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A Study into Understanding User Requirements to Inform the Design of Customizable Robotic Pain Management Devices

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Abstract— **Previous research into using robots for pain management has shown promise. However to date, there seems to have been little research investigating user requirements for robotic pain management devices which could be used by adults living with chronic pain, and how these might be translated into custom products. We carried out a user study comprising online surveys and interviews with people who have lived experience of chronic pain to investigate their perspectives. We had a total of 44 participants in our study. Our research revealed a preference for robotic devices for pain management which have an abstract or animal-like form, noting that contact points with the body should feel soft, warm, and light. Study participants also felt that the user should initiate the interaction and should have control of the robot, as well as the type and intensity of touch. Favored touch types included massaging, rubbing, and stroking. From the emerging requirements, given the diversity of experiences, design-related attributes identified could be used for a form-customization application, such as interactive evolutionary computation (IEC), as a means to personalize the embodiment of robotic devices. Prioritized form factors for customization through included size, weight, and feel.**

I. INTRODUCTION

Robots will likely play an important role in future healthcare ecosystems, and are already used in medical settings for telehealth [1] and physical therapy [2]. These robots are required to physically interact with humans, who are often experiencing pain, so it is important to consider the impact of physical contact in human-robot interactions. Human responses to both touch and pain can elicit varying emotional and physical reactions, which can influence long-term outcomes, dependent upon gender, age, cultural background, environmental context, and emotional state [3], [4]. Developing technologies to support pain management is further complicated by the complex and varying nature of pain. In addition to temporary acute pain, many people using healthcare services will be living with chronic pain that will persist and change over time.

Chronic pain is an umbrella term for any pain which persists longer than 12 weeks [5]. Up to 20% of adults worldwide experience chronic pain [6], and in the UK 10-14% of adults experience pain that is moderately or severely disabling [7]. Chronic pain conditions include arthritis, fibromyalgia, complex regional pain syndrome (CRPS), angina, and back pain, amongst many others [5]. In addition to physical restrictions, the condition can also affect mental health and overall quality of life [8].

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Despite the prevalence of chronic pain, and a shift in pain management techniques away from pharmacological treatments, research into robotic applications for chronic pain management has so far been limited. Initial studies have shown promise in the application of robots for pain management, however little research has considered the needs or desires of potential end-users. user-centered design (UCD) includes end-users in the development of new technologies from their conception [9], and aims to improve outcomes and acceptance [10]. The principles of UCD require that the needs of end-users be identified during the design process to create products that meet users' requirements, rather than requirements assumed by designers. The process returns to the end-users repeatedly throughout iterative stages of research, analysis, ideation, prototyping, and testing.

Due to the unique nature of the pain experience, and the likelihood that technology acceptance can be improved through customization [11], it may also be beneficial to expand UCD principles even further, and consider how individual users may be able to alter technologies to suit their needs. This may improve acceptance of robotic technologies and allow users to feel a bond with machines [12]. One method to enable exploratory customization of a product's physical form factors is interactive evolutionary computation (IEC). Evolutionary computation is inspired by the process of natural selection [13], and IEC can allow users to crossbreed 3D forms to produce new generations with more desirable traits, until the user finds a form they find acceptable.

This research implemented the initial research and analysis stages of the user-centered design process to inform future designs of robotic devices for pain management. People living with chronic pain were invited to take part in an online survey, from which participants were sourced for semi-structured interviews. Combined results were analyzed to understand what people living with chronic pain may desire from a therapeutic robot, and inform requirements for elements that users might like to customize.

II. RESEARCH QUESTIONS

Established UCD research methods, including a survey and interviews, were used to address the following questions, to inform future design for robotic interventions for chronic pain management.

1. What are core product features for a robotic device intended for pain management?

2. How is robotic or artificial touch currently perceived by users living with chronic pain?

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3. What form features would potential end-users of assistive robotic devices like to customize, and what features would be prioritized for customization in an IEC application?

