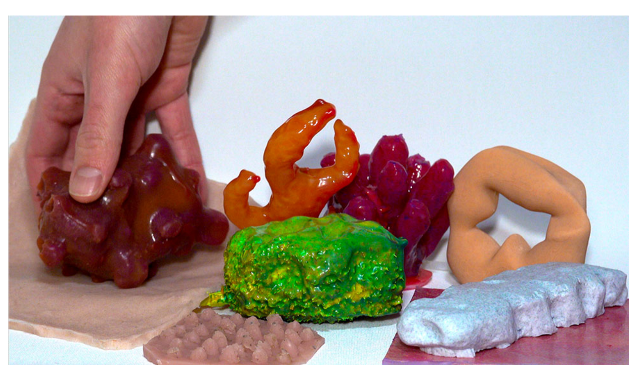

Fig. 1 The selected soft biomorphic prototypes. A human hand is included in the photo to give an impression of their sizes

subjectivity in the process. By systematically assessing and selecting prototypes based on parameters such as form, tactility, movement, or levels of abstraction versus realism, it would be possible to ensure a more representative sampling of the design space and a more transparent and reproducible selection process.

The selected prototypes (see Fig. 1) are presented individually in Table 1. The reader is highly encouraged to watch the supplementary video (https://youtu.be/col9OP5FcPw) to get a better impression of the prototypes.

5 Study 1

The purpose of the first study was to explore which ideas about personal robot uses, interactions, and relations that would emerge in people's encounters with prototypes featuring biomorphic traits. *Interactions* are situations where two or more entities react to each other over a short time span, and *relations* instead denote how two or more entities behave towards each other, and may be of a longer duration [87, 88]. A design evaluation workshop was held in five renditions, each with two different participants and the first author as facilitator (see Fig. 2). As the study was conducted amidst a COVID-19 lockdown, measures were taken to reduce the spread of disease, and the five sessions were organized in small groups consisting of people who lived together. Inspired by common practice within *participatory design* and *co-design*, we sought to facilitate active partaking from participants through this format [89–91]. Video recordings of the sessions were made with a camera on a tripod.

5.1 Participants

The 10 included participants (female: n = 5, male: n = 5; age: range 26–53 years, M = 33.10, SD = 10.28) were a convenience sample and had professions in areas including engineering, pensions, publishing, and audiologopedics. 80% (n = 8) stated no familiarity with robots, and the rest (n = 2) that they knew only little about robots. All participants were Danish citizens living in Copenhagen, Denmark. Each workshop session featured one female and one male participant that were in a domestic partnership. It was a coincidence and not a deliberate choice that only heterosexual couples were recruited. The participants did not receive any compensation for their participation.

5.2 Procedure

Each workshop session had a duration of 54 to 66 min. After receiving information about the study and signing consent forms, the two participants were briefed that the research aimed at exploring how to design soft personal robots. They were informed that they would be shown different prototypes, which they were allowed to touch. The prototypes' names were not disclosed to prevent biasing associations.

The first exercise was a warm-up exercise to initiate thinking about personal robots. The participants were asked to imagine that they had their own unique personal robot at home and asked to describe briefly what this robot could do, how they would use and interact with it, how it looked and what materials it was made from.

The second exercise ("show and tell") sought to investigate if specific or recurrent visions of interactions and relations were triggered in the meeting with our soft biomorphic prototypes. After revealing the prototypes, the participants were asked to envision them as elements or whole bodies of personal robots, and that all prototypes were capable of movement. The first participant was asked to choose one of the soft biomorphic surfaces (Table 1, prototypes 1–3) and the second was asked to choose one of the static soft biomorphic objects (Table 1, prototypes 4–6). Both participants were then asked to give a detailed description of their chosen object, share their impression of it, and to consider what actions they imagined it to perform and in which contexts.

In the third exercise, the participants were given 10 min. to collaboratively come up with a future scenario that featured a personal robot and took place in a domestic setting. The exercise was inspired by *fictional inquiry* [92], a design method wherein roleplay is used to interrogate people's visions of desirable futures. It also drew on the *co-constructing stories* technique [93], in which storytelling, focused on past experiences and anticipated future experiences, is used for formative design concept feedback and to reveal potential users' attitudes and visions. The participants were asked to include one of the three dynamic soft biomorphic prototypes (Table 1, prototypes 7–9) in the story and to envision that it took place in the future, and that the story's characters were very familiar with the robot.

In the fourth and final exercise, the two participants were asked to revisit their responses from the first exercise and reflect on if their encounters with the soft biomorphic prototypes had influenced their ideas of an ideal personal robot, as they might not have been familiar with this technology when formulating these, and if the soft prototypes might be integrated into their ideal personal robots (see Fig. 2).

5.3 Thematic Analysis

To analyze the collected video data from the workshop, we transcribed the video recordings (speech and actions performed) and conducted a thematic analysis using an inductive coding scheme [94, 95]. Two of the authors read through the transcription and established preliminary codes separately, which they shared with each other and mutually agreed on

Table 1 The soft biomorphic prototypes selected for the first study and their attributes and design inspirations (The images of prototypes 1–3 are cropped and magnified to show the surface textures, and show squares of the following sizes: 1 displays 5 × 5 cm; 2 displays 10 × 10 cm; 3 displays 20 × 20 cm)

Soft biomorphic surfaces			
	1. *Rugged Surface*	2. *Colored Surface*	3. *Skin-like Surface*
Soft biomorphic attributes	Rugged, round parts, irregular in size, placement, and texture	Irregular and asymmetrical surface textures	Rugged surface texture; elevated, tortuous, and curvilinear bumps
Inspiration	Mammalian skin tags, and nipples	Mammalian skin texture	Mammalian skin, veins, and pores
Static soft biomorphic objects			
	4. *Claw*	5. *Ring*	6. *Tuberous Form*
Soft biomorphic attributes	Asymmetrical and arciform, sweeping form; glossy, rugged, uneven surface; alternating material hardness	Annular, askew, and contorted form	Bulbous, asymmetrical form; Irregular, shifting surface texture
Inspiration	*Overall form*: lobster claws, human finger, octopus tentacles	*Overall form*: human ears, bended fingers, bones; *Colors*: mammalian skin; *Surface texture*: growth rings in trees	*Overall form*: vegetable tuber, human heart; *Colors*: mammalian viscera, sebaceous glands
Dynamic soft biomorphic objects			
	7. *Purple Tentacle*	8. *Gray Tube*	9. *Green Oval*
Soft biomorphic attributes	Bulbous overall form; curvilinear, irregular bumps sticking out	Irregular, rounded overall form; asymmetrical and partly rugged surface	Rugged surface texture; elevated, tortuous, and curvilinear bumps
Movement	*Gyrated, erratic*: rapidly alternating between quick movements and being still	*Erratic*: shifts between smaller, repeating inflations that make the object grow, and longer inflations that make it attain an arciform shape	*Calm, pulsating*: alternates between subtle inflations and deflations periodically and longer, more voluminous inflations
Inspiration	*Overall form*: sea anemone, corals, and animal paw pads; *Colors*: dragon fruit; *Movements*: fish, sea life	*Overall form*: human colon, knuckles on a human hand; Surface texture: mammalian bones and tooth cavities; *Colors*: Shorthaired Pointer fur; *Movements*: caterpillar	*Overall form/Colors*: non-vascular plants, bullfrog; *Surface texture*: water surface, moss; *Movements*: organ (heart/lung)

Fig. 2 Selected still images from the workshop

condensing into 9 applicable codes. They then individually coded 20% of the data and the inter-rater reliability was calculated and found to be high (Cohen's $\kappa = 0.814$). Hence, the first author proceeded to code the remaining data and subsequently developed three themes in dialogue with the corresponding author.

5.4 Results

The following three overarching themes were found to capture the central ideas expressed about personal robot applications, interactions, and relations that the prototypes elicited in the workshop sessions.

5.4.1 Organic Qualities—Both Appealing and Uncanny

Most participants (n = 7) remarked that the prototypes' forms, surface textures, colors, or movements had organic or natural qualities, when they gave descriptions of the prototypes in the second exercise. Some attributed these to the irregularities and variations in surface texture or color, to others, it was the softness that made the prototypes appear "*natural*" and "*warm*". Half of the participants (n = 5) equally mentioned resemblances to specific natural organisms or body parts including mammalian organs, limbs, insects, aquatic plants, and cephalopods. These organic qualities were variously, sometimes even interchangeably, described as being desirable and uncanny in the proposed and imagined interactions and relations with the prototypes. Some participants (n = 3) felt that these qualities could contribute a sense of emotional comfort in the interaction with a personal robot and enhance the social and emotional connection with it, e.g.:

> *"It [the robot] must be organic, so it's like that... In the tasks where it might have to interact with children or have to interact with me in, one way or another, I want it to be something that appears friendly, and that I feel is like ... a mammal in some way. Or, you know, something that is relatable"* (P1.10)

Other participants (n = 4) found the organic qualities of the prototypes' forms, textures, or colors, to be somewhat unappealing or uncanny because they made the prototypes appear very "*natural-appearing*" (P1.2) or like "*alien*" versions of organic things. Several (n = 4) in addition associated the prototypes' organic aesthetics with notions of them being "*uncontrollable*" or "*autonomous*", capable of making their own decisions and having some degree of sentience or agency. Interestingly, some participants (n = 4) also remarked on that the prototypes had both organic qualities and traits from fabrication that revealed they were man-made. These participants appreciated the organic qualities but also found it positive that the prototypes had cues that made them appear "*constructed*", "*man-made*", or "*clinical*", as it made it possible to separate the prototypes from living beings. Elaborating on this, one participant explained he saw potential in

