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Advancing the Development of Intelligent Wearable Robots for Elderly Assistance: An Innovative User-Centric Co-Creation (UC^3) Framework

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ABSTRACT

Sarcopenia is an involuntary loss of muscle mass along with age, bringing pressure and challenges to older adults who demand independence. Wearable robots are promising solutions to address the adversities brought by sarcopenia. Using an innovative User-Centric Co-Creation (UC^3) Framework, we conducted an iterative, transdisciplinary, multistage study in Hong Kong, to develop intelligent wearable robots to assist older adults in performing daily living tasks. A multimethod approach combining participatory workshops, quantitative assessments, and laboratory experiments was adopted. A total of 16 participants joined six sessions of participatory workshops to provide user requirements. 91 healthy older adults joined an experiment to provide reference data, and 66 older adults with sarcopenia potential joined an experiment to provide user data. User requirements provide insights for robotic design, reference group data informed the robotic team on system design, and user experiments in turn provided evidence for the robotic group to further improve robotic systems and identify outcome indicators at three levels, including physiological level, functional level, and behavioral level. Following the UC^3 Framework, we involved users as equal partners in the development process and collected insightful data to develop wearable robots in iterative cycles.

Keywords: Wearable robots, Elderly assistance, User-centric co-creation, Gerontechnology

INTRODUCTION

Population aging is gaining prominence as a significant policy concern. This is primarily due to the simultaneous increase in both the absolute number and proportion of older individuals within populations worldwide (World Health Organization, 2021). In Asia and the Pacific, the number of people aged 60 years or over is increasing at an unprecedented rate and is projected to account for around 63 percent of the global population by 2050 (United Nations, 2022). Notably, China currently has the largest number of older adults in the world (265 million) and this number is expected to reach 509 million by 2050 (United Nations, 2022). While the majority of countries have established measures to promote active and healthy aging, involuntary loss of muscle mass, strength, and function, termed sarcopenia, is one of the most striking effects of aging (Papadopoulou, 2020). Sarcopenia increases the risk of functional decline that brings negative impacts on independent living living (e.g., transfer to toilet, locomotion, climbing stairs; Bertschi et al., 2022), physical activity (Ohtsubo et al., 2022), and quality of life (Umegaki et al., 2020).

As the global population continues to age, innovative solutions are needed to address the consequences of sarcopenia. Wearable robots, also known as exoskeletons, have emerged as a promising technology with the potential to assist individuals with sarcopenia in overcoming physical limitations (Goher and Fadlallah, 2020). According to the ASTM F48, wearable robots "augments, enables, assists, and/or enhances physical activity through mechanical interaction with the body", and "may include rigid or soft components, or both" (Lowe et al., 2019). Rigid systems utilize parallel link mechanisms aligned with the limbs to facilitate load transmission and provide assistance to the joints, however, they are criticized for being bulky and non-optimal human-machine coordination (Goher and Fadlallah, 2020). In light of these, soft wearable systems have flourished in recent years. Soft wearable robots simulate the working principles of human muscles and tendons, providing greater performance in terms of comfort, convenience, and coordination (Morris et al., 2023).

With a growing interest in developing soft wearable robots (Cakmak et al., 2022), researchers from multiple disciplines collaborate on wearable robots' development that follows user-centered design (UCD), to improve acceptance and adoption (Baltrusch et al., 2020). Despite this trend, a recent integrative review shows three major gaps: (1) inadequate transdisciplinary collaboration, (2) insufficient user engagement, and (3) ineffective data curation (Cheng et al., 2022). To fill these gaps, we unfolded an innovative User-Centric Co-Creation (UC^3) framework to develop intelligent soft wearable robots, to actualize "intelligent robotic elderly assistant to create hope" (i-REACH). The UC^3 framework is exceptional in that unlike previous approaches, it highlights the importance of treating potential users as peer researchers and involving them in each of the development cycle. This paper outlines the processes of applying the UC^3 framework in i-REACH to obtain user requirements and experiment data.

METHODS

Study Design

To meet the objectives, a multistage, multimodal design was adopted for this study. Instead of a study that included the users in the prototype testing stage, we decided to include users in the idea generation and conceptualization stage. Following the UC^3 framework, described in detail below, we developed two wearable robot prototypes (i.e., hand robots and knee robots) to assist older adults in daily living, between June 2021 and December 2022.