III. RELATED WORK

A. Chronic Pain Management

Chronic pain can be the result of another healthcare condition or a initial injury, and exist in the absence of an observable cause. It is contributed to by biological, social, and psychological factors [14]. Current recommended treatment involves building a supportive relationship between patient and medical staff, and working collaboratively to identify suitable pain management techniques [15].

Traditionally chronic pain has been treated pharmacologically, but recently there has been a rising awareness of the disadvantages of over-reliance on analgesics. Healthcare professionals are now seeking to complement or replace painkiller usage with alternative pain management methods, such as massage, physiotherapy, or psychological interventions [14]. Other non-pharmacological methods of pain management include traditional acupuncture [16], therapeutic touch [17], and transcutaneous electrical nerve stimulation (TENs) [18]. Whilst the mechanism of chronic pain is not fully understood, it is likely that benefits from these treatments come from distraction or pain gating. Pain distraction involves shifting focus from the pain, and on to other stimuli, making the pain less pronounced. Pain gating is a contested theory which involves interrupting neurological signals at the spinal column, preventing them from reaching the brain [19].

New technologies have been applied for pain management including health apps [20], [21], virtual reality [22], and wearable devices [23], [24]. These have shown some efficacy in reduction of perceived pain in the short-term, however more rigorous studies are needed to verify their success and to observe reduction in perceived pain in the long-term.

B. Robotics for Pain Management

Research into robots for pain management has largely focused on using socially assistive robots (SARs) to treat acute pain in children undergoing medical procedures. Studies used the humanoid robot NAO performing established distraction techniques on children undergoing vaccination [25], [26], and intravenous (IV), or catheter insertion [27]. Other research using SARs implemented the MAKI [28], Paro [29] and Pepper and SanBot Elf [30] in a similar manner. In our literature review we identified a paucity of research in this area, however 13 out of 17 papers reviewed showed a statistically significant improvement in pain perception or pain anxiety compared to no intervention [31].

Few robots were designed specifically for pain management, however a squeezable soft robot designed for this purpose reduced pain perception during initial trials [32]. Zhang et al. conducted user-centered design workshops, in which children indicated preferences for zoomorphic robots which reduced pain through distraction [33]. A notable exception to the distraction performing SARs is the Calmer bed which seeks to soothe pre-term infants during medical procedures by mimicking a parental chest. Two small studies indicated reduced levels of pain based on observational measurements of infant pain [34], [35].

One larger study conversely used healthy adults in a trial with experimentally induced acute pain. Participants who physically interacted by stroking and touching Paro, a robotic baby seal, reported reduced pain perception and salivary oxytocin, a hormone linked to anxiety and pain [36]. This reduction in pain was also increased when the robot interacted with the participant [37].

C. Robotics for Chronic Pain Management

All contemporary research into chronic pain management with robots has used Paro as an intervention for people with dementia, as a replacement for animal assisted therapy. Paro has been shown to have general quality of life benefits for this population [38]. Long-term interventions have shown that Paro may reduce observed pain and unscheduled medications [39], and increase relaxation [40].

D. Interactive Evolutionary Computation for Customized Design

In IEC expert defined traits (phenotypes) are translated into code (genotypes) and used to generate potential solutions to a problem. From an initial population, solutions can be repeatedly crossbred and mutated to produce generations of offspring. The preferences of a human being may be difficult to quantify and measure, so by introducing an interactive element the end-user can evaluate and crossbreed solutions until they find one that is personally satisfying [41].

IEC has been used for to generate 3D forms including sculptures [42], abstract forms based on natural morphology [43], and soda bottles [44]. In robotics, a mobile phone application was used to create simple robotic forms through IEC [45]. Customization may help to improve acceptance and usability of robotic technologies [35], [46], and IEC allows users to influence and create their own 3D forms.

Most research conducted so far into robotic interventions for chronic pain management has been technology led. Additionally, though older adults are those most likely to experience long-term pain [7], research has not focused on this group. Therefore this research sought to use UCD methodologies to understand people's perceptions of existing robots, and investigate the potential of customizable robotic interventions for chronic pain management among adults.