> *"combin[ing] the ambition to be, like, true to nature with the aesthetic dimension you can add when constructing something. (…) [T]o make the lifelike less creepy and more beautiful in such a completely basic appealing way"* (P1.1)

5.4.2 The Sensation of Touching the Prototypes

Nearly all participants (n = 8) explicitly assessed the experience of touching the prototypes during the second exercise. Some found the prototypes very pleasant to touch due to their compliance, smooth surfaces, or "*inviting*" visual appearances (P1.4), which made participants express ideas of engaging in close physical contact with the prototypes in the third exercise. For example, a participant imagined touch as a pleasing way to interact with a soft personal robot for entertainment purposes:

> *Then you go over [to the robot] (*P1.5 makes a calm movement with his hand, gently and repeatedly pats Purple Tentacle as if it is a small animal*). It would be very pleasant if it was like that anyway.... You know, not like tapping an app [on a phone]. But it would be very nice if you woke it [the robot] up just like that (*P1.5 caresses Purple Tentacle repeatedly*). (P1.5)*

Others described in the second exercise that they found the sensation of touching the soft materials too similar to the sensation of touching something organic which was not appealing to them in a context of interacting with technological artifacts. A number of participants (n = 4) changed their initial statements about the prototypes after having touched them for an extended period. For instance, one participant stated in the first exercise that she did not like the idea of having physical contact with a personal robot. Reflecting on her idea of an ideal personal robot in the fourth exercise, she now mentioned that she would like to engage in physical interaction with a personal soft robot by holding the robot in her hands to decrease stress levels, after having touched the prototypes on and off for more than 30 min. (P1.8).

5.4.3 Soft Biomorphic Robots for Emotional and Physical Well-Being

All participants (n = 10) imagined the prototypes to have specific functions in a domestic setting and to interact with humans. This occurred particularly in the third exercise where the participants envisioned the dynamic soft biomorphic prototype to perform practical tasks, such as cooking, and cleaning, and to take part in social interactions for companionship, entertainment, and care. A surprising finding to emerge from the data was that most participants (n = 7) expressed ideas about physically engaging with the soft biomorphic prototypes or integrating them on the body specifically to enhance emotional or physical well-being in either the second, third, or fourth exercise. Some imagined holding a moving robot for relaxation, and others imagined the prototypes would be fit for wearing on the skin to measure biometric data, or reduce anxiety or stress, while "*concealing the technology*" (P1.9). Related to this, in the third exercise, the majority (n =6) openly discussed the prototypes' potential to take part in activities related to detecting emotional state and helping stimulate positive affect, and as something that "*(…) brings the good vibes*" (P1.4) when you are interacting with it. These participants imagined that soft biomorphic prototypes might help people relax through touch, robot movements, vibrations, or temperature regulation. It was particularly the prototypes' soft materials and dynamic movements that drove these ideas, but some also coupled it to the prototypes' visual aesthetics and "*lifelike*" appearances. Other participants (n = 2) linked the interaction with the prototypes to interactions that are social in the manner of how one interacts or communicates with an animal for enjoyment and pleasure, which is also known to help regulate emotions and improve mood [23, 24].

5.5 Discussion

Study 1 sought to explore which visions of interactions, relations, and personal robot applications encounters with biomorphic soft robots are generative of (**RQ2**). In accordance with prior work [60], we found that participants were eager to touch and interact with the soft prototypes. One of the most interesting findings was that nearly all participants expressed ideas of using or interacting with the soft biomorphic robots as a means to increase emotional or physical well-being. This could suggest that a biomorphic design aesthetic is well-fitting for personal robots intended to foster well-being and could signal to a person the robot's ability to take part in comforting, e.g., in applications such as care or therapeutic robots. This novel finding is worthy of further study, as it can have implications for several proposed use cases of soft robots, including recent work on using soft robotics technology for stress and anxiety relief and supporting well-being [65–68, 96]. Participants also noted how soft biomorphic traits can help to "*conceal the technology*" and "*make it [the technology] appear organic*" and they associated the prototypes' likenesses with living organisms with notions of social interaction or communication. This could also be an indication that a soft biomorphic design aesthetic is appropriate more generally in soft robotics applications that involve social HRI. The findings also suggest that although the prototype designs were not intended to resemble any specific animal or organism, a transference of existing social interaction models used with animals occurred, as some participants imagined interacting with the prototypes as if they were animals. Moreover, some participants argued that the "*organic*" aesthetic made the prototypes appear autonomous and self-governed, which could indicate that this specific design aesthetic has an effect on perceived agency. If this is the case, a biomorphic design aesthetic might be applicable for applications wherein it is important that the user perceives the soft robot as an autonomous agent.

5.6 Limitations

Study 1 has some limitations. Firstly, only a subset of the biomorphic prototypes was included. If other designs had been selected, the participants' perspectives on the soft biomorphic design aesthetic may potentially have differed. Moreover, we did not include any soft robots with a traditional geometric design aesthetic to compare with in the study. Hence, the study's results do not allow us to determine if the findings are driven by the biomorphic design aesthetic specifically or perhaps a more general effect of the soft robotic embodiment. The number of included biomorphic prototypes was limited to nine to avoid overwhelming participants and to allow for an initial in-depth exploration of participants' qualitative assessments of this aesthetic before subsequently comparing them with traditional designs (see 6 Study 2).

We acknowledge another limitation in asking people potentially unfamiliar with robotics and the physiology of soft organisms to come up with ideas for soft robot use cases. Indeed, in Study 1, the majority of the participants expressed a lack of familiarity with robots, including soft robots, which may have constrained their ability to propose practical functionalities for the prototypes. However, this user-centered design approach allows participants to focus on high-level aspects of use cases rather than practical implementation, and doing so, to potentially also draw on cultural imaginaries about robots (e.g., fictitous robots they are familiar with from movies with abilities that are currently unrealizable in reality). By involving individuals with diverse backgrounds, this approach additionally has the potential to introduce new perspectives, knowledge, experiences, and issues unfamiliar to us as researchers [97]. Thus, we chose this approach to engage participants in imaginative exercises to explore how their knowledge and experience might stimulate creativity in the task and allow them to uncover pressing ideas and insights for further investigation in the development of personal soft robots.

Lastly, we conducted the thematic analysis by collating all data from the workshop, as we wanted to uncover general themes emergent in interaction. Hence, we did not differentiate between the different exercises of the workshop where participants performed different tasks. Thematic analyses of data from each stage of the workshop might have yielded more nuance, however at the cost of generalizability. Likewise, the decision to evaluate all prototypes together allows us to assess the ideas about applications, interactions, and relations the biomorphic design aesthetic produces overall, but not the more fine-grained determinants of these, e.g., specific formal traits such as shapes, colors, or surface textures.

6 Study 2

Motivated by the findings of Study 1 and to overcome the above-mentioned limitations, we carried out a second study to investigate if personal soft robots with enhanced biomorphic qualities are considered more appealing and more appropriate for applications wherein soft robots are used to support well-being through physical interaction than other soft robotics designs (**RQ3**). Secondly, we wanted to explore whether the soft robotic prototypes were considered more appealing following physical interaction with them, than at first sight, as indicated by Study 1 and prior work [60].

We designed the interaction scenario of Study 2 to emulate a use situation, wherein the moving soft robotic prototypes are used to support well-being through bodily contact. This proposed application was based on the idea that "breathing" soft robots might be used to facilitate relaxation (see 2 Related Work) through entrainment. Entrainment refers to the activity in which independent rhythmical biological systems interact [98], and one system temporally entrains the other system's frequency [99]. Prior work on HRI has shown this principle to be applicable to technologies that use tactile stimuli to reduce anxiety [100] or regulate the heart rate to improve mental health [101].

We selected two of the dynamic soft biomorphic prototypes, *Gray Tube* and *Green Oval*, to use for the study. We considered these the most appropriate designs for physical handling, holding in the hands, and bodily contact as they are three-dimensional forms capable of supporting their own weight without buckling and are compact and coherent morphologies. In addition, we designed two new simplified geometric versions of the selected prototypes, *Geometric Tube* and *Geometric Oval* (see Fig. 3). We chose a simplified geometric design with monochrome coloring for these prototypes, as a contrasting alternative to the biomorphic aesthetic of the original prototypes. The geometric prototypes were made from the same materials and have the same overall shapes, sizes, colors, and movements as the two soft biomorphic robotic prototypes on which they are based, but lack the intricate details, surface textures, and polychromatic coloring

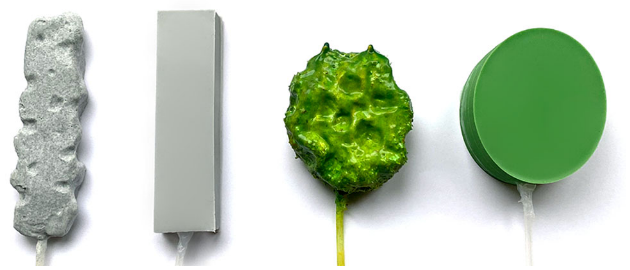

Fig. 3 The four soft robot prototypes. From left to right: *Gray Tube*, *Geometric Tube*, *Green Oval*, and *Geometric Oval*

of the biomorphic designs. Comparing these prototypes with the biomorphic designs thus allows for assessing whether the findings in Study 1 can be considered effects of the original prototypes' biomorphic design aesthetic.

We programmed a pulsing movement pattern for the prototypes, meant to resemble relaxed breathing in domestic animals (15 breaths per minute (BPM), following [102]), in which the prototypes calmly inflated and subsequently deflated. Although all prototypes used the same pulsing frequency and identical hardware for actuation, the variation in size and configuration of the air chambers resulted in different internal pressures and associated force transfers. Consequently, the prototypes with smaller air chambers (*Gray Tube* and *Geometric Tube*) exhibited pulsing experienced as more powerful compared to those with larger air chambers (*Green Oval* and *Geometric Oval*).

