Applying an Innovative User-Centric Co-Creation (UC^3) Approach in Developing Intelligent Wearable Robots for Elderly Assistance: From a Transdisciplinary Lens

VIVIAN W. Q. LOU, CLIO Y. M. CHENG, KE CHEN, CALVIN K. L. OR, YONG HU and NING XI

Vivian W. Q. Lou, Department of Social Work and Social Administration; Sau Po Centre on Ageing, The University of Hong Kong, Hong Kong, China
Clio Yuen Man Cheng, Department of Social Work and Social Administration; Sau Po Centre on Ageing, The University of Hong Kong, Hong Kong, China
Ke Chen, Department of Psychology and Behavioral Science, Zhejiang University, Zhejiang, China
Calvin K. L. Or, Department of Industrial and Manufacturing Systems Engineering, The University of Hong Kong, Hong Kong, China
Yong Hu, Department of Orthopaedics & Traumatology; Neural Eng. & Clin Electrophysiology Laboratory, The University of Hong Kong, Hong Kong, China
Ning Xi, Emerging Technologies Institute, The University of Hong Kong, Hong Kong, China

ABSTRACT

Mobility difficulties is a major public health issue which affects the ability of older adults to perform daily living activities and its prevalence increased with age. Assistive technology such as wearable robots has the potential to support older adults with mobility difficulties, yet there remain substantial challenges to developing wearable robots that can accommodate the needs of older adults and aid in performing daily living activities. In the current study, we developed and validated an innovative User-Centric Co-Creation (UC^3) approach. First, we engaged older adults from the design phase of exoskeletons and treated them as equal partners. Second, we initiated an interactive testing platform to perform trilevel data curation, physiology, function, and behavioral level, to inform kinesiology-based parameters for wearable robots' development. We invited a total of 16 older adults to join six co-creation workshops on wearable robots. Next, we used a multi-method pilot study using the UC^3 approach to validate the interactive testing platform (N=15). After a successful pilot study and validation, a total of 157 participants were recruited in two waves. First, we recruited 91 healthy older adults aged 65 or above, between July and August 2021 to act as the reference group. Second, we invited 66 older adults with mobility difficulties between December 2021 and December 2022, who are the target users of the wearable robots. Subsequently, a total of 55 participants in the second wave joined an experiment with knee robots between May 2022 and February 2023. All the participants were invited to join experiment procedures at three levels: physiology level, function level, and behavior level. Gait motion analysis and balance ability were included at the *physiology level*. Maximum voluntary contraction at three knee angles (performed using knee extension test) and maximum handgrip strength were included at the *function level*. The Short Physical Performance Battery, a group of measures that combines the results of 4-meter walk speed, 5-time chair stand test, and balance tests, was included at the *behavioral level*. Following the UC^3 approach, we engaged older adults as equal partners in wearable robots' development and developed a performance-based risk hierarchy with a transdisciplinary team's support. Prior to conducting the three-level analysis to inform the development of wearable robots, we instigated a risk hierarchy based on recommended cut-offs on handgrip strength (M: < 28 kg, F: < 18 kg), 4-metre walk speed (< 1.0 m/s), 5-time chair stand test (≥ 12 s), and SPPB total score (≤ 9). Among all the 157 participants, 29 (18.5%) were classified as having no risks, 51 (32.5%) were classified as having one risk, 29 (18.5%) were classified as having two risks, 20 (12.7%) were classified as having three risks, the remaining 28 (17.8%) were classified as having four risks. In general, we found evidence for a novel UC^3 approach to inform wearable robots' development. We started with a full engagement of target users, followed by a trilevel data curation at the physiology level, function level, and behavioral level. Lastly, continuous improvement and discussions with experts in a transdisciplinary team confirmed the validity of the UC^3 approach. All in all, elucidating the unmet needs for daily activities at the physiology, function, and behavioral level will provide valuable insights into the development of intelligent wearable robots and will unlock the key to an independent living lifestyle in old age.

