An Exploration of Material Choice for Personal Robots

ABSTRACT
Robots are emerging as a new category of products, ranging from personal to service applications. Many envisioned and emerging scenarios of use for these products involve their users engaging in physical "touch" interactions. While different paradigms of robot construction, including Silicone-based humanoid robots, soft robots, and novel rapid-prototyping techniques, have been explored, very little is known about user experience of touch between humans and robots or how materials can influence the design of robots for personal use. We explored user experience with 3D-printed hard and soft materials for a household robot through a user-enactment study with 16 participants. Our results show that, while participants showed an overall preference toward softer materials over harder materials, these preferences were shaped by a complex and nuanced set of factors including anthropomorphic characterizations, context-dependent preferences, and opportunities for mixed-material use.

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g., HCI): User Interfaces—*haptic I/O; prototyping; user-centered design*

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Material choice; product design; user experience; personal robots; household robots; human-robot interaction

INTRODUCTION
Robots represent an emerging category of consumer products that will physically interact with their environments and users. Users of these products will uniquely interact with them through physical "touch." Touch interactions are not only essential for robots to effectively assist their users in domains such as therapy [21], but they also promise to enrich user interaction by providing emotional bonding and social support [25]. To succeed as personal products that offer physical assistance as well as social and emotional companionship, robots must effectively support touch interactions [15].

The product design of most robots follows the design of conventional products, composed of rigid, interlinked parts. While this approach provides structure and conforms to existing manufacturing practices, it does not support the range of unique touch interactions robots engage in or elicit the types of responses for which personal robots are designed. Prior work across HCI and robotics has explored how soft robots may overcome some of these barriers to facilitate interaction with the physical world and users [20, 23], novel methods of fabrication to support touch interactions [10], and how material use shapes aesthetic experience with interactive artifacts [18].

Figure 1. We explored material use in the fabrication of a personal robot, asked participants to enact a series of "touch" interactions with the robot based on envisioned scenarios of use for the robot, and studied their experience with the materials.

Despite a growing body of work on materiality, affective touch, and soft robots, user experience with materials used to design robots and what materials best support touch interactions with a robot remain under-explored. In this note, we explore material choice for a personal robot through the fabrication of hard and soft materials and a user-enactment study to understand preferences toward and experience with them (Figure 1).

RELATED WORK
Previous HCI research explored the notion of "materiality" to characterize not only the building of the physical and digital materials that support desired functionality but to entail the shaping of the entire user experience, including aesthetic qualities of design [7, 8, 17] and engagement of materials in a socio-cultural environment [24]. This body of work has explored the role of designer engagement with objects and materials on design ideation [13] and the use of materials and artifacts as a medium for creative expression [19, 17, 18, 12]. For example, a system called Spyn [18, 19] aimed to connect a knitter's experience and story to the user of the knitted artifact, concluding that a material perspective allows physical artifacts to be linked with creative expression and reflection.

Touch interactions with robots have been studied primarily in the context of designing therapeutic, socially assistive, and companion robots. DiSalvo et al. [5] explored the design space for therapeutic robots for remote communication among individuals, using velour and silk-upholstered fabrics to better mediate touch interaction between remote partners. Soft materials, particularly synthetic fur, were used in the construction of other robots designed for rehabilitation and social support through touch, including Paro, a robotic seal [22], and Huggable, a robotic teddy bear [21]. Touch interactions have also been explored in the context of designing tangible user interfaces to control robots from a distance [9].

Prior work across robotics has investigated construction and fabrication methods to improve the physical or interactive capabilities of robots. Research in the area of "soft robotics" explored how elastomeric materials can overcome barriers in motion and object manipulation faced by hard, rigid materials [20]. For example, the materials of the "octobot," the first autonomous robot completely composed of soft materials, enabled the robot to effectively navigate and adjust to its environment [23]. Soft, Silicone-based materials have also been used to build extremely life-like humanoid robots and androids [16]. Related work in HCI includes explorations of novel fabrication methods to create soft, felt-like interactive artifacts from wool and wool-blend yarns [10].

While these bodies of work illustrate the rich space of material use to support the functional and aesthetic dimensions of user experience with a robotic product, a more systematic study of material choice will inform the future development of envisioned applications of personal robots.

MATERIAL EXPLORATION

We examined how soft and hard materials supported user experience with a household robot using the Hello Robo Maki platform [1]. The Maki robot is particularly well-suited for studying touch interactions, as it was designed as a multipurpose household robot that must be moved by its users through physical interaction. Because robotic products, including widely used robots such as the Roomba [2] and the AIBO [4] are explicitly designed to suspend all movement when their users physically interact with them in order to improve user safety and product reliability, we chose to use an immobile robot that lacked the mechanical and electrical components in the study.