6.1 Hypotheses

We hypothesized that:

H1 *Participants will deem the soft biomorphic prototypes more appealing than the geometric prototypes.*

Following results from Study 1, we anticipated that the soft biomorphic prototypes would receive higher appeal ratings than the geometric prototypes would. This hypothesis was further motivated by the *biophilia* hypothesis [21] and recent research in soft robots and HRI that shows a preference for biophilic robot designs [68].

H2 *Participants will deem the soft biomorphic prototypes more appropriate than the geometric prototypes for interactions intended to support well-being.*

Based findings from Study 1, we expected that the soft biomorphic prototypes would be rated more appropriate for the application of improving well-being than the geometric prototypes.

H3 *All included prototypes will be rated more appealing after physical interaction than at first sight.*

We predicted that all four prototypes would receive a higher appeal rating post-interaction, as we observed in Study 1 that some participants changed their attitude towards the prototypes after having interacted with them for a while. Furthermore, this was motivated by prior work on soft robotics in HRI [60].

6.2 Participants

A total of 32 participants (female: n = 15; non-binary: n = 1; male: n = 16) were recruited through convenience sampling at the University of Southern Denmark's main campus in Odense, Denmark. The participants' ages ranged between 19–45 years (M = 24.5, SD = 5.86), and they self-reported their nationalities as Danish (n = 23), German (n = 2), Kurdish (n = 1), Nepalese (n = 1), Polish (n = 1), Mexican (n = 1), Greek (n = 1), Bosnian (n = 1), and Spanish (n = 1). All participants were university students enrolled in the following study programs: psychology, computer science, physiotherapy, law, biology, media science, engineering, applied mathematics, political science, biomedicine, global management and manufacturing, English, sports, robot technology, biochemistry, economics, and pharmacy. All participants were asked to indicate to which extent they agreed with the statement "*I generally consider my knowledge and skills in the field of technology/robots to be high*" on a 7-point Likert scale ranging from "*1 – does not apply at all*" to "*7 – applies fully*" (M = 3.5, SD = 1.87). No compensation was given to the participants.

6.3 Procedure

All participants took part in the study experiment individually with the first author as facilitator. Before the experiment, participants were briefly informed that the purpose of the project was to generate knowledge about which robot designs are suitable in contexts related to improving well-being by means of robotics technology. They were told that we wanted their feedback on four robot prototypes we had designed, and that they would interact with all prototypes shortly.

Upon having signed an informed consent form, the participant was taken into a classroom (see Fig. 4). The participant was seated near a table where the four prototypes were laid out. They were told that the prototypes in front of them were examples of soft robotics and were intended to provide relaxation and improve well-being. The facilitator informed them that this would occur by holding the prototypes in contact with one's body. A demonstration sequence, in which each prototype moved one by one was shown, each moved for 10 s in the relaxed pulsing pattern. Subsequently, participants filled in the pre-interaction questionnaire. For each prototype they were asked to "*Indicate your overall impression of the robot pictured above on the scale below from 1 to 7*" with a

Fig. 4 Experimental setup in a classroom at the University of Southern Denmark's main campus in Odense

7-point Likert scale ranging from "*1 – unappealing*" to "*7 – appealing*".

Participants were then asked to pick up a prototype and gently hold it with both hands in contact with their chest until the prototype stopped moving. These movements were identical with how the prototypes moved pre-interaction, the only difference being that each movement pattern now lasted 30 s. Participants then filled out the post-interaction questionnaire that contained the same questions as the pre-interaction questionnaire and in addition asked for each prototype to "*Indicate how appropriate you find the robot's design for its intended use on the scale below from 1 to 7"* on a 7-point Likert scale ranging between "*1 – inappropriate*" to "*7 – appropriate*". For each rating, participants were also given the opportunity to elaborate why they had chosen a specific value. Lastly, after providing general comments and demographic data, all participants were given the opportunity to ask questions.

6.4 Statistical Analysis and Tabulation of Comments

Statistical analyses of participants' ratings were run in IBM SPSS. Initially, a Shapiro–Wilk test of normality was conducted ($p > 0.05$), which showed that, except for the three ratings for *Geometric Tube* (pre-interaction appeal, $p = 0.16$; post-interaction appeal, $p = 0.06$; post-interaction appropriateness, $p = 0.053$), the data was not normally distributed. Visual inspections of histograms confirmed these results. Subsequently, the data was analyzed using Wilcoxon Signed Rank Tests and Friedman Tests as appropriate (see 6.5. Results).

Participants' comments concerning the prototypes' appealing, unappealing, appropriate, and inappropriate qualities were gathered in a table to allow comparison across the different classes of prototypes (see Table 3).

6.5 Results

6.5.1 Pre-and Post-Interaction Appeal Ratings

To investigate whether the prototypes were rated more appealing after physical interaction than at first sight, four separate Wilcoxon Signed Rank Tests comparing pre- and post-interaction appeal ratings for the four prototypes were conducted (see Table 2). For *Gray Tube* and *Geometric Oval*, no significant difference in appeal rating was found. For *Geometric Tube*, a statistically significant increase in appeal post-interaction, $z = 2.11$, $n = 32$, $p = 0.04$, with a small effect size ($r = 0.26$) was found. For *Green Oval*, a statistically significant increase in appeal post-interaction, $z = 2.43$, $n = 32$, $p = 0.002$, with a medium effect size ($r = 0.30$) was found.

6.5.2 Overall Appeal Ratings for all Four Prototypes

Friedman Tests were conducted to compare the four prototypes' appeal ratings using data from ratings pre- and post-interaction, to assess if any of the prototypes were rated as more appealing than others.

Pre-Interaction Pre-interaction, there was a statistically significant difference between appeal ratings for the four prototypes (χ^2 (3, n = 32) = 15.11, $p = 0.002$). Inspection of

Table 2 Median values for all ratings and statistics for pre-interaction and post-interaction appeal ratings comparison

Prototypes	Pre-interaction appeal: median (25-75th percentile)	Post-interaction appeal: median (25–75th percentile)	Appropriateness: median (25–75th percentile)	Wilcoxon Signed Rank Test: Pre-interaction appeal vs. Post-interaction appeal
Gray Tube	5 (4–6)	5 (3–6)	4 (3–5.75)	$z = -1.26$; $p = 0.21$; $r = 0.16$
Geometric Tube	4 (3–5)	4 (3–5)	4 (4–5.75)	$z = 2.11$; $p = 0.04$; $r = 0.26$
Green Oval	3 (2–6)	5 (2.25–6)	5 (3–6)	$z = 2.43$; $p = 0.02$; $r = 0.30$
Geometric Oval	5.5 (4–6)	5 (4–6)	5 (4–7)	$z = -0.58$; $p = 0.56$: $r = 0.07$

median values showed the following ranking of the four prototypes: *Geometric Oval* (Md = 5.5), *Gray Tube* (Md = 5), *Geometric Tube* (Md = 4), and *Green Oval* (Md = 3) (see Table 2). Post-hoc tests (including Bonferroni correction for multiple tests) showed that there was a statistically significant difference between ratings for *Geometric Tube* and *Geometric Oval* (*Geometric Tube – Geometric Oval*: $p = 0.002$). No significant differences were found between other prototypes.

Post-Interaction For post-interaction ratings, no statistically significant difference was found between overall appeal ratings for the four prototypes (χ^2 (3, n = 32) = 6.72, p = 0.081).

6.5.3 Appropriateness Ratings for all Four Prototypes

A Friedman Test was conducted to compare appropriateness ratings for the four prototypes. No statistically significant difference was found (χ^2 (3, n = 32) = 6.32, $p = 0.097$).

6.5.4 Participant Comments in Post-Interaction Questionnaires

The participants' comments were explored through categorization to gain insight into which formal traits of the four prototypes they found appealing, unappealing, appropriate, or inappropriate. A total of 125 comments were provided in the questionnaires. Comments made under ratings for appeal and appropriateness were categorized as being either positive, negative, both positive and negative, neutral, or ambiguous. Neutral and ambiguous comments were excluded. Positive comments concerning overall appeal were tabulated under the prototype to which they belonged under the column *Appealing Qualities* (n = 22). Similarly, negative comments were tabulated under *Unappealing Qualities* (n = 14). Likewise, positive comments concerning appropriateness were tabulated under *Appropriate Qualities* (n = 18) and negative comments under *Inappropriate Qualities* (n = 22). Comments containing both positive and negative parts were separated into their negative and positive constituent parts and tabulated as above (*Appealing Qualities* (n = 6), *Unappealing Qualities* (n = 6), *Appropriate Qualities* (n = 3), *Inappropriate Qualities* (n = 3)). General comments that mentioned specific qualities of the prototypes (n = 7) were tabulated in a separate cell of the table (nonspecific general comments (n = 4) were excluded).

Comparing the comments made for each of the soft biomorphic protypes and their geometric equivalents, contained in Table 3, reveals that both overlapping and distinct traits were mentioned as being appealing/unappealing and appropriate/inappropriate aspects of the biomorphic and geometric design aesthetics respectively.

For both *Gray Tube* and *Geometric Tube*, participants found it **appealing** that they were comfortable to hold and had pleasant inflations. In addition, *Gray Tube* was considered appealing due to its surface texture being pleasant to touch, its "*hum*" (P2.21), and its "*organic*" visual appearance (P2.17).

In terms of **unappealing** qualities, participants found that Gray Tube's "*pulse frequency is much too high*" (P2.11) and that its movements could not be felt clearly, which was experienced as if it was "*dying*" and had "*difficulties breathing*" (P2.23). For *Geometric Tube*, participants found it unappealing that its shape was boring, that it looked "*too hard/inorganic for the purpose*" (P2.25), and that it was not pleasant to touch.