IV. METHODS

Applying UCD methods, an online survey and follow-up interviews were conducted with people living with chronic pain. All research was conducted online, due to the Covid-19 pandemic, which made it unviable to conduct in-person research with participants experiencing chronic pain who are more likely to be medically vulnerable. Approval for the research was provided by the ethics committee of the Faculty of Environment and Technology at the University of the West of England, reference number FET.20.07.060.

A. Survey

The survey was self-administered online and hosted on the Qualtrics survey design website from November 2020 to February 2021. Participants were recruited through emails via the study team's health and academic networks, as well as social media call-outs. An additional 30 people were paid £2.50 to take the survey through the paid survey website Prolific, having answered a screening question about living with long-term pain. Therefore, all participants self-reported as experiencing chronic pain. Survey sections included: demographic and pain condition information, touch sensations, robotic touch, and product preferences and customization.

1) Demographic and Pain Condition Information: Basic demographic information was attained from participants as well as levels of touch comfort, as an individual's attitudes to touch, pain, and robots likely differ based on a variety of cultural and environmental factors [47]. Questions to attain information about the participants pain condition were based on the Short Form McGill Pain Questionnaire [48], including pain location, frequency, and descriptors.

2) Touch Sensations: Participants were then asked to think about a variety of tactile stimuli, in relation to their own pain. The first subsection asked participants to consider the common and opposing physical qualities of hardness, softness, warmth, coldness, heaviness, and lightness. These were rated on a five-point Likert-type scale [49] where 1 is unpleasant, 2 is somewhat unpleasant, 3 is neutral, 4 is somewhat soothing, and 5 is soothing.

The next subsection evaluated types of touch that may be produced using haptic technologies or touch types that could be mimicked by a robot, established in previous research [50]. This included pulsing vibration, continuous vibrations, suction, poking, stroking, tapping, rubbing, massaging, tickling, and grabbing. The same unpleasant-pleasant Likert-type scale was used. Participants were also asked about preferred intensity of touch, as touch perception has both dimensions of valence and arousal [51].

3) Robotic Touch: Participants were shown pictures of 15 robots with height comparisons, along with written descriptions and interaction style based on the robot's end effectors or intended contact point with the body, an example is shown in Figure 1. They were asked to rate their level of touch comfort on a scale where 1 was very uncomfortable and 5 was very comfortable, on a Likert-type scale. Participants were asked to rate for conditions where the robot was the active agent in the touch interaction ("if the robot touched me"), and where it was passive ("if I touched the robot").

Fifteen examples were given to expose participants, who may not be familiar with the range of robot morphology, to a wide variety of forms. As the questions progressed, the robots became more organic and human-like in appearance, with examples based on established robotic morphology categories: functional, animal-like, and human-like [52]. The functional category was further subdivided for this research into "industrial" and "abstract" categories, separating robots possessing a mechanical appearance associated with industry from those with a more neutral functional form. The robots and their descriptions are shown in Table 1, with key images in Figure 2.