We used 3D-printing as a rapid-prototyping technique and fabricated a complete Maki robot using a MakerBot Replicator 2X printer [3]. In preliminary studies, we observed that participants exclusively interacted with the torso part of the robot and thus additionally fabricated the front torso of the robot using the materials included in our investigation. This torso part also had the largest surface area and better supported visual and tactile inspection than other parts did. Unlike the complete robot, the size and the single-part structure of the torso encouraged users to touch, grab, squeeze, stroke, and closely inspect the materials. A complete Maki robot was fabricated to assist users in visualizing use scenarios while providing a reference model for where the parts belonged.

Figure 2. The three materials used for the torso part of the robot are Polyurethane (PU) (left), Silicone-coated Acrylonitrile Butadiene Styrene (middle), and Acrylonitrile Butadiene Styrene (ABS) (right).

The space of materials that are available to product designers is multidimensional, such as plastics that vary in elasticity, ductility, and fracture mechanisms. A comprehensive study may require tens, if not hundreds, of different materials, and choosing any subset from this space would have limited applicability. To serve as a starting point and to establish a methodological framework for studying material choice, our exploration focused on plastic materials. We characterized the space of plastic materials as (1) *structurally hard*, (2) *structurally soft*, and (3) *hybrid*, i.e., structurally hard, tactilely soft, materials, as described below and shown in Figure 2.

We chose Acrylonitrile Butadiene Styrene (ABS) to represent a "structurally hard" material due to its ubiquitous use in product design and to its availability for 3D-printing. To represent "structurally soft" plastics, we chose Polyurethane (PU), a lower-modulus material that provides flexibility and absorbs impact that rigid materials such as ABS lack. PU appears sturdy and offers some amount of structure, yet its structure is malleable when touched. The last material was a "hybrid" of hard and soft materials, soft to the touch, yet offering a hard structure, which we created by evenly coating the outside of 3D-printed ABS with Silicone (SI), providing the material with a unique grip. We fabricated the torso part in all three materials and the complete robot in ABS.

To confirm the softness/hardness of the base materials, we utilized Dynamic Mechanical Analysis (DMA), a method used to determine the softness/hardness of the polymeric materials by analyzing their viscoelastic properties. Our DMA analysis showed that ABS had a storage modulus of 9×10^8 Pascals and a loss modulus of 1.4×10^7 Pascals and PU had a storage modulus of 4.4×10^5 Pascals and a loss modulus of 4.3×10^4 Pascals. Our analysis indicated that the storage modulus of ABS is substantially larger than that of PU, confirming that ABS is a stiffer material. The storage-to-loss moduli proportion of the materials show that the deformation energy of PU is elastically recoverable while more of the deformation energy of ABS is viscously dissipated as heat. These properties shape material behaviors such as the sound a material makes during impact or whether it bounces or fractures.

USER EXPERIENCE STUDY

Our study involved participants enacting a set of scenarios of use that illustrate touch interactions with the household robot, interacting with parts fabricated using different materials, and reflecting on how the materials would support the scenarios.

Participants – We recruited 16 participants between 20 and 68 years old from a campus community. The study protocol was approved by the relevant Institutional Review Board (IRB). Participants provided written informed consent prior to their participation and received $10 per hour as compensation.

Procedure – During the study, participants sat at a table with the torso parts laid out in front of them, the complete Maki robot placed at the end of the table, and an interviewer sitting next to them. Throughout the study, participants were asked to *think aloud* [6]. The interviewer asked the participants to inspect the torso fabricated using the three materials and respond to a questionnaire on material characteristics. Users then enacted five scenarios that represented household activities in which they would interact with the household robot through touch, developed by distilling interaction scenarios discussed or explored in the HRI literature. The scenarios included (1) carrying the robot from one place to another, (2) rotating it so that it would face the participant, (3) gently pushing it away from the participant for privacy, (4) hugging it, and (5) dropping it accidentally (enacted using the torso parts). After each scenario, participants were asked to reflect on how each material would support the activity. Below is an example scenario that required the participant to carry the robot:

> For the first activity, imagine that you are in the kitchen, cooking following instructions from your household robot, *Minnie*. After you finish cooking, you want to move Minnie into your home office for company while you work. You have to carry/move the robot from one room to the next. Can you please move Minnie from the table in the corner to the table far away?

