Navigating the Maze of Routine Disruption: Exploring How Older Adults Living Alone Navigate Barriers to Establishing and Maintaining Physical Activity Habits

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Older adults, especially those living alone, are less likely to meet recommended physical activity levels than other age groups. However, current physical activity promoting technologies have seen low uptake among older adults, likely due to poor attention to their unique needs. To understand the perspectives of older adults living alone towards physical activity, including their motivations for and the challenges encountered in maintaining routines, we conducted a qualitative study with 17 participants. Through thematic analysis of semi-structured interviews and diaries, we reveal their diverse motivations for engaging in physical activity while also detailing how their intentions and routines are habitually disrupted by multidimensional and interrelated barriers, including changing personal and environmental circumstances, lack of stimulus to maintaining motivation, and limited access to resources. We suggest future PA promoting technologies to leverage social interaction to develop commitments and employ a holistic design approach to addressing the interplay between the barriers.

CCS CONCEPTS • Human-centered computing • Human computer interaction (HCI) • Empirical studies in HCI

Additional Keywords and Phrases: Older adults, Living alone, Physical activity, Health, Social support, Design implications

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1 INTRODUCTION

Physical activity (PA) offers important benefits for physiological and psychological health [1,27], but many older adults, especially those living alone, miss out on these benefits by regularly falling short of recommended PA levels [75,76]. Older adults often experience barriers to engaging in PA, including difficulty with fatigue [41], concern over falling [58], and a

lack of time, motivation, and access to facilities [68]. These concerns are heightened for older adults living alone, who have been found to engage in less PA [76] and to experience increased incident frailty [75] than those living with others. More importantly, barriers at different levels intersect to hinder PA engagement, as suggested by research on long-term care residents [5], but it remains unclear what compound challenges older adults living alone are facing.

While technology has exhibited the potential of supporting exercise behavior [2,49] and older adults hold positive attitudes towards adopting technology for PA purposes [2], commercially available PA promoting technologies have seen little uptake among older adults, especially relative to other age groups [44]. Reasons accounting for older adults' unwillingness to adopt are multitude, including lack of technology knowledge [40], cost of purchasing new devices [34], and mistrust and skepticism regarding the ability and usefulness of those technologies [22,40]. The low perceived usefulness is partly because those commercial devices mostly focus on the needs of younger adults based on the findings from prior research that has primarily focused on younger adults with older adults being the least targeted population [3]. Given that past research on PA promoting technologies has rarely targeted older adults [3] who have potentially unique goals and requirements for PA support, it is not unexpected to find that existing PA promoting technologies are mismatched to older adults' needs [12,71]. Despite the inadequate attention on older adults, research to date has looked at how technologies could support PA engagement among older adults through, for instance, increasing their self-awareness and motivation for PA [51], enhancing their compliance with PA programs [42], and helping them find enjoyable activities [20]. However, since the barriers older adults encounter to engaging in PA are not isolated but interrelated [5], current technologies that mostly address individual barriers (e.g., tracking activities through wearables to increase awareness of PA) tend to be incapable of entirely matching to older adults' needs and promoting PA in a comprehensive way. While research has started to investigate how technologies could deal with the barriers older adults encounter to engaging in PA, prior studies mostly focus on community-dwelling older adults' experience of their success in overcoming the barriers and how technologies played or could play a part [20,30,59], which makes it hard to identify the experience and needs of those living alone and being inactive. With respect to technology design, some studies have broadly explored individual problem scenarios regarding PA engagement [20,52], while some focused more on specific barriers to PA, including the lack of knowledge about PA benefits [26] and the lack of information about local PA programs [48], which leaves it unclear as to an overview of the challenges older adults have for engaging in PA, let alone the solutions to a multitude of challenges. Contributing to this problem is a lack of research digging deeper into the experiences of PA in later life, particularly for inactive older adults living alone.

With the objective of understanding older adults living alone and their needs and challenges with respect to remaining physically active, we examine the following research questions:

1. What challenges do inactive older adults living alone encounter to being physically active?
2. What are implications for designing future technology to support them in maintaining PA routines?

To this end, we conducted a qualitative study detailing the experiences and perspectives of 17 older adults (aged 65 or over) who lived alone and who were not physically active. We invited them to record their everyday PA in one-week diaries, before conducting semi-structured interviews to deeply understand their experiences regarding PA in their daily lives, including their current PA practices, their goals and motivations for engaging in PA, and the barriers and challenges they encountered to meeting these goals. Our thematic analysis revealed a diversity of needs and barriers among this group for engaging in PA. Our identified themes highlighted that while our participants had different motivations and perspectives for PA, they experienced both permanent and intermittent disruptions to maintaining their PA routines due to evolving

health conditions, changing environmental factors, lack of stimuli to sustain motivation, and limited access to suitable PA resources.