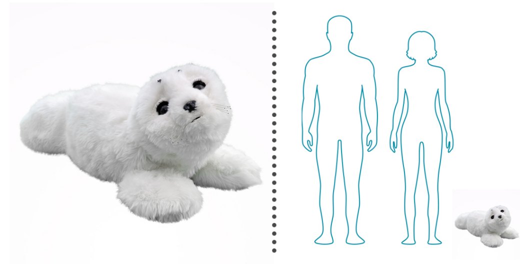

Fig. 1: Paro Survey Image Example

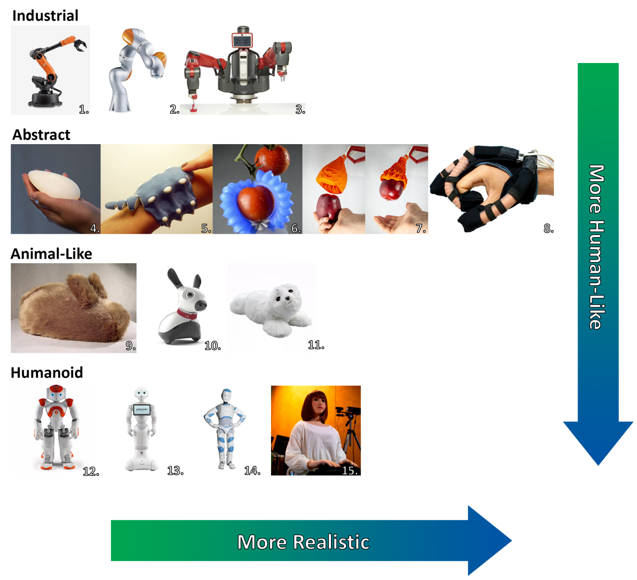

Fig. 2: Robots in Survey

4) Product Preferences and Customization: Participants were asked to rate product attributes, and how important they would be in the creation of a custom robotic device for pain management, using a Likert-type scale of 1 very unimportant – 5 very important. Attributes included physical qualities such as styling, feel, size, and weight, which could be used to inform features for IEC, and functional qualities including price and how well it works. Also assesed was if the participants currently altered their own products digitally or physically, through personalization by altering aesthetics, or customization by changing the functionality.

Data gathered from the survey was analyzed, with one-way ANOVA and independent sample t-tests applied as appropriate to seek differences between groups based on previous literature; for example, attitudes to robot touch based on gender [53]. Outcomes were used to inform construction of the follow-up interviews. Results will be discussed in the following section.

B. Interviews

To complement the quantitative data obtained from the survey, follow-up interviews were used for further qualitative analysis. This method was used to deepen insights arising from the survey, recognizing the complexity of the experi-

Label	Name	Description
1	Small Robot Arm	Robot designed to help with repetitive tasks. Primarily made of plastic and metal. Imagine the robot grasping your arm.
2	Medium Robot Arm	Robot designed to help with repetitive tasks. Primarily made of plastic and metal. Imagine the robot grasping your arm.
3	Baxter	Robot designed to do repetitive tasks alongside humans. With soft, flexible joints that give way and a reactive face on a tablet. Made of hard plastic and metal. Imagine the robot grasping your arm.
4	Haptic Meditation Device	Device designed to create soothing sensations, with vibrations to guide meditation. Made of hard plastic. Imagine the device sitting in the palm of your hand.
5	Wearable Robot	Small robot designed as an interactive companion. Made of hard plastic and fabric. Imagine the robot on the back of your arm.
6	Soft Robotic Gripper 1	Soft robot designed to grab objects. Made with inflatable silicone and has no rigid parts. Imagine the robot grasping your arm.
7	Soft Robotic Gripper 2	Soft robot designed to grab objects. Made with flexible plastic sheet and has no rigid parts. Imagine the robot grasping your hand.
8	Soft Robotic Glove	Soft robot designed to help people with low strength to flex their hand. Made with inflatable silicone and fabric, and has no rigid parts. Imagine the robot flexing your hand.
9	The Haptic Creature	Robot pet designed as an alternative to pet therapy. Mimics breathing and purring. Made with plastic and metal parts covered in fur. Imagine the robot sat in your lap.
10	Miro	Interactive robot pet designed for fun and education. Moves around, makes sounds and has basic facial expressions. Made from hard plastic. Imagine the robot rubbing against your hand.
11	Paro	Interactive robot pet designed as an alternative to pet therapy. Mimics baby seal noises, breathing and purring.. Made with plastic and metal parts covered in fur. Imagine the robot sat in your lap.
12	NAO	Mini robot designed for interaction. Can walk, dance, and speak. Made of hard plastic. Imagine the robot stroking your arm.
13	Pepper	Robot designed for interaction. Can move around, dance and speak. Made of hard plastic. Imagine the robot stroking your arm.
14	Romeo	Robot designed for interaction. Can walk, dance, and speak. Made of hard plastic. Imagine the robot stroking your arm.
15	Erica	Robot designed for interaction. Can move its arms and speak. Made of metal and plastic, covered in flexible silicone. Imagine the robot stroking your arm.

TABLE I: Robots in Survey

ence of living with chronic pain. Participants were recruited through an opt-in question at the end of the survey. Those taking part through Prolific could not be contacted further, therefore all interviewees were recruited through call-outs.