INTRODUCTION

Mobility has a broad definitions and meanings depending on the specific context it is used for. In the aging context, we refer mobility as the older adults' ability to change their positions or locations or move from one place to another by walking and basic ambulation [1]. Additionally, we also included basic hand manipulation functions such as moving small or large objects using one hand or both [2]. In this sense, mobility is considered essential for older adults to maintain independent living and a good quality of life [3]. At the same time, physiological factors such as changes in bones, joint problems, neurological diseases, and muscle strength loss due to sarcopenia, can pose negative effects on the mobility of older people [4].

In general, mobility impairments cause undesirable physical, cognitive, and social consequences for older adults. Loss of independence in daily living, higher disability and injuries rates, immature institutionalization, and an increase in hospital admission [5] all accumulated to huge societal cost. Consequently, the ability to perform activities of daily living (ADL) start to diminish with age leading to depression, isolation, and mortality [6]. For this reason, much interest has been devoted on early screening and interventions for preventing mobility difficulties among older adults [7,8]. Exercise intervention was found to be effective but only with moderate effects [9].

Besides traditional treatment methods, assistive technologies (AT) gain popularity for it can compensate for declining function among older adults [10]. A critical review of existing evidence related to wearable robots' development, one of the AT, revealed three major gaps: (1) insufficient target user involvement, (2) single level data curation, and (3) non-transdisciplinary research and development [11]. In order to fill the above three gaps in one go, we developed an intelligent robotic system using an innovative User-Centric Co-Creation (UC^3) approach. Our research objectives are (1) to actualize full engagement of older adults in exoskeleton development; (2) to triangulate physiology, function, and behavioral level data to inform imperative kinesiology-based design parameters for exoskeleton development; and (3) to exemplify transdisciplinarity in exoskeleton development.

User-Centric Co-Creation (UC^3) Approach

In our study, older adults were treated as co-developers who fully engaged at all stages of exoskeleton development. More importantly, they are seen as equal partners with the possibility to actively influence the process [25]. Next, we will perform a trilevel data curation, collecting data from three levels: physiology, function, and behavioral. Data were collected from both healthy and sarcopenic older adults to support a clear understanding of the necessary kinesiology-based design parameters. Finally, our team consisted of older adults as their own experts, as well as professionals from social sciences, family medicine, computer science, and engineering. We derived a committed goal for social goods and hold weekly transactive planning meeting to ensure a smooth transdisciplinary collaboration.