Illustrating how our participants experience reconstructing and maintaining PA routines, we contribute to a deeper understanding of nuanced experiences of older adults living alone and the barriers they encountered to being physically active. We uncover how those multidimensional barriers were interrelated, highlighting that the interplay between the barriers not only renders it more challenging for older adults to maintain activity routines but also diminishes the potential for PA promoting technologies. We further clarify the role of social interaction in sustaining PA motivation. From our findings, we suggest that future technologies should provide flexibility to enable older adults (1) to develop their own definitions for what it means to be 'physically active', (2) to be resilient in response to changing circumstances, and (3) to navigate the interplay between multiple barriers in establishing and maintaining activity routines.

2 RELATED WORK

An increasingly robust body of research indicates that technology can promote PA engagement for a broad population of users. In particular, PA is the most frequently targeted behavior in the area of behavior change—aka persuasive—technology [56]. These technologies support people's PA through employing a variety of behavior change strategies and system features, such as self-monitoring PA data [35], leveraging social support by sharing PA data with friends [14,35], giving people credit or rewards for their activities [14], encouraging people to set goals, and offering people reminders for sticking to their goals [53]. Moreover, these PA promoting approaches are conveyed via different platforms such as wearable activity trackers [40] and the verbal feedback of virtual coach [19], with mobile and handheld devices being the most used platform [3]. Past research, primarily targeting younger adults, has demonstrated the potential of these technologies for not only simply promoting PA [8] but also motivating people to make durable changes [23].

Though older adults have been relatively underrepresented in studies of PA promoting technologies [3], a small body of research suggests these technologies are feasible for effectively supporting older adults' exercise behavior [49]. For instance, activity monitors can increase older adults' awareness of personal PA behavior [18], and an intervention incorporating technologies and behavior change strategies is effective at enhancing adherence to PA training programs [42]. Studies have also highlighted the potential role of PA promoting technologies for older adults by leveraging social motivators [26], establishing and adapting routines [20], and finding enjoyable activities [20].

While some deployment studies of PA promoting technologies have reported positive attitudes towards them among older participants [2], such enthusiasm is not reflected in studies of consumer behavior, which have instead reported lower levels of adoption relative to other age groups [44]. Barriers, including the need to overcome the mistrust towards new technologies [22], recognize the benefits of new technologies [39], address gaps in requisite base knowledge [40,51], and finance the substantial costs of acquiring hardware and services [34], are one set of factors working against adoption, not to mention the poor usability of those technologies such as activity-tracking wearables [66]. However, negative perceptions of the potential usefulness of PA technologies [57,71] may be the larger, or at least more overlooked, concern [50].

Broadly speaking, the needs of older adults are rarely prioritized in the design of novel technologies, with the result that many new systems, though intended to serve "everyone," fail to provide useful services that benefit older adults, fit within their lifestyles, or accommodate their requirements [28]. This has been true for PA-related technologies as well [3], with research reporting a mismatch between current designs and older adults' needs and preferences [71]. This mismatch includes the use of design and motivation strategies poorly aligned with older adults' unique needs [12] and mismatched expectations for activity intensity due to unclear design objectives [3]. Even where research has considered older adults as potential users of PA technology, studies have tended to make "a priori decisions on the technology that will be used" [25]

rather than engage in questions of how to best design such technologies for them. Research has also tended to treat older adults as a homogenous group [73], without capturing their great diversity across various factors, including physical capacity, socio-economic status, and technology familiarity [17].

Research specifically focusing on older adults is emerging and has suggested a series of recommendations for designing PA promoting technologies. For example, wearable activity trackers need to take personal challenges into consideration and be considerate of individual performance [71], while being context-sensitive to provide just-in-time information to nudge activity engagement [59]. PA data visualization should emphasize pleasure over performance and respect older adults' agency of deciding appropriate PA goals [70]. Notwithstanding various design recommendations, studies agree upon that there is no general rule concerning designing for older adults due to the breadth of their needs and preferences [11,70]. It becomes necessary to thoroughly understand a specific target group and create design profiles based on physical and cognitive abilities, motivation, contextual, behavioral, and psychological factors in terms of PA engagement, before making design decisions [11,69]. Moreover, older adults face multiple barriers to remaining physically active that intersect with each other [5]. Yet, existing technologies tend to address those barriers individually, while overlooking the connection between multiple barriers. Without a complete picture of what barriers to PA older adults encounter and how the barriers interact, PA promoting technologies may not be capable of providing older adults sufficient support they need.