Each interview took under an hour and the structure followed that of the survey, including the key topics of pain experience, views on robotics, and customization. Interviews began by establishing basic information about the participant, and discussing current techniques which they use or avoid for pain management. This was followed by a discussion about robots, physical human-robot interaction, and an exercise to imagine their ideal robot for pain management. Participants were again shown images of robots from the survey, to expand upon initial impressions. Interviews took place via Zoom video conferencing software, with cameras on. Once complete, any video data was deleted and audio files were transcribed and analyzed using thematic analysis [54].

V. RESULTS

A. Survey

A total of 44 participants completed the survey, 30 paid participants recruited through Prolific and 14 through call-outs. Age demographics were contrary to those typically associated with chronic pain, with the majority of respondents aged 18-25 years (29.5%) and participants over 65 accounting for only 9% of responses [7]. The majority of respondents identified as female (56.8%), followed by male (36.8%), and non-binary (4.5%). Pain conditions most frequently identified included osteo or rheumatoid arthritis (n=9), chronic back pain (n=8), migraines (n=5), gynecological pain (n=3), and fibromyalgia (n=3). Due to limitations of the sample size, no statistically significant results were found based on age, ethnicity, country of residence, touch comfort, or pain demographics.

1) Touch Sensations: Warmth was rated as the most soothing tactile material property (mean=4.1), followed by softness (m=3.6) and lightness (m=3.5). Coldness was regarded as neutral (m=2.4), and heaviness (m=2.2) and hardness (m=2.1) were rated unpleasant. Massaging (m=4.0) and stroking (m=3.3) were rated as pleasant. Touch intensity preference aligned with touch type rating, however these results indicated a higher level of standard deviation.

2) Robotic Touch: The passive robot touch condition was rated as more comfortable than the active robot touch for every scenario. Paro was rated most comfortable (active mean=4.1, passive mean=4.2), and Erica the most uncomfortable (active mean=2.3, passive mean=2.8). Results for all robots are shown in Figure 3. Robots with an abstract or animal-like appearance were rated most favorably, with passive animal-like robots most comfortable. Overall, participants preferred a robot with a softer appearance, including soft robots containing no hard parts, and those covered in soft materials. In analysis of only participants who identified as male or female, the only statistically significant difference was in comfort with the haptic creature, which women rated as more comfortable than men in the passive condition, (female mean = 4.2, male mean= 3.4, p=0.022), and also approaching statistical significance in the active condition (female mean = 4.3, male mean= 3.5, p=0.057).

3) Product Preferences and Customization: When rating priorities for a hypothetical device for at-home pain management, functionality was the top priority (m=4.9), followed