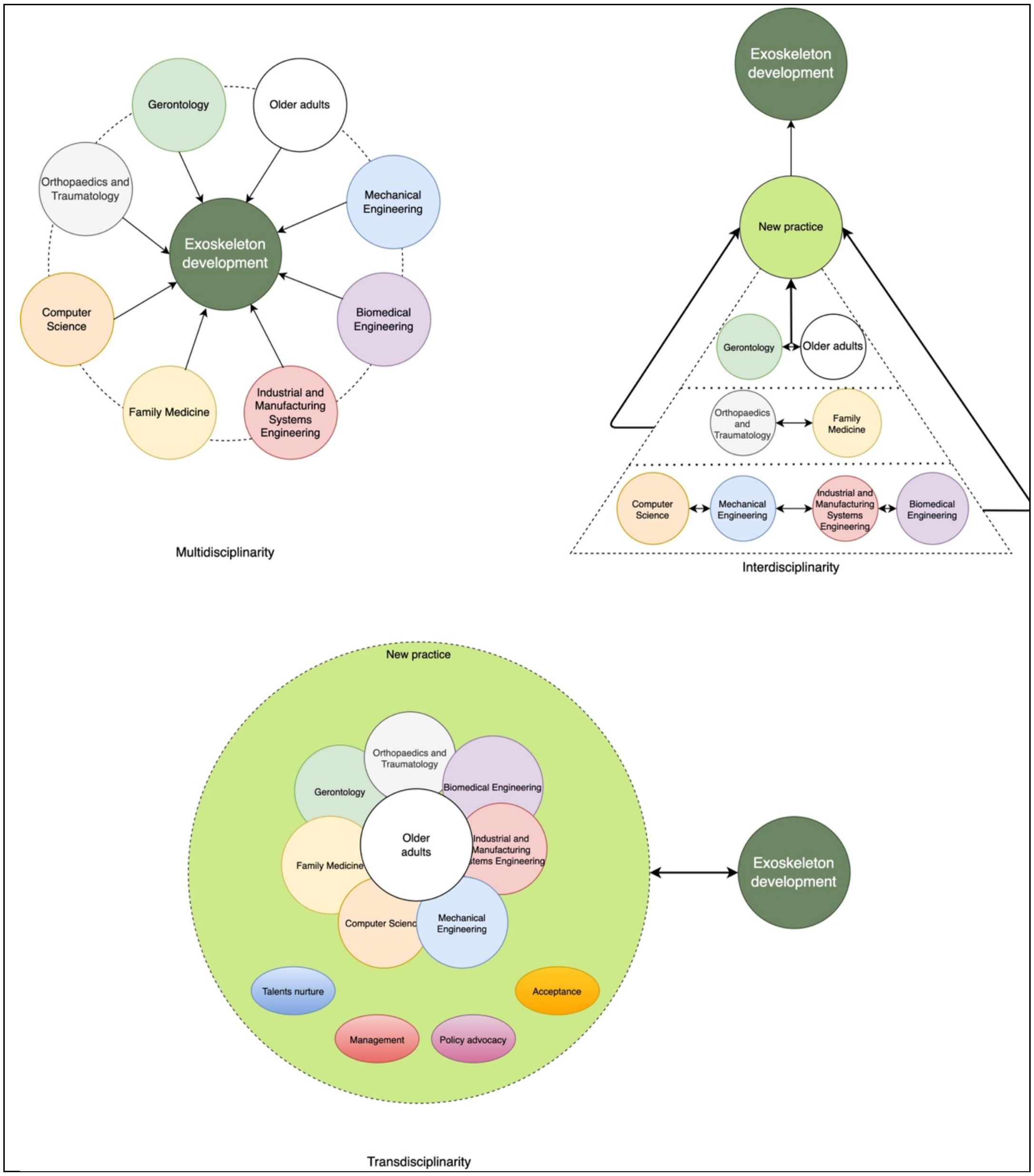

Figure. 1. A comparison of multidisciplinary, interdisciplinary, and transdisciplinary approaches to exoskeleton development.

Trilevel Data Curation

Using a UC^3 approach, we developed a trilevel data curation method to enhance health benefits of older adults with sarcopenia. Behavioral level data are explicit performance observations, which are usually treated as the goals of wearable robots. Possible behaviors that wearable robots could assist with including balancing, walking, stair climbing and chair rising [36], all of these are important motions when performing daily activities. Function level data are more subtle than behavioral level and difficult to be determined by observations, such as muscle strength among sarcopenic older adults. Despite its elusive nature, it is salient to understand the joint movement and strength needed to support the development of exoskeleton [37]. Physiology level data are implicit yet principal elements to inform kinesiology parameters for wearable robots development. For instance, motions in a gait cycle, balance ability and force spread, muscle response detected by electromyographic (EMG) devices among older adults, will inform the reaction time and level of compensatory force needed to perform activities of daily living. In essence, this trilevel data capturing process is necessary and interlocking to provide non-exhaustive yet informative parameters to guide our exoskeleton development.

MATERIALS AND METHODS

Study Population

A total of 157 participants were recruited in two waves. First, we recruited 91 healthy older adults between July and August 2021 to act as a reference group. All the participants met the following inclusion and exclusion 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; (4) without self-reported cognitive impairments; (5) able to participate independently in a laboratory setting; and (6) voluntary participation. We excluded those who reported (1) having Osteoporosis and (2) with a history of the spine, knee, hip, and ankle joint surgery, to ensure safety in the experiment. Second, we recruited 66 older adults with sarcopenia potential between December 2021 and December 2022, who are the target users of the wearable robots (i.e., user group). Subsequently, a total of 55 participants in the user group joined an experiment with knee robots between May 2022 and February 2023. All the participants met the same inclusion and exclusion criteria as the reference group, except they reported with a SARC-F score ≥ 4. Written informed consent was obtained from all participants in the study. This study has been approved by the Human Research Ethics Committee of The University of Hong Kong (EA1903040).