Taken together, these findings suggest that while there exists a potential for PA promoting technologies to effectively support older adults in improving and maintaining PA behaviors, realizing this potential across a broad demographic of older adults will require more thoughtful designs that account for specific needs and design priorities. Underpinning this, is a need to better understand older adults' motivations and goals for PA in later life, the barriers and challenges they are encountering in meeting their PA goals, and the kinds of supports they require for successfully engaging in PA. This work must also strive to better address diversity in later life experiences by targeting smaller sub-demographics and carefully tracking other characteristics so that findings can be appropriately applied. As a first step, we approach this gap with a focus on older adults living alone who are not physically active. We focus on this particular group in that the PA-related statistics for this group suggests they may have greater and more urgent challenges concerning PA and a heightened need for better support, that technology interventions may better suit those who are currently inactive but motivated to change [20], and that there lacks a deep understanding of this group.

3 METHODS

To understand the experience of older adults living alone regarding their daily PA and identify the barriers they encounter to remaining physically active, we conducted a qualitative study consisting of diaries and semi-structured interviews with 17 participants. To better understand what impedes older adults from engaging in PA and how to motivate them, we specifically focused on those who held an intention to improve their PA levels, but who were, at the time, physically inactive. Figure 1 provides an overview of the study procedure, which was reviewed and approved by the McGill Research Ethics Board.

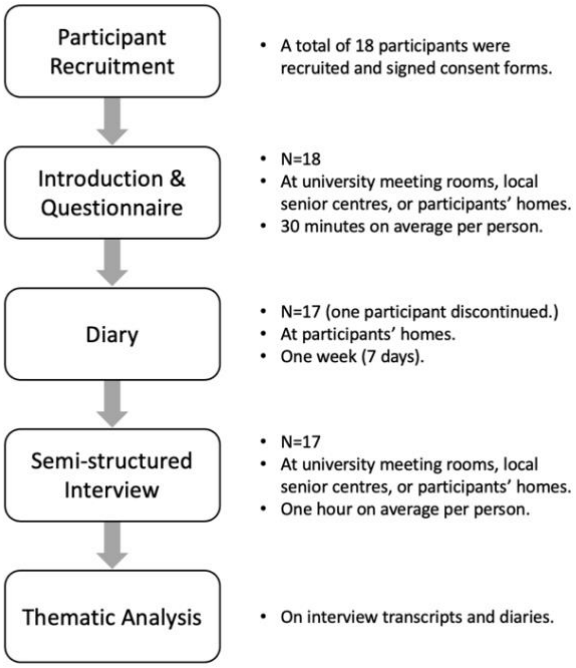

Figure 1: Study procedure

3.1 Participants

We recruited participants through local senior centers and community groups by sending listserv emails, posting messages on social media, distributing fliers at senior-oriented events, and word of mouth. People were eligible to participate in this study if they self-reported that they (1) were aged 65 or over and living alone, (2) partook in no more than 2.5 hours of moderate- to vigorous-intensity aerobic activity each week, (3) wanted to improve their activity levels, and (4) felt comfortable participating in the study activities in English. Participants interested in this study were provided with detailed information before signing informed consent forms.

In total, 18 participants were recruited, from which, 17 (aged 66–93, average age 78, female 14, male 3) completed the study. All lived alone in Greater Montreal, except one (Nancy) who reported primarily living alone but sometimes staying with family. Most (14) reported having an average or better health compared to their peers. Participants varied in their financial comfort, with 8 reporting positively (feeling somewhat or very comfortable) to this question, 3 reporting negatively (feeling somewhat or very uncomfortable), and the rest (6) reporting neutrally. All participants (16) reported engaging in less than 2.5 hours of PA per week; however, one participant (Josette) elaborated that while her PA fit this description in recent months, she had historically been more active. Most participants (9) exercised no more than twice per week. Walking was the most common type of PA among our participants. In terms of their motivation (i.e., stages of change [61]), 9 participants reported an intention to improve their PA levels in the next month (i.e., preparation stage) and 7 reported this for within the next six months (i.e., contemplation stage), while one had already started taking action (i.e., action stage). Participants were generally not very familiar with technology, with an average technology proficiency score

of 3.2 (out of 5). Participants were less familiar on average with mobile devices (average score 2.69) than computers (average score 3.89). More detailed participants' background information is shown in Table 1.