The first phase was designed primarily to understand the user requirements of the wearable robots while potential users familiarized themselves with the prototypes and provided initial feedback. The second phase explored the feasibility of experiment set-up and looking at reference data to inform robotic system designs. The third phase collected user data to improve wearable robot prototypes and seek outcome indicators to test the effectiveness of the wearable robots at three levels: physiological, functional, and behavioral.

Procedures and Participants

In the first phase, a 6-session participatory workshop was conducted with a total of 16 participants who were recruited via the networks of Sau Po Centre on Ageing, The University of Hong Kong (HKU), between June and August 2021. All of them met the following inclusion criteria: (1) aged 50 or above; (2) self-declared without memory or cognitive problems (e.g., dementia); (3) self-reported having mobility difficulties (i.e., primary user) or taking care of a person with mobility difficulties (i.e., caregiver) at the time of recruitment; (4) residing in Hong Kong; (5) able to communicate with the researchers in Cantonese, English or Mandarin; and (6) participate voluntarily. During the workshops, we introduced i-REACH, collected user requirements of wearable robots, developed prototypes based on those data, showcased the prototypes, and collected feedback via direct communication with the participants.

In the second phase, a controlled experiment was conducted with 91 participants between July and August 2021 to act as a reference group. Participants were recruited via researchers' networks and social media, with the following inclusion criteria: (1) aged 65 or above; (2) with a SARC-F score (measurement of sarcopenia potential) below 4; (3) living in the community in Hong Kong (i.e., not institutionalized); (4) self-reported without cognitive impairments; (5) able to participate independently in a laboratory setting; and (6) participate voluntarily. We tested the feasibility of the experiment setup, established linkages between functional and behavioral level data, and used the data to inform wearable robots' development.

In the third phase, an expanded experiment was conducted with 66 participants between December 2021 and December 2022 to act as a user group. Participants were recruited using similar strategies as Stage 2, with additional efforts such as health booths, as well as distributing leaflets in all the public housing estates in Hong Kong. All the participants met the same inclusion and exclusion criteria as the reference group, except they reported difficulties in mobility and/or manipulability (26 obtained a SARC-F score < 4; 40 obtained a SARC-F score ≥ 4). We tested the practicality of the experiment setup and devices, and collected data at physiological, functional, and behavioral levels, to further improve the wearable robots.

Data Collection, Assessments, and Analysis

In the first phase, we collected the qualitative data including audio recordings, video recordings, memos, and worksheets. These data were synthesized to form user requirements and provided valuable indicators for developing wearable robot prototypes. Table 1 shows the characteristics of the participants.

Table 1. Characteristics of participants in the first phase.

Code	Age	Gender	Category
A1	75	F	Primary user (with mobility difficulties)
A2	58	F	Caregiver
A3	63	M	Caregiver
A4	60	M	Caregiver
A5	59	F	Caregiver
A6	54	M	Caregiver
A7	87	M	Caregiver
A8	62	F	Caregiver
A9	54	F	Caregiver
A10	66	M	Caregiver
A11	76	F	Primary user (with mobility difficulties) and caregiver
A12	63	M	Caregiver
A13	60	F	Caregiver
A14	58	F	Caregiver
A15	70	M	Caregiver
A16	69	M	Caregiver

In the second and third phases, we collected subjective measures before inviting the participants for experiments. Subjective measures include the eHealth Literacy Scale (Norman and Skinner, 2006), the SarQoL® questionnaire (Beaudart et al., 2017; Lou, 2023), and the brief 14-item Senior Technology Acceptance Model (STAM; Chen and Lou, 2020). Demographics including gender, year of birth, marital status, highest education level, employment status, income sources, self-perceived financial status, housing, living arrangement, and medical history were obtained. These data provide overall insights to triangulate the results obtained from standardized experiments.

For the purpose of informing wearable robots' development, we collected experiment data at three levels: physiological, functional, and behavioral. *Physiological level data* were extracted using a motion capture system. Four selected parameters during gait motion were analyzed, including step length, stride length, opposite foot contact, and foot off. *Functional level data* included maximum voluntary contraction (MVC) using knee extension test at 73°, 52°, and 30° angles (Ushiyama et al., 2017), and maximum handgrip strength (Mehmet et al., 2020). *Behavioral level data* were collected using the Short Physical Performance Battery (SPPB) which consists of balance tests, gait speed tests, and chair stand tests (Guralnik et al., 2000). The experiment setup and devices used were published elsewhere (Lou et al., 2023).