Participants who found *Gray Tube* and *Geometric Tube* **appropriate** mentioned size, stating that both prototypes fitted well in one's hand. Additionally, *Geometric Tube* had an appropriate shape and a "*very neutral design that makes you want to interact with it*" (P2.8).

Both prototypes were deemed **inappropriate** because they were not pleasant to hold. *Geometric Tube* was also deemed inappropriate due to its angular and "*strict*" shape (P2.24) or its "*dull*" color and shape (P2.10). Some also found *Gray Tube* inappropriate because its surface had too many "*bumps*" (P2.11), because it "*looks like a brick*" (P2.14), and because its vibration was deemed "*the least calming*" of the four prototypes (P2.24).

For *Green Oval* and *Geometric Oval*, participants found both prototypes **appealing** because of the pleasant sensation when touching and holding them, their visual appearances, and their calming movements.

Participants that elaborated on **unappealing** qualities mentioned for both *Green Oval* and *Geometric Oval* that they had unappealing pulse frequencies and visual appearances. Additionally, a few found *Green Oval's* vibrations and how it felt to hold it unappealing. For *Geometric Oval*, one participant found it unappealing because it was "*too clunky*" and did not have a good effect on her (P2.1), while another highlighted touching it as being unappealing.

As for **appropriate** qualities, participants commented that *Green Oval* "*had the best vibration*" (P2.24), that it was nice to hold and touch due to its texture, size, and shape. *Geometric Oval* was deemed appropriate because of its "*very neutral design*" (P2.8) and due to its color and round edges, because it fitted well in the hand and was pleasant to hold.

Green Oval was considered **inappropriate** because it looked "*nasty*" (P2.8), "*weird*" (P2.11), "*chaotic*" (P2.14), or "*lightly repulsive*" (P2.24), and due to its color and shape. For *Geometric Oval*, participants instead mentioned that the form was "*clumsy*" (P2.1, P2.7), that its size was too difficult to hold, and that a more "*rounded/organic*" shape would look more calming (P2.25).

Table 3 Participants' comments that elaborate on qualities that are considered appealing, unappealing, appropriate, or inappropriate as well as general comments about the prototypes' qualities

	Appealing qualities	Unappealing qualities	Appropriate qualities	Inappropriate qualities
Gray Tube	It is comfortable to hold (P2.7) Felt pleasant to touch, and the inflation was pleasant (P2.9) Organic looking and nice to interact with (P2.17) It applied pressure, which felt fun and calming as it takes the attention away from everything else (P2.20) Had a good hum that calmed me down, not too fierce (P2.21) I think it looks nicer than the others (more organic and calming) (P2.25) It has a nice texture to the touch (P2.28)	I don't think it was very calming (P2.8) The pulse frequency is much too high. [T]oo much rumble (P2.11) Seems almost "dying", reminds me of someone having trouble breathing (P2.23) I couldn't feel it as much as the others (it felt like less pressure on the chest when it was breathing) (P2.25)	I think it has an obvious shape to hold in the hand because it seems like something you would naturally hold around (P2.1) Fits well in the hand (P2.19) His size looks touchable and likely to interact with (P2.32)	There are too many bumps and things on it (P2.11) It does not sit well in the hand (P2.12) It looks like a brick, which is not pleasant (P2.14) Its vibration was the least calming [of the four robots] (P2.24) I think a little bigger/wider would be nicer to hold, it feels a little too skin[n]y (P2.25)
Geometric Tube	Was pleasantly surprised by the effect of this [robot], because I did not expect much due to the shape (P2.1) I found it super comfortable to hold and quite calming (P2.8) The inflation was pleasant (P2.9) The movement was pleasant (P2.14) Pleasant to interact with (P2.17) It has a nice appearance (P2.24)	Pulse frequency too high (P2.11) The shape is very boring (P2.12) Boring aesthetically (P2.17) Looks too hard/unorganic for the purpose, is not the nicest of them to hold (P2.25) Not super nice to the touch (P2.28)	Very neutral design that makes you want to interact with it (P2.8) It fits well in the hand (P2.12) The material is nice and soft on the hands (P2.21) Better shape (P2.23)	It gets a little too clumsy to hold (P2.1) Too angular, not soothing (P2.7) The color and shape are relatively "dull" (P2.10) Its angular shape seems "strict", not soothing. (P2.24)
Green Oval	It has both a good and noticeable effect, and it fits well in the hand due to the shape (P2.1) It is pleasant to interact with (P2.2) Nice in touch (P2.4) Nice aesthetic (P2.17) It's fun to hold it and to wear on the chest, calming effect (P2.20) It was my favorite, I liked how it made me feel (P2.22) It lays nice in the hand, feels calming when moving (P2.25) It's nice to touch it (P2.28)	I don't think it was so comfortable to hold it (P2.8) It rumbles way too much. I got stressed. [P]ulse frequency too high (P2.11) A little too hard movements (P2.14) A bit difficult to interact with (P2.17) Far too fierce hum, you get nervous from the hum and feel nauseous (P2.21) The frequency was not appealing (P2.26) It doesn't look super pleasant (P2.28)	It fits well in the hand, and you can sort of squeeze it/hold it (P2.1) [Its] round shape seems better to be held in hands (P2.4) The shape is suitable to hold, and resembles a stress ball. Good with its color (P2.10) Fits perfectly in the hand (P2.12) It had the best vibration (P2.24) Size, and texture is nice (P2.25) It[s] touch is really nice (P2.32)	Its exterior does not appeal to me (P2.2) It looks a bit nasty and [it] doesn't make you want to touch it (P2.8) It looks weird (P2.11) It looks chaotic (P2.14) I personally am not too fond of the color and shape (P2.16) The design and color are terrible (P2.21) Does not have a safe appearance (P2.23) It is slightly repulsive to look at (P2.24) [Its] color was for me personally not the most calming. A little to chaotic to look at (P2.25)

Table 3 (continued)

	Appealing qualities	Unappealing qualities	Appropriate qualities	Inappropriate qualities
Geometric Oval	It was not as comfortable as the angular one but was relatively nice to hold (P2.8) Most comfortable movement (P2.11) Okay nice looking and easy to interact with (P2.17) Good [visual] appearance but [it] was very round (P2.23) Felt surprisingly nice to hold[,] and the pressure on chest while its moving feels really calming (P2.25) It[s] touch was nice (P2.32)	It was too clunky and I don't feel the effect was very great (P2.1) Too high frequency (P2.11) Not the best look (P2.25) Not super nice to touch (P2.28)	Very neutral design that makes you want to interact with it (P2.8) Its function is [good]. (P2.11) Fits quite well in the hand (P2.12) Pleasant green color and round edges (P2.14) It was pleasant to hold. Fitted the hand well (P2.15) I think the color is better than the gray [robots] and the shape is also more comfortable to hold (P2.16) The round shape and green color are calming (P2.24)	It's too clumsy to hold (P2.1) It is a bit clumsy to hold (P2.7) The form is not good (P2.11) The size is too big and hard to hold (P2.21) [It is] too rounded (P2.23) A little more rounded/organic would maybe look a little more calming (P2.25) Maybe [apply] rounded edges so it fits a bit better in the hand (P2.26)
General	If the purpose is to create a robot that can stimulate the tactile senses, I think that it has a really good effect when the shape is "skewed", and you can therefore hold it on/on in different ways (P2. 1) It surprised me how the exterior [of the prototypes] and the interaction did not match. Those [prototypes] who looked attractive were not as pleasant to interact with as those who looked less attractive (P2.2) The bigger, round robots where better because they were bigger (P2.4) The shape of the rectangular [prototypes] was the best, but the texture of the green [prototypes] was the best (P2.5) Soft edges make them [the prototypes] more appealing (P2.12) Soft material can help calm you down (P2.21) It felt like the bigger it is the easier it was to press it onto the chest which helped feel the calming move[me]nts (P2.25)			

The number following "P2." indicates the participant tag

Interestingly, participants also compared how well-aligned the prototypes' visual appearances, tactile qualities, and movements were in some instances (n = 9). In these cases, participants mentioned discrepancies between the prototypes' formal attributes. For instance, one participant argued that *Gray Tube* "*looks nicer than the others*" but that she "*couldn't feel it as much as the others*" (P2.25), and another that *Geometric Tube* was "*boring aesthetically*" but "*pleasant to interact with*" (P2.17). Another participant mentioned how *Geometric Oval's* "*(…) form is not good*" but that "*its function is*" (P2.11), while a different participant argued that *Green Oval* "*(…) doesn't look super pleasant*" but that "*it's nice to touch it*" (P2.28).

6.6 Discussion

Study 2 sought to investigate if soft robots with enhanced biomorphic qualities are considered more appealing and appropriate for applications wherein soft robots are used to support well-being by means of physical interaction (**RQ3**) and, additionally, whether soft robotic prototypes in general are rated as more appealing following physical interaction than at first sight.

We hypothesized that the soft biomorphic prototypes would be considered more appealing than the geometric prototypes (**H1**). The results did not support this hypothesis, as the only statistically significant difference found in appeal ratings for the four prototypes was between the two geometric prototypes (*Geometric Tube* and *Geometric Oval*, pre-interaction data).