Physiology Level Measurements And Analysis

Gait motion analysis was included at the physiology level. We selected four parameters to understand the gait motion of the participants, including (a) step length (cm), (b) stride length (cm), (c) opposite foot contact (%), and (d) foot off (%). Step length is the distance between the point of initial contact of one foot and the point of initial contact of the opposite foot [12]. We assume that in normal gait, the right and left step lengths are similar. Stride length is the distance between successive points of initial contact of the same foot [12], right and left stride lengths are normally equal. Opposite foot contact is the heel of the opposite foot contacts the ground while the toes of the reference foot still touch the ground, providing double support [12]. Foot off is the moment when the heel begins to lift off the ground in preparation for forwarding propulsion of the body [12]. The motion capture system was set up using four NiNOX 125 cameras by Noraxon. These cameras provide synchronized video for reference and 2D marker tracking, the maximum resolution is 1280 x 960 (30fps). The gait motion was captured during the 4-meter walk (see Behavioral level measurements and analysis). For recording and processing, we adopted two myoRESEARCH® module configurations to analyze the data, including the myoPRESSURE® and myoVIDEO®.

Function Level Measurements And Analysis

MVC at three knee angles and maximum handgrip strength were included at the function level. We used a knee extension machine by VITOX Fitness with a hand-held dynamometer (HHD) by Lafayette Instrument (model 01165) fixed on the pole contacting the anterior of the tibial bone, at 50-100mm above the lateral malleolus. First, we measure the MVC using the HHD of each leg independently twice to identify the weaker leg. Next, we instructed the participants to perform isometric knee extension test on the weaker leg and measured MVC using HDD at three knee angles (i.e., 73°, 52°, and 30°). Regarding the handgrip strength test, we used the Jamar Smart Digital Hand Dynamometer for the reference group participants. After reviewing the experiment procedure of the reference group and considering the weight of the dynamometer, we used the Baseline 12-0286 Electronic Smedly Hand Dynamometer to conduct the handgrip strength test among the user group potential to ensure safety. We measured the maximum handgrip strength of each hand three times, alternatively [13]. For data analysis, we recorded the largest strength among all six attempts.

Behavioral Level Measurements and Analysis

The SPPB is a group of measures that combines the results of 4-meter walk speed, 5-time chair stand test, and balance tests [14], it was included at the behavioral level. It has been used and applied widely to predict the possible disability in older adults and was recommended as a predictive to classify older adults with sarcopenia potential [15]. Participants were first instructed to perform balance tests. They were asked to stand unsupported for 10 seconds with their feet in three positions: feet together, semi tandem, and full tandem, three attempts for each position. Next, the participants were asked to keep their arms folded across their chests and perform stand up and sit down as quickly as possible 5 times without stopping. A total of two attempts were required. Finally, the participants were asked to complete a 4-metre walk for six attempts. We timed each attempt in seconds, thus, to obtain the average gait speed. The SPPB total scores range from 0 (worst performance) to 12 (best performance). It is obtained by adding up the score a participant attained in balance tests, 5-time chair stand test, and 4-metre walk test.

Comparative Analysis

We compared all variables of interest between the reference group and user group to validate our recruitment strategy, using t-tests. Next, we calculated a performance-based risk hierarchy by using the recommended cutoffs for handgrip strength (M: < 28 kg, F: < 18 kg), 4-metre walk speed (< 1.0 m/s), 5-time chair stand test (≥ 12 s), and SPPB total score (≤ 9) [1]. For in-depth analysis at the physiology, function, and behavioral level, we first conduct linear models to explore the relationship between gender and all interested variables at each level. At the physiology level, we conducted a bivariate correlation to understand the linkage of the four chosen parameters under gait motion analysis. At the function level, we conducted another bivariate correlation to ensure the data quality of knee MVC. We are interested in the differences in performances along the risk hierarchy, therefore, we conducted the one-way analysis of variance tests to explore group differences. Tukey's Honest Significant Difference tests (post hoc tests) were used to provide specific group comparisons. All the data analysis procedures were performed using SPSS and R.

RESULTS

Participant Characteristics

Data were obtained from 157 older adults living in the community (65-84 years, *M* = 69.05 years, *SD* = 3.39). Around two-thirds of our participants were female ($n = 102$) and married ($n = 99$). We successfully recruited target participants using SARC-F screening. There were significant ($p < .05$) differences in maximum voluntary contraction (MVC) at 42˚ knee angle (kgf), maximum handgrip strength (kg), handgrip strength (kg), 4-meter walk speed (m/s), 5-time chair stand test (s), SPPB.