Measures – Our study utilized two sources of data: *qualitative* reflections provided during think-aloud and interview segments and *quantitative* responses to questionnaires. Qualitative reflections were captured at multiple points during the study. During the scenarios and material inspection, participants were prompted to think aloud, and their reflections were video recorded. Participants also discussed how each material would support the interactions in each scenario. After completing all scenarios, participants responded to questions regarding their overall experience with the materials. Quantitative data included responses to brief questionnaires administered after interacting with each material. They included seven-point Likert-scale items measuring material characteristics, including smoothness, visual appeal, durability, in order to establish a measure of overall material desirability.

FINDINGS

We describe the findings from our analysis of data from questionnaires and interviews below and integrate qualitative and quantitative findings in the Discussion section.

Findings from the Qualitative Data

Data from interviews were transcribed, coded for significant phenomena, and analyzed using content analysis [14]. The analysis involved iteratively categorizing the codes using affinity diagramming until high-level categories emerged and became stable. This analysis yielded a number of themes, offering insights into material choice for personal robots as well as for household products in general. Given the focus of our study, we present findings that inform material use in personal robots. Below, we describe the themes *anthropomorphic characterizations*, *blending materials*, and *context-dependent preferences* and provide illustrative excerpts from our data.

Anthropomorphic Characterizations – Our data included several instances of participants interacting with the robot socially or describing and engaging with it in anthropometric terms.

> **P4:** *"Hi Minnie, how are ya? Here you go [picks up Minnie]."*

> **P3:** *"...I like the bendy aspect of it. [PU] is more 'human' than the other two materials. You can just do a lot more with it. You want your robots to seem like they are breathing. This one would almost seem like it would be breathing."*

These characterizations included references to clothing and facial features. Many participants expressed that Minnie should be dressed up. A participant noted the robot's lack of a nose and hair upon first seeing it. Several participants described Minnie as appearing like a "baby." Such characterizations were also embedded in participants' descriptions of the materials. Participants described positive, desirable characteristics of materials, such as PU's softness, as being more "human-like" and "natural." Negative characteristics, such as the "oily" texture of the Silicone-ABS material, were described as "unhumanlike," "lifeless," "made by a factory," or "artificial."

> **P11:** *"I'm never a big fan of plastic. But I like something that feels more human. When you touch something and it feels safe. But due to durability, [PU] is the safest. [ABS] is always the worst no matter what..."*

> **P3:** *"[ABS] seems like it would have come straight from a factory...I don't want to use the word non-human... but it is and artificial. [PU and ABS] look very similar but [PU] does look a little bit more expensive or of higher quality than [ABS]. [ABS]... looks so cheap."*

These observations suggest that, whether positive or negative, users' anthropomorphic characterizations of personal robots must be a key consideration in material choice, as materials can be seen as being consistent or inconsistent with user perceptions of the robot as a social entity.

Blending Materials – After completing the enactments with the robot and inspecting the materials, the majority of the participants felt that an ideal robot should be made with a combination of materials. Their comments suggest that multiple materials in a robot can support and signify various functions. For example, some participants were apprehensive about how the robot should be physically handled. While most participants picked the robot up by its torso, some questioned whether or not they should pick it up by the head.

> **P10:** *"When picking up Minnie, it isn't obvious for how I should do it. If there is a handle on the head to know how to pick her up. It was like you were picking up someone's... dog you are not sure how to do it."*

Material use can be an effective design tool to clarify such confusions by signaling how users may best physically interact with the robot. While picking up the robot by its torso or head may be equally safe and effective, we expect the former to be much more socially appropriate, given the characterizations that we observed in our data. Thus, material choice in the design of a personal robot can be a particularly powerful tool that guide users in interacting with an artificial social entity.

> **P13:** *"So you could have places where you would usually grip, rotate, push, squeeze made of [PU] or [SI] like little hand grips... bumpy hand-piece like for bicycle handle bars..."*

Participants made several suggestions for using hard and soft materials, including using ABS on the robot's face could prevent deformation that could result from using elastomeric, rubbery materials such as PU and the use of the Silicone-coated ABS material on parts where the robot should be picked up. They also reflected on the surface textures of the materials; PU's soft, smooth surface was seen as offering comfort, while the more uniform, textured surface of the SI material was seen as being more "functional" for manipulating the robot.