Based on Study 1, we hypothesized that participants would find the soft biomorphic prototypes more appropriate than the geometric prototypes for supporting well-being through HRI (**H2**). We found no significant differences between the ratings for the four prototypes, and the results did therefore not support this hypothesis. The results from Study 2 suggest that in Study 1 it might have been the soft robots' soft materials and not the soft biomorphic aesthetic per se that made people suggest applications for them in improving well-being. A participant in Study 2 also alludes to this in a general comment, stating that "*[s]oft material[s] can help calm you down*" (P2.21). However, categorization and analysis of comments provided indication that it was not solely their soft materiality that was taken into account, when considering their appropriateness. Participants also mentioned, e.g., visual appearance, stating that *Geometric Tube* looked "*(…) too hard/inorganic for the purpose*" (P2.25), and that *Green Oval* looked "*(…) a bit nasty and [it] doesn't make you want to touch it*" (P2.8). But, also, more specifically form and color, mentioning being "*(…) not too fond of the color and shape*" of *Green Oval* (P2.17) or explaining that *Geometric Tube's* "*(…) color and shape are relatively 'dull'*" (P2.10). Others focused on movement, expressing that *Green Oval* "(…) *had the best vibration*" (P2.24), or the sensation of touching the prototypes, mentioning how *Geometric Oval* "(…) *was pleasant to hold"* because it *"(…) [f]itted the hand well*" (P2.15). As participants mentioned the prototypes' visual appearances, forms, colors, movements, and tactility as affecting their evaluations of appeal and appropriateness, it is plausible that these design aspects interact in a more complex and intricate way in these assessments, than what is captured in the distinction between a biomorphic and geometric design aesthetic. However, contrasting the participants' comments about the biomorphic and geometric prototypes shows that there are distinctions between what words participants use to describe the two styles, particularly their visual appearance and overall form. For instance, where biomorphic prototypes' visual appearances and forms are described as "*chaotic*" (P2.14), "*organic*" (P2.17), "*repulsive*" (P2.24), and "*weird*" (P2.11)", the geometric prototypes are designated as "*neutral*" (P2.8), "*boring*" (P2.12), "*angular*" (P2.7), "*strict*" (P2.24), and "*dull*" (P2.10). This may suggest that the two styles' visual appearances and overall forms are perceived differently and maybe even as contraries, with the biomorphic design aesthetic being "organic" and the geometric design aesthetic being "angular". Thus, although no quantitative statistically significant differences were found between the appropriateness ratings, the qualitative data indicates that the two groups of prototypes are perceived differently from one another in terms of their visual appearances and overall forms.

Based on results of Study 1 and prior work, we hypothesized that interaction with the soft robotic prototypes would lead to an increase in appeal rating (**H3**). We found partial support for this hypothesis, as appeal ratings for *Geometric Tube* and *Green Oval* were statistically significantly higher post-interaction. This finding indicates that physical interaction with soft robots can have a positive impact on how appealing people find them to be, but that this is not always the case. It is possible that this effect is dependent on interaction time or the context and framing of the interaction, which were different in Study 2 than in Study 1, and therefore we did not manage to produce the effect consistently. To understand this finding better, we compared the change in pre- and post-interaction appeal rating for each participant for all prototypes. We found that post-interaction, several participants had changed their rating of a prototype one step or more (±) on the 7-point Likert scale (*Gray Tube*—62.5% (n = 20); *Geometric Tube* – 62.5% (n = 20); *Green Oval* – 59.4% (n = 19); *Geometric Oval* – 78.1% (n = 25)). In fact, a larger proportion had changed their rating two or more steps (±) (*Gray Tube*—28.1% (n = 9); *Geometric Tube* – 25% (n = 8); *Green Oval* – 25% (n = 8); *Geometric Oval* – 31.3% (n = 10)). This could indicate a polarizing rather than unidirectional effect of the interaction, i.e., that post-interaction some participants found them more appealing and others less, hence we did not find any statistically significant difference with the Wilcoxon test. However, this hypothesis does not generalize easily as a statistically significant higher post-interaction appeal rating was indeed found for both *Geometric Tube* and *Green Oval*.

6.7 Limitations

Study 2 is subject to certain limitations. Only two out of the nine soft biomorphic prototypes from Study 1 were included. Hence, the chosen designs may not have possessed the full set of qualities that drove the findings of Study 1. Furthermore, the participants did not evaluate a fully functional biomorphic robot validated to improve well-being by means of physical interaction, but only prototypes framed as possessing this ability. Another limitation of the study consists in the self-report measure used. Only two rating items for each prototype, namely *appeal* and *appropriateness,* were used to ensure a fast completion time, as participants were not financially compensated. Other validated self-reporting measurement instruments that include more sub-items for each construct may have been more suited to detect a difference in how participants assessed the two categories of prototypes. Instead of measuring *appeal* we might, for instance, have used the *likeability* scale from the Godspeed Questionnaire series [103] or the *warmth* scale from the Robotic Social Attributes Scale (RoSAS) [104]. Instead of *appropriateness*, we could have used *intention to use* from Heerink et al.'s [105] extension of the Unified Theory of Acceptance and Use of Technology (UTAUT) measure.

7 General Discussion

The present work has sought to explore how specific design features of silicone-based soft robots can increase their organic qualities (**RQ1**); which visions of interactions, relations, and personal robot applications encounters with such biomorphic soft robots are generative of (**RQ2**); and if soft robots with enhanced biomorphic characteristics are considered more appealing and appropriate for supporting well-being through physical interaction (**RQ3**). To address **RQ1**, we formulated a soft biomorphic design aesthetic aimed at enhancing the inherent organic qualities through visual, haptic, and kinetic added attributes, and explored it through the construction of a set of prototypes. **RQ2** and **RQ3** were addressed in the first and second study, respectively. Combined, this work allows us to identify some central issues and tentative guidelines concerning the enhancement of biomorphic traits in soft personal robots.

A common theme emerging from both studies is the negotiation between how organic appearing versus geometric or "constructed" a soft personal robot should be. While some participants in both studies argued that the soft biomorphic prototypes' organic aesthetic made them more appealing and increased their desire to interact with the prototypes, others argued that the organic features of some prototypes made the prototypes appear "alien", "uncontrollable", or "chaotic", and decreased their desire to interact with them. This division would appear to mirror the often-cited uncanny valley hypothesis [106], which states that if a robot's appearance becomes more human-like, it will have a positive effect on observers' emotional responses until a threshold whereafter it becomes eerie. The associated recommendation of Mori [106] that designers should strive for a restrained level of human likeness and only a "considerable sense of affinity" also bears similarities with comments by participants from the first study who appreciated that the biomorphic prototypes possessed both biomorphic and "man-made" or "constructed" traits. Comments from participants in Study 2 (Table 3) showed that although many people found the geometric prototypes' simple and "clinical" aesthetic appealing, multiple participants did not find their sharp-edged designs appealing or appropriate for HRI to support well-being. Based on these insights, we propose to consider the biomorphic and geometric design aesthetics as two poles within the design space of soft robotics. Mixing or mediating between these two styles could potentially provide a shortcut to discovering designs for personal soft robots that are considered appealing, as they embody both organic and man-made qualities. The suggestion to mix the two styles aligns with findings of prior work showing that robots mixing biomorphic and product-like aesthetics were favored over strictly biomorphic or strictly device-like embodiments [107]. Our findings suggest that this principle might be extended to soft robotics technology as well. Thus, designers need to find a suitable balance to suit the specific use of the personal robot and its intended tasks and interaction modes. For instance, personal robot designs intended for close physical HRI might benefit from increasing the biomorphic characteristics over the geometric characteristics to aim for softer and more organic curves that afford bodily interactions. Based on the findings from Study 1 and 2, we summarize the formal attributes that are assessed as making the prototypes appealing/unappealing (Table 4). We recommend designers to use this overview for inspiration when designing soft personal robots intended for close physical HRI.

As evident from Table 4, the perception of softness can be assessed both as appealing and unappealing, even when utilizing the same physical material. This intricacy needs careful attending to when designing soft robots. It also highlights the need for further research into the perception of different shore hardness silicones in personal soft robot designs. Moreover, it is crucial to investigate how other underlying design aspects may contribute to the varied perception of the same material as appealing or unappealing in different prototypes. Future studies should thus explore additional design dimensions to comprehensively account for the factors influencing the perceived appeal of soft robot designs.

Prior research that would appear to challenge the recommendation to mix biomorphic and geometric design aesthetics, however, also exists. Löffler et al. [78] found that the uncanny valley effect extends to zoomorphic robots as a quadratic function, where robots that are either high or low in animal-likeness are preferred over designs with medium animal-likeness. They therefore argued that robot designers should maintain consistency in the level of animal-likeness being either low or high, rather than incorporating a combination of realistic and unrealistic features in robot designs. According to Löffler et al.'s [78] findings, the best predictors for animal-likeness in robot designs were natural color schemes and proportions, the use of plastic or metal, joint visibility, and the presence of a snout. Comparing these findings with our soft biomorphic prototypes (see 4 Prototypes Designs), it can be seen how many of these characteristics are contained in our designs. For instance, all prototypes are made from flexible soft silicone and, thus, avoids the use of metal and plastics; all prototypes follow natural color schemes; most of the prototypes do not have joint visibilities (e.g., *Claw*, *Tuberous Form*, *Green Oval*); and some of the designs contain natural proportions (e.g.,

Table 4 Summary of formal attributes in soft personal robot designs that were assessed as appealing and unappealing respectively

	Appealing formal attributes	Unappealing formal attributes
Overall form	Rounded/organic forms; Soft shapes	Sharp-edged forms; Highly natural-appearing forms
Color(s)	Monochromatic	Colorful; Big variety of hues
Size	Holdable in hand(s)	Too big to hold in one's hand(s)
Tactile qualities	Physical softness; Smooth in touch	Surfaces that feel similar to touching soft organic tissue
Movements	Vibrations; Calm motions; Soft movements	Fast motions; Fierce movements

Rugged Surface and *Skinlike Surface*). Thus, as the biomorphic prototypes are predominantly "animal-like" following these characteristics, it can be argued that a biomorphic design aesthetic can be mixed with a geometric style and still contain appropriate levels of biomorphic traits to ensure that the soft robot designs are not deemed uncanny. Furthermore, similar to our recommendation that personal robot designs must balance between biomorphic and geometric traits to achieve appealing and appropriate designs, Löffler et al. [78] argued that robot designers must balance between imitating living creatures and conveying that a robot is a thing and not a living creature to ensure usable robots for HRI.