Performance-based Risk Hierarchy

Adhering to the UC^3 approach, we developed a performance-based risk hierarchy with a transdisciplinary team's support. Prior to conducting the three-level analysis to inform the development of intelligent robotics, we instigated a risk hierarchy based on recommended cut-offs [15] on handgrip strength (M: < 28 kg, F: < 18 kg), 4-metre walk speed (< 1.0 m/s), 5-time chair stand test (≥ 12 s), and SPPB total score (≤ 9). Among all the 157 participants, 29 (18.5%) were classified as having no risks, 51 (32.5%) were classified as having one risk, 29 (18.5%) were classified as having two risks, 20 (12.7%) were classified as having three risks, the remaining 28 (17.8%) were classified as having four risks. Overall, around 49% of the participants were tested to have two risks or above. In this study, we define low-risk group to include participants with none or only one risk ($n = 80$). Medium-risk group includes participants with two to three risks ($n = 48$), while high-risk group includes participants with all four risks ($n = 29$). Due to continuous transdisciplinarity engagement, we improved our protocol and upgraded our equipment along with the experiments, thus the number of participants involved in different tasks were differed.

Physiology Level Analysis

We included gait motion at the physiology level. There are four chosen parameters in assessing gait motion ($n = 38$), they are (a) step length (cm), (b) stride length (cm), (c) opposite foot contact (%), and (d) foot off (%). We first examined the relationship between the four parameters in gait motion among the participants who completed this experiment ($n = 38$). Results indicated that step length was positively associated with stride length ($r = .985$, $p <.001$), as well as negatively associated with double support ($r = -.634$, $p <.001$) and foot off ($r = -.612$, $p <.001$). We conducted group comparisons along the risk hierarchy. There were significant differences in the step length ($F_{(2,35)} = 5.696$, $p = .007$) and stride length ($F_{(2,35)} = 5.300$, $p = .010$) between participants in different risk hierarchy groups.

Function Level Analysis

We included knee MVC and maximum handgrip strength at the function level. We first examined the relationship between MVC at 73˚ knee angle, 52˚ knee angle, and 30˚ knee angle among the participants who completed this experiment (n = 108). Results indicated that MVC at three different knee angles was significantly (p <.001) correlated with each other, indicating satisfactory data quality. Next, we examined the relationship between demographic characteristics and knee MVC. Male participants (n = 44)had a significantly higher knee MVC at 73˚ knee angle (M = 25.91, SD = 7.92, t(106) = -8.165, p = <.001), 52˚ knee angle (M = 23.63, SD = 7.07, t(106) = -6.728, p = <.001), and 30˚ knee angle (M = 19.92, SD = 6.12, t(106) = -7.962, p = <.001), compared to female participants (n = 64). We also observed that the knee MVC decreased with smaller knee angles among male participants, but not among female participants. We conducted the one-way analysis of variance to determine whether there are any statistically significant differences in knee MVC along the risk hierarchy. There were significant differences in knee MVC at 73˚ knee angle ($F_{(2,105)}$ = 6.704, p = .002), 52˚ knee angle ($F_{(2,105)}$ = 9.223, p <.001), and 30˚ knee angle ($F_{(2,105)}$ = 14.385, p <.001), between participants in different risk hierarchy groups. Post hoc tests revealed that the high-risk group participants had a significantly worse knee MVC at 73˚ knee angle (p = .001), 52˚ knee angle (p <.001), and 30˚ knee angle (p <.001) as compared to the low-risk group. Next, we conducted an analysis of maximum handgrip strength.

Similar to knee MVC, gender was found to have significant association with handgrip strength. Male participants (n = 55) had a significantly higher handgrip strength (M = 31.77, SD = 6.78, t(155) = -11.378, p <.001), compared to female participants (n = 102). It indicated good support for the handgrip strength cutoff by gender. There were significant differences in maximum handgrip strength ($F_{(2,154)}$ = 33.08, p <.001) between participants in different risk hierarchy groups. Post hoc tests revealed that the high-risk group participants had a significantly lower handgrip strength as compared to the low-risk group (p = <.001) (Table 1).