A performance-based risk hierarchy (Lou et al., 2023) was developed, following the recommended cutoffs on sarcopenia diagnosis by the Asian Working Group for Sarcopenia (Chen et al., 2020): (M: < 28kg, F: < 18 kg), gait speed test (< 1.0 m/s), chair stand test ($\geq$ 12 s), and SPPB total score ($\leq$ 9).

RESULTS

Phase 1 – From User Requirements to Initial Prototypes

We enrolled 8 males and 8 females (54–87 years, M = 64.63 years, SD = 8.90). Among them, one reported being the primary user, another one reported being the primary user and the caregiver simultaneously. The remaining 14 reported being the caregivers, mainly taking care of a person with mobility difficulties. With careful design, we focused on one theme per session and collected feedback from the participants accordingly. Figure 1 displays a group photo of the workshop.

Figure 1: Participatory workshops organized by the i-REACH project.

Participants reflected that their care recipients or themselves have difficulties in daily living. Three major barriers were repeatedly mentioned: inability to walk for long distances, insufficient muscle strength to climb the stairs, as well as incompetence in carrying heavy things such as food purchased from the supermarket. Additionally, participants provided valuable insights into user requirements such as concerns about the usefulness and the ease of use of wearable robots. After gauging initial feedback and requirements, we decided to develop two wearable robots: hand robots and knee robots.

Participants tried the first generation of the wearable robot prototypes in the participatory workshop and offered suggestions for improvements. For instance, they requested anti-allergic materials, with adjustable size, and being waterproof. Moreover, concerns about marketable products were raised. For example, the durability of the wearable robots, privacy issues based on the insertion of sensors, and maintenance service. Finally, they found that the prototypes were too bulky and inconvenient to the users. Table 2 details the workshop themes, activities, and feedback from the participants.

Despite these, the feedback was generally positive, and users found the wearable robots promising to assist daily living among older adults with sarcopenia potential. More importantly, they believed that wearable robots could bring hope to older adults who wish to maintain independent living in the community.

Table 2. Selected themes, activities, and feedback collected at the participatory workshops.

#	Themes	Activities	Example feedback/requirements
1	Context exploration	Participants were invited to reflect on mobility difficulties they or their care recipients faced	• Constant rest time needed during walking • Difficulties in stair climbing • Unable to carry heavy things
2	Unmet needs examination	Participants were invited to conduct the user, task, environment (UTE) analysis	• Usefulness (tailor-made, enhance effectiveness in performing daily living tasks, trendy, lightweight, safe) • Ease of use (easy to control, able to learn within a short period, affordable price, with maintenance service)
3	Robots' components showcase	Researchers presenting nanosensors and two prototypes (hand robot and knee robot)	• Adaptable (durability, reset functions, soft wearables, waterproof, non-intrusive, privacy)
4	Prototypes' try on (I)	Participants were invited to try on the two prototypes (hand robot and knee robot)	• Acceptance (easy to wear on and off by the user, anti-allergy, size, portable, noise, balance, fall detection, hygiene, price)
5	Co-creating robots	Participants were invited to design and co-create ideal robots	• Focus on lower limb robots and demand effectiveness in assisting walking, sit-to-stand, and stair climbing
6	Prototypes' try on (II)	Participants were invited to try on the two prototypes (hand robot and knee robot)	• Current prototypes are too bulky • Hydraulic-powered knee robots are inconvenient to users • Wearing the robots requires assistance from another person, reduces independence • Materials used for hand robots are rigid which creates uncomfortable feelings

Phase 2 and 3 – From Comparisons to Robotics Systems Design

Data were collected from 157 participants who resided in the community of Hong Kong, with ages ranging from 65 to 84 years ($M = 69.05$ years, $SD = 3.39$). Approximately two-thirds of the participants were female ($n = 102$) and married ($n = 99$). We differentiated the participants according to the performance-based risk hierarchy (Lou et al., 2023). Overall, it was found that approximately 49% of the participants had two risks or more. For this paper, we defined the low-risk group as participants with either no risks or only one risk, consisting of 80 individuals. The medium-risk group encompassed participants with two to three risks, totaling 48 individuals. Lastly, the high-risk group included participants with all four risks, amounting to 29 individuals. Table 3 indicates the physiological, functional, and behavioral level data along the performance-based risk hierarchy.