> **P9:** *"Maybe a combination. It would be nice for the body... where you would touch her the most... to be softer and if the electronics were going through the head they could be sealed with a harder material. A combination because I could see myself dropping it. [PU] for the body maybe [SI] for the top."*

> **P3:** *"I would think the body should be [PU] even the back of the head. For its face you might want [ABS] just because I've had toys that have had the bendy material for the mouth and it just looks scary and... tears just because it is moving a lot more than other pieces... I think that it is more aesthetically pleasing ... toys I used to have when the faces were hard."*

These observations highlight mixed-material use as a key design tool to simultaneously address diverging user needs and expectations that stem from viewing with personal robots as physical products as well as social entities.

Context-dependent Preferences – Throughout the study, we observed participant preferences to diverge based on the context of the interaction. Aspects that made a material preferable for a particular scenario made it undesirable for other purposes, as illustrated in the responses below to scenarios involving picking up and carrying and those involving hugging the robot.

> **P6:** *"Well, if you are going to pick it up, you want something that is grippy, so I guess for that [SI] would be best. [PU] would be difficult like if your hands were damp or something... [SI] would be sticky and gross, especially if it is hot out so I wouldn't want to hug it. [ABS] is very cold and would be like hugging a wall. [PU] would probably be the best for human interaction things like hugging..."*

> **P7:** *"[PU] is nicer and feels good hugging... If I am holding it and my hands smush it, I feel uncomfortable with [PU]."*

The grip of the Silicone-coated ABS made it appealing to participants for picking up and carrying the robot, but its stickiness made it undesirable for hugging. Participants expressed an overall preference toward the structural softness that PU offered, although softness was also noted as a disadvantage when the safety of the robot's internal components were considered.

These context-based differential perceptions and preferences indicate that, unlike singular interaction scenarios involving conventional products, personal robots as social entities will offer a wide range of physical, touch-based interactions, making material choice a complex, context-dependent design problem.

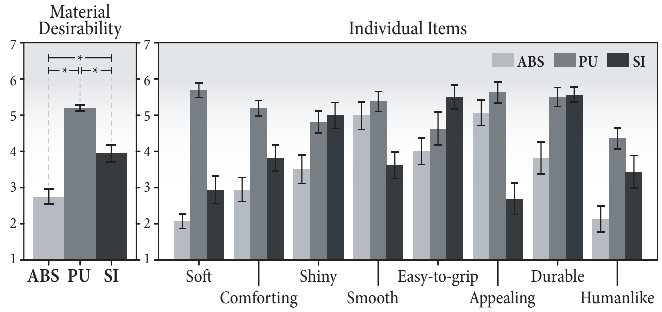

Figure 3. Data from the product desirability measure and individual items included in the questionnaire. (*) denotes a significant difference.

Findings from the Quantitative Data

The analysis of our quantitative data first involved an exploratory-confirmatory factor analysis [11] to construct a scale of *material desirability*, producing a four-item scale including items "durable," "humanlike," "soft," and "comforting" (Cronbach's $\alpha = 0.748$). We analyzed data from this scale using a repeated-measures analysis of variance (ANOVA), followed by pairwise comparisons using Tukey's Honestly Significant Difference (HSD) Test to control for Type I error.

Our analysis of the material desirability measure showed that participant ratings were affected by the use of the different materials, $F(2,30) = 39.90$, $p < .001$. All pairwise comparisons were significant at alpha level 0.05. PU was rated as the most desirable material ($M = 5.19$, $SD = 0.43$), followed by Silicone-coated ABS ($M = 3.94$, $SD = 1.00$), which was followed by ABS ($M = 2.73$, $SD = 0.93$). Figure 3 illustrates these comparisons as well as all individual items administered.

DISCUSSION

Physical touch is essential for the user experience of personal and household robots. In this note, we describe the fabrication of hard and soft materials and a user-enactment study that investigated preferences toward material use in a personal robot. Our results show that, while participants showed an overall preference toward softer materials over harder materials, these preferences were shaped by a complex and nuanced set of factors including anthropomorphic characterizations, opportunities for mixed-material use, and context-dependent preferences. These findings highlight the need for considering perceptions of the robot as a social entity in material selection and mixed-material use as an opportunity to simultaneously address address diverging design requirements that result from the robot being a mass-produced household product while being perceived as a social entity. We also found user experience to depend on interaction context, suggesting that designers must target specific scenarios of use in material use.

Our work offers preliminary insights into factors that shape user experience of material choice for the design of personal robots and establishes as a methodological basis for future research. Future work may examine more materials and robotic platforms, extend our investigation to *in situ* and long-term user experiences, and explore how user preferences change in more interactive and complex scenarios of use.

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