Another discovery of the present work concerns the relationship between a prototype's visual appearance, tactile qualities, and movements. Qualitative data from Study 2 shows how a few participants compared the consistency between different formal attributes when evaluating a prototype's appeal or appropriateness for supporting well-being in HRI. In multiple cases, participants mentioned discrepancies between the prototypes' formal attributes. For instance, one participant expressed that *Green Oval* was "*(…) lightly repulsive to look at, however, it had the best vibration*" (P2.24), and another mentioned that *Gray Tube* "*(…) looks nicer than the others (more organic and calming) but I couldn't feel it as much*" (P2.25). Similarly, a different participant explained in a general comment that the robots *"(…) who looked attractive were not as pleasant to interact with as those who looked less attractive*" (P2.2). A design recommendation would therefore be to strive for coherence between a robot's visual, tactile, and kinetic qualities to make the most appealing and appropriate designs for personal robots in HRI. This recommendation bears similarities to arguments put forth in [108], that a robot's appearance and overall form should match its movements, and in [13], that a robot's capabilities should match its form and behavior. To achieve this coherence between visual appearance, tactile qualities, and movements, we suggest also aligning the design with its intended use context and user group by prioritizing user-centered design and iterative prototyping. By emphasizing the intended users' ideas, needs, expectations, and cultural norms, their aesthetic, tactile, and kinetic expectations and preferences can be determined. Through user involvement, testing, and identification of inconsistencies between the different attributes, designers must iteratively refine the design to ensure appealing and appropriate robots for the specific use case scenario.

8 Conclusion

In this article, we proposed a novel design paradigm for soft robotics, through the concept of *Soft Biomorphism*, aimed at attaining aesthetic similarities with soft-bodied organisms while avoiding representing (an abstraction of) a specific organism. We designed a range of soft biomorphic prototypes and conducted two empirical studies. Study 1 sought to interrogate which personal robot applications and notions of human–robot interactions and relations the biomorphic design aesthetic is generative of. We found that most participants associated this aesthetic with soft personal robots aimed at fostering physical and emotional well-being. Based on these findings, we conducted a second study (Study 2) to examine whether soft robots with enhanced biomorphic qualities would be considered more appealing and appropriate for applications wherein soft robots are used to support well-being through physical HRI. While the results did not show a statistically significant preference for soft biomorphic prototypes over geometric prototypes, qualitative data indicated that participants perceived the two aesthetic styles differently from each other in terms of visual appearance and overall form. Moreover, we found significant differences in appeal ratings post-interaction for certain prototypes, indicating that physical interaction with soft robots can affect perceived appeal. Based on our findings, we highlighted central issues to take into consideration when using biomorphic aesthetics in soft personal robot designs and gave tentative design recommendations to combine biomorphic and geometric traits as well as an overview of appealing and unappealing formal attributes. Finally, we recommended to align the robot's formal attributes (visual appearance, tactility, and movement) to ensure appropriate designs.

9 Future Work

The present work has taken first steps in exploring soft biomorphism as a design aesthetic for soft robotics and assessing its benefits and effects on HRI. Future work should aim to elucidate the findings of this largely exploratory study with respect to specific types of soft personal robots. The contribution of specific formal attributes of biomorphic soft robots to the high-level impression of the robot and the experience of the HRI should be examined in more detail as well as their interaction. Furthermore, it needs to be established what level of soft biomorphism is appropriate for specific applications and different types of HRI with soft robots.

Acknowledgements We thank the participants for their participation. We also thank Cao Danh Do for assisting with 3D printing of molds for prototypes.

Funding Open access funding provided by University Library of Southern Denmark. Funding was provided by Syddansk Universitet, Digital Autonomous Production (SDU I4.0 DAP) program.

Data Availability The datasets generated during and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical Approval Approval was obtained from the Research Ethics Committee of University of Southern Denmark. The procedures used in our studies adhere to the tenets of the Declaration of Helsinki.

Consent to Participate Informed consent to participate and to collect and process personal data was obtained from all individual participants included in the studies.

Consent to Publish The authors affirm that all human research participants signed informed consent regarding publishing their data and photographs.

References

1. Pfeifer R, Lungarella M, Iida F (2012) The challenges ahead for bio-inspired "soft" robotics. Commun ACM 55(11):76–87. https://doi.org/10.1145/2366316.2366335
2. Rus D, Tolley MT (2015) Design, fabrication and control of soft robots. Nature 521(7553):467–475. https://doi.org/10.1038/nature14543
3. Bar-Cohen Y (2006) Biomimetics—using nature to inspire human innovation. Bioinspir Biomim 1(1):P1–P12. https://doi.org/10.1088/1748-3182/1/1/P01
4. Kovač M (2014) The bioinspiration design paradigm: a perspective for soft robotics. Soft Rob 1(1):28–37. https://doi.org/10.1089/soro.2013.0004
5. 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, proceedings. ROMAN 2003, Millbrae, CA, USA, p. 55–60. https://doi.org/10.1109/ROMAN.2003.1251796
6. 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), Kurashiki, Okayama, Japan, pp 591–594. https://doi.org/10.1109/ROMAN.2004.1374827
7. Walters ML, Koay KL, Syrdal DS, Dautenhahn K, Te Boekhorst R (2022) Preferences and perceptions of robot appearance and embodiment in human-robot interaction trials. Accessed: Feb. 11, 2022. [Online]. Available: http://uhra.herts.ac.uk/handle/2299/9642
8. Deng E, Mutlu B, Mataric MJ (2019) Embodiment in socially interactive robots. FNT in Robot 7(4):251–356. https://doi.org/10.1561/2300000056
9. Arnold T, Scheutz M (2017) The tactile ethics of soft robotics: designing wisely for human-robot interaction. Soft Rob 4(2):81–87. https://doi.org/10.1089/soro.2017.0032
10. Sun YC, Effati M, Naguib HE, Nejat G (2022) SoftSAR: the new softer side of socially assistive robots—soft robotics with social human-robot interaction skills. Sensors 23(1):432. https://doi.org/10.3390/s23010432
11. Laschi C, Mazzolai B, Cianchetti M (2016) Soft robotics: Technologies and systems pushing the boundaries of robot abilities. Sci Robot 1(1):eaah3690. https://doi.org/10.1126/scirobotics.aah3690
12. Thrun S (2004) Toward a framework for human-robot interaction. Human Comput Interact 19(1–2):9–24. https://doi.org/10.1080/07370024.2004.9667338
13. Jones KS, Schmidlin EA (2011) Human-robot interaction: toward usable personal service robots. Rev Human Factors Ergonom 7(1):100–148. https://doi.org/10.1177/1557234X11410388
14. Bering Christiansen M, Jørgensen J (2020) Augmenting soft robotics with sound. In: Companion of the 2020 ACM/IEEE international conference on human-robot interaction, Cambridge United Kingdom, Mar. pp 133–135. doi: https://doi.org/10.1145/3371382.3378328
15. Christiansen MB, Jørgensen J, Belling ASE, Beloff L (2020) Soft robotics and posthuman entities. J Artist Res. https://doi.org/10.22501/jar.549014
16. 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 (University of Caldas, Manizales, Colombia, 2017): 153–160
17. Jørgensen J (2019) Constructing Soft Robot Aesthetics: Art, Sensation, and Materiality in Practice. PhD thesis. IT University of Copenhagen
18. Belling A-S, Buzzo D (2021) The rhythm of the robot: a prolegomenon to posthuman somaesthetics. In: Proceedings of the fifteenth international conference on tangible, embedded, and embodied interaction, New York, NY, USA, pp 1–6. https://doi.org/10.1145/3430524.3442470
19. Pêpe J (2015) Exo-biote, variation 0. Jonathan Pêpe. https://jonathan-pepe.com/Exo-biote-variation-0 (accessed Jun. 13, 2022)
20. Farahi B (2015) Caress of the Gaze. Behnaz Farahi. https://behnazfarahi.com/caress-of-the-gaze/ (accessed Jun. 13, 2022)
21. Wilson EO (1984) Biophilia. Harvard University Press, Cambridge
22. Neill C, Gerard J, Arbuthnott KD (2019) Nature contact and mood benefits: contact duration and mood type. J Posit Psychol 14(6):756–767. https://doi.org/10.1080/17439760.2018.1557242
23. Beck AM, Katcher AH (1996) Between pets and people: the importance of animal companionship. Purdue University Press, West Lafayette
24. Barker SB, Wolen AR (2008) The benefits of human-companion animal interaction: a review. J Vet Med Educ 35(4):487–495. https://doi.org/10.3138/jvme.35.4.487