Behavioral Level Analysis

After examining the function level data, we conducted an analysis on the behavioral level. We included data of 4-metre walk speed (n = 157), 5-time chair stand test (n = 155), and SPPB total score (n = 157) at this level. Two participants were unable to perform 5-time chair stand test due to physical difficulties. We conducted a comparative analysis by risk hierarchy. There were significant differences in all three behavioral level variables along the risk hierarchy, including 4-metre walk speed ($F_{(2,154)}$ = 85.167, p = <.001), 5-time chair stand test ($F_{(2,151)}$ = 76.107, p = <.001), and SPPB total score ($F_{(2,154)}$ = 194.4013, p = <.001). Post hoc tests revealed that the high-risk group had a significant lower speed in walking as compared to the low-risk group (p <.001). Further, the high-risk group used significantly more time to perform the 5-time chair stand test, as compared to both the medium-risk group (p <.001) and the low-risk group (p <.001). Finally, the high-risk group scored significantly lower for SPPB, as compared to both the medium-risk group (p <.001) and the low-risk group (p <.001) (Table 1).

TABLE I. PHYSIOLOGY, FUNCTION, AND BEHAVIORAL LEVEL CHARACTERISTICS BY RISK GROUPS (*N*=157)

	Low-risk (*N*=5)	Medium-risk (*N*=15)	High-risk (*N*=18)	*F*
Physiology 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)	$F_{(2,35)} = 1.372$
	Low-risk (*N*=41)	Medium-risk (*N*=41)	High-risk (*N*=26)	
Function level				
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)	$F_{(2,105)} = 14.385$
	Low-risk (*N*=80)	Medium-risk (*N*=49)	High-risk (*N*=28)	
Function level				
Handgrip strength (kg)***	27.90 (7.87)	21.94 (7.34)	15.23 (5.56)	$F_{(2,154)} = 33.079$
Behavioral level				
4-meter walking (m/s)***	.98 (.20)	.67 (.13)	.54 (.17)	$F_{(2,154)} = 85.167$
SPPB (range: 0-12)***	11.84 (.40)	9.78 (1.46)	7.75 (1.14)	$F_{(2,154)} = 194.401$
	Low-risk (*N*=80)	Medium-risk (*N*=49)	High-risk (*N*=26)	
Behavioral level				
5-time chair stand (s)***	8.14 (1.87)	13.17 (4.92)	17.01 (3.91)	$F_{(2,151)} = 76.107$

Note. $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

DISCUSSION

In this study, we used a novel UC^3 approach to successfully achieve three objectives: (1) to actualize full engagement of older adults in exoskeleton development; (2) to triangulate physiology, function, and behavioral level data to inform imperative kinesiology-based design parameters for exoskeleton development; and (3) to exemplify transdisciplinarity in exoskeleton development. Under this iterative UC^3 approach, we demonstrated the possibility to treasure the voice of older adults and respected them as full partners in all co-creation activities in our study. Additionally, a trilevel data curation process was found to be effective in ascertaining user characteristics and needs in the physical and psychosocial context of older adults' daily life. We found differences at the physiology, function, and behavioral level data among participants along the performance-based risk hierarchy, which is not possible if a transdisciplinarity concept has not been incorporated. By joint effort, mutual learning, and a common goal to enhance older adults' independence living ability, an interactive testing platform with transdisciplinary effort is achievable in exoskeleton development.

We initiated the UC^3 approach to exemplify the feasibility and manageability to involve older adults in the process of technology development, bringing a solution the pain points of the technology development field [16]. By engaging older adults during the design phase, they possess a sense of ownership of the study. A multimethod pilot study confirmed the necessity in developing exoskeleton to assist older adults in performing daily living tasks. Further, the participants provided valuable insights in the design and aesthetics of the exoskeleton. These early-stage information gauging are cherished to guide the brainstorming process of the research team, it also avoided the common barriers towards future adoption of the exoskeletons, such as unfavorable appearance, heavy and bulky [17]. Our pilot study also supported the development of an interactive testing platform for trilevel data curation. Pilot study findings ensured a safe and smooth experiment protocol which integrates expertise from our transdisciplinary collaboration.