Table 1: Participants background information

Name [a]	**Gender (Age)**	**Health Condition**	**Financial Comfort**	**PA Level** [b]	**Most Common PA Type** [c]	**Motivation Level** [d]	**Technology Proficiency** [e]
Michele	F (84)	Fair	Very Comfortable	Inadequate	Walking, biking	Contemplation	High
Carolyn	F (73)	Poor	Very Uncomfortable	Inadequate	Walking	Preparation	Mid
Kathleen	F (72)	Fair	Neutral	Very Inadequate	Walking	Preparation	Mid
Sandra	F (79)	Average	Somewhat Uncomfortable	Very Inadequate	Walking	Preparation	Low
Paul	M (78)	Average	Neutral	Very Inadequate	Walking	Contemplation	Low
Elizabeth	F (83)	Good	Very Comfortable	Inadequate	Walking, swimming	Preparation	Low
Christian e	F (80)	Good	Somewhat Comfortable	Inadequate	Walking	Preparation	High
Josette	F (75)	Average	Somewhat Uncomfortable	Adequate	Walking, home exercise	Action	Mid
Linda	F (66)	Good	Neutral	Inadequate	Walking	Preparation	Mid
Doris	F (72)	Average	Neutral	Inadequate	Walking	Preparation	Mid
James	M (81)	Average	Neutral	Very Inadequate	Walking	Contemplation	Low
Ann	F (74)	Average	Neutral	Very Inadequate	Qi Gong	Preparation	Mid
Donna	F (76)	Average	Somewhat Comfortable	Inadequate	Stretching	Contemplation	Low
Norman	M (79)	Good	Very Comfortable	Very Inadequate	Walking	Contemplation	High
Claudine	F (77)	Good	Somewhat Comfortable	Inadequate	Walking, swimming	Contemplation	Low
Nancy	F (93)	Excellent	Somewhat Comfortable	Inadequate	Walking	Contemplation	Low
Helen	F (87)	Good	Somewhat Comfortable	Inadequate	Stretching, lifting weights	Preparation	Mid

[a] All of the participant names have been replaced by pseudonyms. [b] PA level is determined by the duration of PA per week, with less than 1 h being very inadequate, 1–2.5 h inadequate, and more than 2.5 h adequate. [c] The type of PA each participant often performed. [d] According to stages of change, a person is at contemplation stage if they intend to take action in the next six months; a person is at preparation stage if they intend to take action in the next month; a person is at action stage if they have already taken action within the past six months. [e] Technology proficiency score is an average of a person's computer proficiency score and mobile device proficiency score, ranging from 1 to 5, with lower than 3 being low, 3–4 mid, and higher than 4 high.

3.2 Procedure

Our research procedure consisted of three main activities: an introductory session to gather background information and distribute study materials, a diary study to collect contextual information regarding PA, and a semi-structured interview to dig deeper into participants' experiences.

During the introductory session, we first provided details about the study and obtained informed consent. Participants then completed a background questionnaire covering their demographic details, PA habits, motivation level, and familiarity with technology. Technology familiarity was measured using the questions from the short versions of the computer proficiency questionnaire [7] and the mobile device proficiency questionnaire [63]. Finally, we provided participants with instructions and materials for completing the diary study. Each introductory session lasted approximately 30 minutes.

The diary component was used to collect participants' PA routines and contextual information about PA in their daily lives and capture the details appearing before/during/after PA that otherwise might be easily ignored or forgotten. Each participant received a printed booklet containing space for them to report each day (for 7 days in total) whether they exercised, what exercise they did, and how they felt about it. Participants were encouraged to take notes regarding their daily exercise but were not required to complete each entry every day. The exercise notes were to help participants gain awareness of their PA routines and experiences. The participant diaries took place at participants' homes in their daily lives by themselves. A week after distributing a diary, we contacted the participant to schedule an interview and collect their diary.

The final stage of the study was the semi-structured interview. Building on the data collected in the dairy, we explored with participants their needs and experiences regarding exercising or intending to exercise. During the interviews, we used the collected diaries as prompts to expand conversation and ask clarification questions to gather detailed information on the themes covered by our interview guide. Interviews took one hour on average and were audio-recorded.

The study was run from November 2022 to February 2023. The introductory sessions and interviews were conducted, depending on the participant's preferences, in a meeting room at our university, an activity room at a local senior center, or at the participant's home. During these in-person interactions, we encouraged participants to wear masks for self-protection even though the mask mandate was already lifted at that time. Each participant received a CA$15 cash honorarium for their time and participation.

3.3 Data Analysis

We conducted thematic analysis [9] on the interviews and diaries. We used Word for Web to transcribe our interview recordings and then manually proofread each transcript to correct transcription errors. We manually transcribed all entries of the collected diaries. Afterwards, both data sources were imported into MAXQDA 2022 for analysis. The first author iteratively performed inductive open coding on both data sets (interviews and diaries) concurrently. Then initial themes were developed from the codes. The two authors met and discussed these initial themes regularly, revising them multiple times before settling on the final set of themes presented here.