25. Frumkin H et al (2017) Nature contact and human health: a research agenda. Environ Health Perspect 125(7):075001. https://doi.org/10.1289/EHP1663
26. Gruber P (2008) The signs of life in architecture. Bioinspi Biomim 3(2):023001. https://doi.org/10.1088/1748-3182/3/2/023001
27. Gruber P (2011) Biomimetics in architecture: architecture of life and buildings. Springer, New York
28. Buccino F et al (2021) Down to the bone: a novel bio-inspired design concept. Materials 14(15):4226. https://doi.org/10.3390/ma14154226
29. Parras-Burgos D, Hernández J, Velázquez JS, Cavas-Martínez F, Cañavate FJF, Fernández-Pacheco DG (2019) Combined Urban furniture designed by a bio-inspired approach. In: Advances on mechanics, design engineering and manufacturing II, Cham, pp 564–572. https://doi.org/10.1007/978-3-030-12346-8_55
30. Castro-González Á, Admoni H, Scassellati B (2016) Effects of form and motion on judgments of social robots' animacy, likability, trustworthiness and unpleasantness. Int J Hum Comput Stud 90:27–38. https://doi.org/10.1016/j.ijhcs.2016.02.004
31. Duffy BR (2003) Anthropomorphism and the social robot. Robot Auton Syst 42(3):177–190. https://doi.org/10.1016/S0921-8890(02)00374-3
32. Fink J (2012) Anthropomorphism and human likeness in the design of robots and human-robot interaction. Social robotics. Springer, Berlinpp, pp 199–208. https://doi.org/10.1007/978-3-642-34103-8_20
33. Jung Y, Lee KM (2004) Effects of physical embodiment on social presence of social robots. In: Proceedings of PRESENCE, pp 80–87
34. Lee KM, Jung Y, Kim J, Kim SR (2006) Are physically embodied social agents better than disembodied social agents?: the effects of physical embodiment, tactile interaction, and people's loneliness in human–robot interaction. Int J Hum Comput Stud 64(10):962–973. https://doi.org/10.1016/j.ijhcs.2006.05.002
35. Bainbridge WA, Hart JW, Kim ES, Scassellati B (2011) The benefits of interactions with physically present robots over video-displayed agents. Int J of Soc Robot 3(1):41–52. https://doi.org/10.1007/s12369-010-0082-7
36. Reig S, Forlizzi J, Steinfeld A (2019) Leveraging robot embodiment to facilitate trust and smoothness. In: 2019 14th ACM/IEEE international conference on human-robot interaction (HRI), Daegu, Korea (South), pp 742–744. https://doi.org/10.1109/HRI.2019.8673226
37. Kwak SS, Kim Y, Kim E, Shin C, Cho K (2013) What makes people empathize with an emotional robot?: the impact of agency and physical embodiment on human empathy for a robot. In: 2013 IEEE RO-MAN, Gyeongju, pp 180–185. https://doi.org/10.1109/ROMAN.2013.6628441
38. 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, Jeju, South Korea, pp 872–877. https://doi.org/10.1109/ROMAN.2007.4415207
39. DiSalvo C, Gemperle F, Forlizzi J, Montgomery E (2003) The hug: an exploration of robotic form for intimate communication. In: The 12th IEEE international workshop on robot and human interactive communication, Proceedings. ROMAN 2003, pp 403–408. https://doi.org/10.1109/ROMAN.2003.1251879
40. Block AE, Kuchenbecker KJ (2019) Softness, warmth, and responsiveness improve robot hugs. Int J Soc Robot 11(1):49–64. https://doi.org/10.1007/s12369-018-0495-2
41. Dörrenbächer J, Löffler D, Hassenzahl M (2020) Becoming a robot–overcoming Anthropomorphism with techno-mimesis. In: Proceedings of the 2020 CHI conference on human factors in computing systems, Honolulu HI USA, pp 1–12. https://doi.org/10.1145/3313831.3376507
42. Scheutz M (2002) Agents with or without emotions?. In: Proceedings of the fifteenth international florida artificial intelligence research society conference, pp 89–93
43. Djajadiningrat T, Matthews B, Stienstra M (2007) Easy doesn't do it: skill and expression in tangible aesthetics. Pers Ubiquit Comput 11(8):657–676. https://doi.org/10.1007/s00779-006-0137-9
44. Złotowski J, Proudfoot D, Yogeeswaran K, Bartneck C (2015) Anthropomorphism: opportunities and challenges in human-robot interaction. Int J of Soc Robot 7(3):347–360. https://doi.org/10.1007/s12369-014-0267-6
45. Bugmann G, Copleston SN (2011) What can a personal robot do for you? Towards autonomous robotic systems. Springer, Berlin, pp 360–371. https://doi.org/10.1007/978-3-642-23232-9_32
46. Oestreicher L, Eklundh KS (2006) User expectations on human-robot co-operation. In: ROMAN 2006 - The 15th IEEE International Symposium on Robot and Human Interactive Communication, pp 91–96. https://doi.org/10.1109/ROMAN.2006.314400
47. Scopelliti M, Giuliani MV, D'Amico AM, Fornara F (2004) If i had a robot at home… peoples' representation of domestic robots. Designing a more inclusive world. Springer Science \& Business Media, London, pp 257–266
48. Butler JT, Agah A (2001) Psychological effects of behavior patterns of a mobile personal robot. Auton Robot 10(2):185–202. https://doi.org/10.1023/A:1008986004181
49. Kim J, Kwak SS, Kim M (2009) Entertainment robot personality design based on basic factors of motions: a case study with ROLLY. In: RO-MAN 2009-The 18th IEEE international symposium on robot and human interactive communication, pp 803–808. https://doi.org/10.1109/ROMAN.2009.5326222
50. Buss M et al. (2011) Towards proactive human-robot interaction in human environments. In: 2011 2nd International conference on cognitive infocommunications (CogInfoCom), pp 1–6
51. Grigore EC, Pereira A, Zhou I, Wang D, Scassellati B (2016) Talk to me: verbal communication improves perceptions of friendship and social presence in human-robot interaction. In: Grigore EC (ed) Intelligent Virtual Agents. Springer, Cham, pp 51–63. https://doi.org/10.1007/978-3-319-47665-0_5
52. Cha E, Dragan AD, Srinivasa SS (2015) Perceived robot capability. In: 2015 24th IEEE International symposium on robot and human interactive communication (RO-MAN), Kobe, Japan, pp 541–548. https://doi.org/10.1109/ROMAN.2015.7333656
53. Cha E, Dragan AD, Srinivasa SS (2013) Effects of robot capability on user acceptance. In: 2013 8th ACM/IEEE international conference on human-robot interaction (HRI), pp 97–98. https://doi.org/10.1109/HRI.2013.6483519
54. Koay KL, Syrdal DS, Walters ML, Dautenhahn K (2009) Five weeks in the robot house–exploratory human-robot interaction trials in a domestic setting. In: 2009 second international conferences on advances in computer-human interactions, pp 219–226. https://doi.org/10.1109/ACHI.2009.62
55. Ito T, Osada J (2022) Relationship between liking the personal robot "Papero" and personality traits. J Sci Design 6(1):185–194. https://doi.org/10.11247/jsd.6.1_1_85
56. McDonnell R, Mutlu B (2021) Appearance. In: The handbook on socially interactive agents: 20 years of research on embodied conversational agents, intelligent virtual agents, and social robotics volume 1: methods, behavior, cognition, (1st edn), Association for Computing Machinery, New York, vol 37, pp. 105–146. Accessed: Jun. 15, 2022. [Online]. Available: https://doi.org/10.1145/3477322.3477327
57. 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, Hong Kong China, pp 667–677. https://doi.org/10.1145/3196709.3196743