Stemming from the UC^3 approach, we validate a trilevel data curation method and embrace its merits to inform kinesiology-based design parameters of exoskeleton development. We conducted a trilevel data curation with 157 older adults to inform kinesiology-based parameters for exoskeleton development. At the physiology level, we found significant differences in the step length and stride length between participants in different risk hierarchy groups. Our results confirmed existing literature in kinetics which showed frail older adults had a shorter step length during usual gait [18].

At the function level, we found significant differences in knee MVC at 73°, 52°, and 30° knee angle between low-risk group and high-risk group participants. This result confirmed earlier study which showed that frail older adults had a lower knee extensor torque [19]. Regarding handgrip strength, significant gender differences were found which confirmed the recommended demarcation of by-gender cutoff values [15]. In addition, our results showed that high-risk group participants had a significantly lower handgrip strength, as compared to the low-risk group. Our findings confirmed earlier study that supported grip strength as a stronger marker of frailty than chronological age [20]. At large, our findings support the need to capture function level data to inform exoskeleton development as the differences in knee MVC and maximum handgrip strength among older adults in different risk groups are significant.

At the behavioral level, we found significant differences in all three included variables: 4-meter walk speed, 5-time chair stand test, and SPPB total score between high-risk group and low-risk group participants. Our results are in line with studies that proved the diagnostic value of SPPB for sarcopenia potential [21]. Along with our project development, future analysis will provide the sensitivity and specificity analysis of SPPB for diagnosing sarcopenia potential. In brief, our findings support the need to capture behavioral level data to inform exoskeleton development as the differences in 4-meter walk speed, 5-time chair stand test, and SPPB total score among older adults in different risk groups are significant.

UC^3 approach ensured a consented common goal to enhance older adults' life can be persistently reinforced among a transdisciplinary team dedicated to exoskeleton development. There are three major principles for fostering the transdisciplinarity in exoskeleton or other AT development [22]. First, all the team members need to discuss and reach a consensus of solving real world complex problem, including assisting older adults to perform daily living tasks independently. Second, a transactive planning with all team members (inclusive of target users) allowed us to transcend disciplinary boundaries and collaborate with interprofessional and community partners to solve a shared problem. Third, it fosters innovative yet feasible thinking about and conducting research, design, development, and implementation. By doing so, we have confidence in future acceptance and adoption of our exoskeletons by sarcopenic older adults.

Our study has a few distinctive features that provide valuable contributions to the literature. First and the foremost, we are the first to fully engaged older adults in exoskeleton development who were treated as equal partners. Fundamentally, we derive a clear logical linkage between the implicit physiology level data, to the subtle function level data, and then to the explicit behavioral level data. Although we used different measures to collect the trilevel data, findings indicated an insightful interlocking relationship. We provide an ideal model to synthesizing different data to distil a feasible and practical plan to develop exoskeletons. Our findings also established the UC^3 approach as a desideratum to inform kinesiology-based design parameters for exoskeleton development, which extend the existing literature in user-centered design in technology, setting an exemplar to practice full involvement of users. Last but not least, our standardized experiment protocol, codebook, and interactive testing platform provide a vivid example of best practices in coordinating and managing a transdisciplinary research team.

CONCLUSION

In conclusion, we found evidence for a novel UC^3 approach to inform exoskeleton development. We started from a full engagement of target users, followed by a trilevel data curation at the physiology level, function level, and behavioral level. Lastly, continuous improvement and discussions with experts in a transdisciplinary team confirmed the validity of the UC^3 approach. One limitation of our study is the small sample size of older adults with high risk of sarcopenia potential. Recruiting the targeted study population is challenging due to both intrinsic and extrinsic factors, including long experiment hours for older adults with muscle strength loss and closure of experiment lab due to the covid-19 pandemic. In the next phase of the study, a jigsaw form of experiment with streamlining procedures will be devised. All in all, elucidating the unmet needs for daily activities at the physiology, function, and behavioral level will provide valuable insights into the development of intelligent wearable robots and will unlock the key to independent living lifestyle at the old age.

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