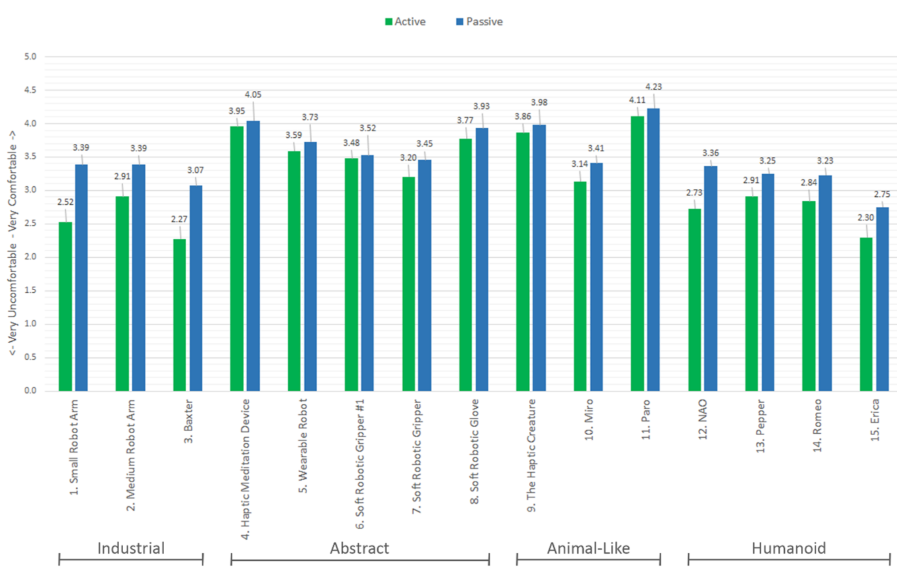

Fig. 3: Robotic Touch Comfort Results

by price (m=4.4), feel (m=4.4), weight (m=4.3), and size (m=4.0), physical features which could be altered using an IEC application. Color and type of styling were rated as least important. Participants indicated that they were generally comfortable altering products themselves but were much more likely to customize digital over physical products.

B. Interviews

Four participants recruited through call-outs agreed to be interviewed, with their information shown in Table 2. Allocated codes are used to preserve anonymity. Thematic analysis was conducted deductively, based on the survey structure. The transcripts were coded, thematically grouped, and then reviewed to establish themes discussed.

Speaking of their experiences, all participants expressed frustration at healthcare access and treatments for chronic pain. They also discussed how pain affects everyday life, limiting mobility and affecting hobbies. Pain management techniques used included cognitive behavioral therapy (CBT), physiotherapy, massage, use of therapy animals, thermotherapy, TENs machines, and other forms of pain distraction, with varying rates of success. All participants found thermotherapy to be beneficial, with Participants A, B, and D applying heat pads to the affected area, whereas Participant C used ice packs.

Participants' negative responses to robotic touch often mentioned the robot's size and the hard materials from which they are typically constructed. Furthermore, concerns were raised about the robot's end effectors and points of contact with the body. Participants also expressed a desire to have control over the robot in order to feel comfortable, as pain can often create a sense of loss of control. All participants saw potential for robotic interventions for pain management, and Participants A and C were keen to remove the human element when interacting with the body in a clinical manner. Participant A stated:

"It would distance yourself from healthcare professionals being the evil ones, inflicting the pain... Shifting the blame of the pain onto something else instead of the person that's trying to help... to take that stress away from them mentally would probably benefit both parties."

Paro was overwhelmingly the favorite, frequently described as "cute" and "sweet". Erica, as the most human-like robot, was often referred to as creepy, however Participant C, whose pain is primarily located in her pelvic region, stated that she may be more comfortable with Erica as she has a female appearance.

Imagining their ideal robotic device for pain management, participants all stated that they would prefer one with a functional purpose, such as massage, rather than a social purpose, such as conversing to provide distraction. Also mentioned by all participants was a desire for some customization or modularity, but were worried about potential cost increases.

The following section discusses combined results from the survey and interviews, and their implications for the design of robots for pain management.

TABLE II: Interview Particpant Demographics

Initial	Gender	Age	Primary Pain Condition
A	Non-Binary	25-34	Fibromyalgia
B	Female	65+	Rheumatoid and Osteo Arthritis
C	Female	45-54	Vulvodynia and Vaginal Pain
D	Female	25-34	Ligament Weakness

VI. DISCUSSION

Initial research into robotic interventions for pain management has shown potential. However, approaches to date have typically been techno-centric, retrofitting existing technology, rather than human-centric, developing the technology with intended users. UCD methods were applied using online surveys and interviews. Findings are presented for consideration in the development of future robotic technologies, identifying physical features for customization using IEC.

Our study found people living with chronic pain would prefer to physically interact with a robot which is soft, warm, and light. Therefore the emerging area of soft robotics may be suitable for pain management [55], especially as they were highly rated by participants. However, Paro was rated highest and is not a soft robot as it contains rigid parts. So in addition to Paro's soft and furry exterior, it may appeal to participants due to its overall appearance.

Thermotherapy is an established method for pain management [56], and interview participants expressed a desire for either hot or cold sensations, depending on their pain condition, so the temperature of the robot surface could be adjustable based on user desires. Participants also indicated that rubbing, massaging, and stroking sensations can feel soothing on or near a pain site, so it may be useful for a robot to either perform the actual motion or mimic it through haptic technologies. Ratings for desired touch intensity showed a large amount of deviation, indicating preference for intensity levels was broad, so users should be able to control and self-administer this robotic touch. Interview participants also indicated a desire to have control, which is necessary to feel safe interacting with machinery, but may also reflect an emotional sense of control over their own pain [8].