58. Zheng CY, Walker K (2019) Soft grippers not only grasp fruits: From affective to psychotropic HRI. In: 2019 Convention of society for the study of artificial intelligence and simulation of behaviour (AISB), p 4
59. Budak EP, Zirhli O, Stokes AA, Akbulut O (2016) The breathing wall (BRALL)—triggering life (in)animate surfaces. Leonardo 49(2):162–163. https://doi.org/10.1162/LEON_a_01199
60. Jørgensen J, Bojesen KB, Jochum E (2021) Is a soft robot more "Natural"? Exploring the perception of soft robotics in human-robot interaction. Int J of Soc Robot. https://doi.org/10.1007/s12369-021-00761-1
61. Klausen TA, Farhadi U, Vlachos E, Jørgensen J (2022) Signalling emotions with a breathing soft robot. In: 2022 IEEE 5th international conference on soft robotics (RoboSoft), pp 194–200. https://doi.org/10.1109/RoboSoft54090.2022.9762140
62. Farhadi U, Klausen TA, Jørgensen J, Vlachos E (2022) Exploring the interaction kinesics of a soft social robot. In: Stephanidis C, Antona M, Ntoa S (Eds.), HCI international 2022 posters, pp 292–299. https://doi.org/10.1007/978-3-031-06394-7_38
63. Scoglio AA, Reilly ED, Gorman JA, Drebing CE (2019) Use of social robots in mental health and well-being research: systematic review. J Med Internet Res 21(7):e13322. https://doi.org/10.2196/13322
64. Moerman CJ, van der Heide L, Heerink M (2019) Social robots to support children's well-being under medical treatment: a systematic state-of-the-art review. J Child Health Care 23(4):596–612. https://doi.org/10.1177/1367493518803031
65. Asadi A, Niebuhr O, Jørgensen J, Fischer K (2022) Inducing changes in breathing patterns using a soft robot. In: 2022 17th ACM/IEEE international conference on human-robot interaction (HRI), pp 683–687. https://doi.org/10.1109/HRI53351.2022.9889343
66. Haynes AC, Lywood A, Crowe EM, Fielding JL, Rossiter JM, Kent C (2022) A calming hug: design and validation of a tactile aid to ease anxiety. PLoS ONE 17(3):e0259838. https://doi.org/10.1371/journal.pone.0259838
67. Hall H et al (2022) Patient and practitioner perspectives on the design of a simulated affective touch device to reduce procedural anxiety associated with radiotherapy: a qualitative study. BMJ Open 12(3):e050288. https://doi.org/10.1136/bmjopen-2021-050288
68. Sabinson EB, Green KE (2021) How do we feel? User perceptions of a soft robot surface for regulating human emotion in confined living spaces. In: 2021 30th IEEE international conference on robot & human interactive communication (RO-MAN), Vancouver, BC, Canada, pp 1153–1158. https://doi.org/10.1109/RO-MAN50785.2021.9515499
69. Botar O (2016) Biomorphism. Routledge encyclopedia of modernism, 1st edn. Routledge, London. https://doi.org/10.4324/9781135000356-REM770-1
70. Tate (2022) Biomorphic–art term. Tate. https://www.tate.org.uk/art/art-terms/b/biomorphic (accessed Feb. 11, 2022)
71. OED Online (2021) organic, adj. and n. OED Online. Oxford University Press. Accessed: Nov. 11, 2021. [Online]. Available: http://www.oed.com/view/Entry/132431
72. Wünsche I (2012) Life into art: nature philosophy, the life sciences, and abstract art. In: Crowther P, Wünsche I (eds) Meanings of abstract art. Routledge, New York
73. Crowther P, Wünsche I (Eds.) (2012) Introduction. In: Crowther P, Wünsche I (Eds.), Meanings of abstract art, (1st edn), Routledge, New York
74. Barr AH (1936) Cubism and abstract art, Museum of Modern Art, vol 1936. New York
75. Alloway L (1965) The biomorphic forties. Artforum 4(1). Accessed: Sep. 09, 2021. [Online]. Available: https://www.artforum.com/print/196507/the-biomorphic-forties-36924
76. Juler E (2015) Life forms: henry moore, morphology and biologism in the interwar years. In: Henry moore: sculptural process and public identity, tate research publication, Accessed: Sep. 15, 2021. [Online]. Available: https://www.tate.org.uk/art/research-publications/henry-moore/edward-juler-life-forms-henry-moore-morphology-and-biologism-in-the-interwar-years-r1151314
77. Sandry E (2015) Re-evaluating the form and communication of social robots. Int J of Soc Robot 7(3):335–346. https://doi.org/10.1007/s12369-014-0278-3
78. Löffler D, Dörrenbächer J, Hassenzahl M (2020) 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, New York, USA, Association for Computing Machinery, pp 261–270. Accessed: Jul. 07, 2022. [Online]. Available: https://doi.org/10.1145/3319502.3374788
79. Fong T, Nourbakhsh I, Dautenhahn K (2003) A survey of socially interactive robots. Robot Auton Syst 42(3):143–166. https://doi.org/10.1016/S0921-8890(02)00372-X
80. Sparrow R (2002) The March of the robot dogs. Ethics Inf Technol 4(4):305–318. https://doi.org/10.1023/A:1021386708994
81. Breazeal C (2004) Designing sociable robots. MIT Press, Cambridge
82. HL Bradwell, Winnington R, Thill S, Jones RB (2021) Morphology of socially assistive robots for health and social care: a reflection on 24 months of research with anthropomorphic, zoomorphic and mechanomorphic devices. In: 2021 30th IEEE International Conference on Robot & Human Interactive Communication (RO-MAN), pp. 376–383. https://doi.org/10.1109/RO-MAN50785.2021.9515446
83. Louis S (1896) The tall office building artistically considered. Lippincotts Magazine
84. Gibson JJ (2014) The ecological approach to visual perception. Psychology Press, New York. https://doi.org/10.4324/9781315740218
85. Gaver WW (1991) Technology affordances. In: Proceedings of the SIGCHI conference on Human factors in computing systems reaching through technology-CHI '91, New Orleans, Louisiana, United States, pp. 79–84. https://doi.org/10.1145/108844.108856
86. Norman DA (1988) The psychology of everyday things. Basic Books, New York, pp xi, 257
87. Cambridge Dictionary (2022) Interaction-definition. Cambridge Dictionary. https://dictionary.cambridge.org/dictionary/english/interaction (accessed Jun. 14, 2022)
88. Lexico (2022) Relation-meaning & definition for UK English. Lexico Dictionaries| English, n.d. https://www.lexico.com/definition/relation (accessed Jun. 14, 2022)
89. Sanders E (2002) From user-centered to participatory design approaches. Design and the social sciences. CRC Press, Boca Raton
90. Rizzo F (2011) Co-design versus user centred design: framing the differences. In: Notes on Doctoral Research in Design. Contributions from the Politecnico di Milano: Contributions from the Politecnico di Milano, FrancoAngeli
91. Zamenopoulos T, Alexiou K (2018) Co-design as collaborative research. Bristol University/AHRC Connected Communities Programme, Bristol. Accessed: Jun. 13, 2022. [Online]. Available: https://connected-communities.org/wp-content/uploads/2018/07/Co-Design_SP.pdf
92. Dindler C, Iversen OS (2007) Fictional inquiry—design collaboration in a shared narrative space. CoDesign 3(4):213–234. https://doi.org/10.1080/15710880701500187
93. Buskermolen DO, Terken J (2012) Co-constructing stories: a participatory design technique to elicit in-depth user feedback and suggestions about design concepts. In: Proceedings of the 12th

participatory design conference on exploratory papers workshop descriptions industry cases-volume 2-PDC '12, Roskilde, Denmark, p 33. https://doi.org/10.1145/2348144.2348156
94. Braun V, Clarke V, Hayfield N, Terry G (2019) Thematic analysis. In: Liamputtong P (ed) Handbook of research methods in health social sciences. Singapore, Singapore, pp 843–860. https://doi.org/10.1007/978-981-10-5251-4_103
95. Braun V, Clarke V (2006) Using thematic analysis in psychology. Qual Res Psychol 3(2):77–101. https://doi.org/10.1191/1478088706qp063oa
96. Sabinson E, Pradhan I, Evan Green K (2021) Plant-human embodied biofeedback (pheB): a soft robotic surface for emotion regulation in confined physical space. In: Proceedings of the fifteenth international conference on tangible, embedded, and embodied interaction, Salzburg Austria, pp 1–14. https://doi.org/10.1145/3430524.3446065
97. Crane B, Still K (2017) Fundamentals of user-centered design: a practical approach. CRC Press, Boca Raton. https://doi.org/10.4324/9781315200927
98. Clayton M (2012) What is entrainment? Definition and applications in musical research. Empir Musicol Rev 7(1–2):49–56. https://doi.org/10.18061/1811/52979
99. Thaut MH, McIntosh GC, Hoemberg V (2015) Neurobiological foundations of neurologic music therapy: rhythmic entrainment and the motor system. Front Psychol 5, Accessed: Nov. 23, 2022. [Online]. Available: https://www.frontiersin.org/articles/https://doi.org/10.3389/fpsyg.2014.01185
100. Costa J, Adams AT, Jung MF, Guimbretière F, Choudhury T (2016) EmotionCheck: leveraging bodily signals and false feedback to regulate our emotions. In: Proceedings of the 2016 ACM international joint conference on pervasive and ubiquitous computing, New York, NY, USA, pp 758–769. https://doi.org/10.1145/2971648.2971752
101. Choi KY, Ishii H (2020) Ambienbeat: wrist-worn mobile tactile biofeedback for heart rate rhythmic regulation. In: Proceedings of the fourteenth international conference on tangible, embedded, and embodied interaction, Sydney NSW Australia, pp 17–30. https://doi.org/10.1145/3374920.3374938
102. Yohanan S, MacLean KE (2011) Design and assessment of the haptic creature's affect display. In: 2011 6th ACM/IEEE international conference on human-robot interaction (HRI), pp 473–480. https://doi.org/10.1145/1957656.1957820
103. 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 of Soc Robot 1(1):71–81. https://doi.org/10.1007/s12369-008-0001-3
104. Carpinella CM, Wyman AB, Perez MA, Stroessner SJ (2017) The robotic social attributes scale (RoSAS): development and validation. In: Proceedings of the 2017 ACM/IEEE international conference on human-robot interaction, New York, NY, USA, pp 254–262. https://doi.org/10.1145/2909824.3020208
105. Heerink M, Krose B, Evers V, Wielinga B (2009) Measuring acceptance of an assistive social robot: a suggested toolkit. In: RO-MAN 2009-The 18th IEEE international symposium on robot and human interactive communication, pp 528–533. https://doi.org/10.1109/ROMAN.2009.5326320
106. Mori M, MacDorman KF, Kageki N (2012) The uncanny Valley [from the field]. IEEE Robot Automat Mag 19(2):98–100. https://doi.org/10.1109/MRA.2012.2192811
107. Löffler D, Dörrenbächer J, Welge J, Hassenzahl M (2020) Hybridity as design strategy for service robots to become domestic products. In: Extended abstracts of the 2020 CHI conference on human factors in computing systems, Honolulu HI USA, pp 1–8. doi: https://doi.org/10.1145/3334480.3382832
108. Hoffman G, Ju W (2014) Designing robots with movement in mind. J Human Robot Interact 3(1):89. https://doi.org/10.5898/JHRI.3.1.Hoffman

Mads Bering Christiansen is a PhD student (2021-) at SDU Soft Robotics, SDU Biorobotics, The Maersk Mc-Kinney Moller Institute, University of Southern Denmark. His research centers on investigating the effects of integrating organic-appearing, biomorphic aesthetics in soft robot designs for human-robot interaction. He is trained as a designer and holds a BA in digital design from Aarhus University (2016), and a MSc in digital design and communication from The IT University of Copenhagen (2018) with a specialization in interaction design, media aesthetics, and creative use of technology.

Ahmad Rafsanjani is Professor at SDU Soft Robotics, SDU Biorobotics, The Maersk Mc-Kinney Moller Institute, University of Southern Denmark.

Jonas Jørgensen is Associate Professor at SDU Soft Robotics, SDU Biorobotics, The Maersk Mc-Kinney Moller Institute, University of Southern Denmark.