Table 3. Physiological, functional, and behavioral level findings by risk groups ($N = 157$).

	L (*N*=5)	M (*N*=15)	H (*N*=18)	Statistics
Physiological level				
Step length (cm)**	39.88 (3.01)	34.25 (4.06)	32.95 (4.28)	$F_{(2,35)} = 5.696$
Stride length (cm)*	76.65 (6.00)	65.68 (7.96)	63.13 (8.87)	$F_{(2,35)} = 5.300$
Opposite foot contact (%)	26.20 (5.04)	30.46 (3.59)	30.69 (6.38)	$F_{(2,35)} = 1.510$
Foot off (%)	63.17 (2.42)	65.19 (1.85)	65.47 (3.41)	$F_{(2,35)} = 1.372$
Functional level	**L (*N*=41)@**	**M (*N*=41)@**	**H (*N*=28)**	
Knee MVC at 73○ (kgf)**	22.39 (8.47)	19.69 (8.75)	15.00 (5.98)	$F_{(2,105)} = 6.704$
Knee MVC at 52○ (kgf)***	21.63 (7.00)	18.66 (7.67)	14.08 (5.85)	$F_{(2,105)} = 9.223$
Knee MVC at 30○ (kgf)***	18.52 (6.26)	14.80 (5.64)	11.03 (4.35)	$F_{(2,105)} = 14.385$
Handgrip strength (kg)***	27.90 (7.87)	21.94 (7.34)	15.23 (5.56)	$F_{(2,154)} = 33.079$
Behavioral level	**L (*N*=80)**	**M (*N*=49)**	**H (*N*=28)#**	
Gait speed (m/s)***	0.98 (0.20)	0.67 (0.13)	0.54 (0.17)	$F_{(2,154)} = 85.167$
SPPB (range: 0–12)***	11.84 (.40)	9.78 (1.46)	7.75 (1.14)	$F_{(2,154)} = 194.401$
Chair stand test (s)***	8.14 (1.87)	13.17 (4.92)	17.01 (3.91)	$F_{(2,151)} = 76.107$

Note. L, low-risk group. M, Medium-risk group. H, High-risk group. MVC, Maximum voluntary contraction. SPPB, Short Physical Performance Battery. @The numbers of participants performing the handgrip strength test in the low-risk group and medium-risk group are 80 and 49, respectively. #The number of participants performing the chair stand test in the high-risk group is 26.

After the preliminary analysis of the data collected at three levels, the research team further improves the wearable robots' design and seeks outcome indicators to test the effectiveness of wearable robots. Regarding the knee robots, physiological level data provided evidence of the relationships between risk hierarchy and two gait motion parameters: step length and stride length. Findings indicated linkages between gait motion and muscle strength, which guided the research team to develop a trigger system using electromyography. At the functional level and behavioral, knee maximum voluntary contraction (MVC) at three angles was important to inform the development of knee robots. With higher risks, participants perform worse in knee MVC. To this end, the research team focuses on improving the knee robots' design from hydraulic-powered to air-powered and decided to use the chair stand test as an outcome indicator in subsequent user experiments.

Apart from the knee robots, we also used the collected data to inform the development of hand robots. Figure 2 shows a schematic diagram of the processes. Further details of the hand robots have been published elsewhere (Liu et al., 2024).