As in human-human touch, participants were receptive to certain types of robot touch, but uncomfortable with others. Participants disliked the idea of active touch from an industrial or human-like robot, and instead preferred passive touch from animal-like or abstract robots. Zoomorphic robots may be preferable in health settings [57], however examples in this survey could be perceived as friendly, so this may not apply to other animal forms. As suggested in our interview findings, there may also be differences in how people react to robots based upon both their own gender, and the robot's perceived gender. Anthropomorphic robotic forms may improve human-robot interaction [58], however as a robot becomes more human-like it can be regarded as unsettling. This reflects the contested Uncanny Valley theory, which suggests that as an artificial human becomes more lifelike, it is more likely to evoke a negative emotional response [59]. However, this usually refers to a robot's appearance, and not how it feels to touch. More research is needed to understand if this transfers to tactile senses [60].

The priority for survey and interview participants was functionality and ensuring the device could aid in pain management, however little research exists on long term efficacy of robots for pain management. Interview participants indicated a desire for customization and modularity, which could be achieved by altering a device's physical form. Prioritized features for alteration were size, weight, and feel, which are form features that could be customized by users.

Participants were generally at ease creating custom products, particularly when using digital interfaces, however as the survey was conducted online it may be that this participant pool is more comfortable with the technology. Nevertheless, it should be considered that a robot for pain management could be altered for an individual end-user, particularly as the experience of pain is so unique. Affordability was also a key consideration, so any robot designed for this purpose should be cost comparable to other options, and customization should not significantly increase costs.

A. Limitations

The main limitation of the research is the small number of participants for both survey and interview. Furthermore, participants were self-selecting and may have been already interested in the research area, also meaning they could be more inclined to optimism about robotic interventions. All these factors create a potential source of bias in terms of study findings. Furthermore, whilst interesting trends were identified in the data, small sample sizes meant conclusions were drawn primarily from descriptive statistics, so results usually did not meet the threshold for statistical significance. Additionally, most survey participants, and half of the interviewees, were aged below 35 years old, therefore participants of the study sample where not reflective of the general chronic pain population. However, the results are still valuable for identifying desirable characteristics for pain management devices in the prevalent age group in this study.

Furthermore, using the umbrella term "chronic pain" during recruitment brought people with a wide variety of pain conditions. What may be a suitable treatment for one individual's condition, may be highly unsuitable for the next. When investigating pain management interventions it may be worth targeting sub categorizations of chronic pain.

VII. CONCLUSIONS

User-centered design methodologies improve development of robotic healthcare technologies by aiding deeper understanding of unmet needs. Our research was focused on user requirements for the design of a robotic intervention for chronic pain, to identify features for customization through IEC. Whilst limitations are acknowledged, findings could inform the development of technologies for pain management.

Data from the survey and interviews with potential end-users indicated preferences for robots which had animal-like or abstract forms. The gender of the user and perceived gender of the robot may also effect comfort in these interactions. The preferred attributes of the parts of the robot that would physically interact with the body were noted as being soft, warm, and light, and producing changeable sensations akin to massaging, rubbing, and stroking. It was noted that the preferred device should allow for the user to initiate the touch interaction and maintain a feeling of control.

Participants noted a desire for modularity within the robotic device, so sensations and intensity can be altered, as well as applied to different areas of the body. Customization through IEC to design unique forms is the next step, enabling users to explore morphological features for robots.

Due to the complex factors effecting chronic pain it would be important to investigate the outcomes that users would value, and the context in which people would be most likely to use these robots, as part of a longitudinal study. Given the diversity of user preferences, rather than running studies with off-the-shelf products, our findings provide the seeds for an IEC algorithm, which combined with rapid prototyping, could enable the design and evaluation of more personalized and affordable robotic solutions for pain management.

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