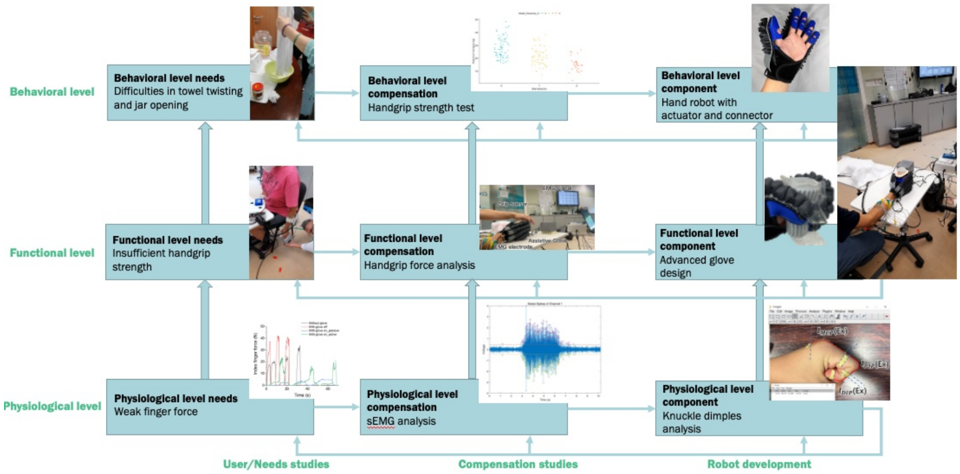

Figure 2: Schematic diagram of the hand robots' development.

DISCUSSION

The application of the UC^3 framework in developing intelligent soft wearable robots for older adults with sarcopenia potential, as outlined in the i-REACH project, has shown promising results. The framework emphasizes the involvement of potential users as peer researchers throughout the development cycle, addressing gaps such as inadequate transdisciplinary collaboration, insufficient user engagement, and ineffective data curation. This approach ensures that the wearable robots meet the specific needs and preferences of the target user group.

In the first phase of the study, user requirements were obtained through a participatory workshop involving 16 participants. Valuable feedback and insights were collected, highlighting the daily living difficulties faced by older adults with sarcopenia potential, including walking long distances, climbing stairs, and carrying heavy objects. This information guided the development of two wearable robot prototypes: hand robots and knee robots. The participants found the prototypes promising and believed that they could enhance independent living among older adults in the community.

In the second and third phases, a controlled experiment and an expanded experiment were conducted to collect data at physiological, functional, and behavioral levels. The data provided insights into the feasibility and effectiveness of the wearable robots. The participants were differentiated into low-risk, medium-risk, and high-risk groups based on their performance in various tests. The results showed that approximately 49% of the participants had two or more risks, indicating the prevalence of sarcopenia potential in the older adult population. This data informed the design of the robotic systems and helped improve the wearable robot prototypes.

The use of the UC^3 framework in the i-REACH project has several advantages. By involving potential users as peer researchers, the framework ensures that their perspectives, needs, and preferences are considered throughout the development process. This user-centered approach increases the acceptance and adoption of wearable robots among the target user group. Additionally, the framework promotes transdisciplinary collaboration, bringing together researchers from multiple disciplines to contribute their expertise and knowledge. This collaboration enhances the development of intelligent soft wearable robots that are effective and practical.

However, there are some limitations to consider. The study sample was recruited from the community in Hong Kong, which may limit the generalizability of the findings to other populations or cultural contexts. Additionally, the study focused on the development and initial testing of wearable robot prototypes, and further research is needed to evaluate their long-term effectiveness and usability in real-world settings.

In general, the application of the UC^3 framework in the i-REACH project has shown promise in developing intelligent soft wearable robots for older adults with sarcopenia potential. The involvement of potential users as peer researchers and the integration of data from multiple levels have contributed to the development of effective and user-friendly wearable robot prototypes. Further research and evaluation are needed to assess the long-term effectiveness, usability, and impact of these wearable robots in improving the quality of life and independent living among older adults with sarcopenia.

CONCLUSION

In conclusion, the application of the UC^3 framework in the i-REACH project has shown promise in the development of intelligent soft wearable robots for older adults with sarcopenia potential. By involving potential users as peer researchers and incorporating their perspectives, needs, and preferences, the framework ensured an enhanced user-centered approach. The participatory workshop and subsequent experiments provided valuable insights into the daily living difficulties faced by older adults with sarcopenia potential and guided the development of effective hand and knee robot prototypes. While further research is needed to evaluate long-term effectiveness and usability, the UC^3 framework offers advantages such as enhanced user-centeredness, increased acceptance, and improved transdisciplinary collaboration. Overall, these wearable robots have the potential to enhance the quality of life and support independent living among older adults with sarcopenia, addressing an important need in this population.

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