4 FINDINGS

Four main themes emerged from the analysis: (1) PA as more than health, (2) social commitment was both a motivator and a barrier to PA, (3) defining own PA routines, and (4) challenges of reconstructing PA routines.

4.1 PA as More Than Health

Our participants shared a diversity of motivations for engaging in PA, which came from both the benefits brought by PA and the enjoyment associated with engaging in PA.

Not surprisingly, health was viewed as a major benefit that motivated participants to engage in PA. Participants regarded exercise as a way of slowing the decline of health, describing PA as important for "*self-preservation*" (Paul), "*maintain[ing] health*" (Nancy), "*keep[ing their] physical strength as long as possible*" (Claudine), "*decreas[ing] stiffness*" (Kathleen), and "*prevent[ing] falling*" (Christiane). This health benefit could give participants a sense of accomplishment when they completed their exercise routines, since they did "*as much as appropriate for [their] age*" (Nancy). This being-proud-of-self feeling seemed to particularly happen to participants who had less interests in exercise, including both Nancy and Christiane.

> Christiane: Nobody does [like to exercise]. But when I convince myself to do it, I feel good about it. I feel good about myself and I feel good in my body.

However, health alone was insufficient motivation for many participants. Participants described seeking out opportunities for PA that were imbedded in or side effects of doing other activities. Walking to complete errands, including shopping and going to appointments, was a common scenario where participants were able to engage in PA while accomplishing another goal or activity, instead of simply doing PA, or as Kathleen described it, "*do[ing] any kind of official walks.*" Sandra similarly described wanting more from PA because "*just walking around aimlessly makes no sense.*" Instead, Sandra considered ways in which her activities of daily living could and did contribute to being active:

> Sandra: I drive to the stores where I have to go. I drive to hospitals and medical appointments. I drive to theatres. But wherever I go, I have to get out, walk through the parking lot, and then walk inside the store or the clinic or the hospital. And those are always long walks because everything's far away.

Socializing and "*meet[ing] up with friends*" (Linda) provided opportunities for some participants to exercise, particularly for those with less motivation to exercise. Nancy described how socializing could encourage her to engage in PA:

> Nancy: [Socializing] encourages physical activity. It involves putting that book down and getting moving and saying, well, I'll phone this person, I'll meet this person, I'll plan to go to a meeting or something like that, so that it encourages daily mobility of whatever kind, not just sitting reading a book.

In addition to meeting in person, socializing also helped to build connections when exercising via virtual platforms. For instance, Carolyn believed that socializing was an integrated "*component of the exercise*" for online exercise meetings, where "*camaraderie, chemistry develops*", and expressed disappointment in how this aspect had been overlooked as her programs limited the socializing part:

> Carolyn: I think with exercises like that on Zoom, it's important for them to bring in people interacting socially as well as doing exercise. […] Like when I go to [a local senior center] and I do exercise with my colleagues, we've been chit-chatting and talking. For some reason they cut that out on Zoom, and I think that's to their detriment, because it's a part of exercising.

The motivation for PA could come from the pleasure associated with it. The pleasure could be exercising itself for some participants who liked exercising—Claudine "*[enjoyed] being physical*" and believed exercising was "*a good way to relax*".

The pleasure also could be enjoying the peripheral sensory experiences from the environment. For example, Kathleen described how she enjoyed being in nature with fresh air, trees, and sunshine, when walking outside; Helen spoke of needing "*visual stimulation*" such as store windows and interesting neighborhoods to motivate her to walk; Carolyn preferred including auditory stimulation like music in PA, "*exercising to classical music, to ballet music, to jazz, mild jazz, to art, looking at art.*" By drawing attention from exercise to environmental stimulators, participants were able to distract themselves from PA they found uninteresting and focus on things they found more enjoyable.

> Helen: If I'm in a very interesting neighborhood with a lot of visual stimulation, then I do enjoy walking. But other than that, just to go for a walk, I don't enjoy it.

Given the important part pleasure played in motivating PA for some participants, they tended to discontinue exercising if the pleasure brought by PA faded away. For instance, Helen exercised by following online videos for a while but stopped after she "*got bored with that.*" This highlights that sustained pleasure is essential for some older adults to engage in PA in the long run.

> Helen: I find [following online videos] doesn't really sustain my interests for a very long time. […] It's very hard for me to be motivated to do something if I don't find it interesting.

More often than not, however, it was after exercising that some participants felt pleasure, yet they did not have enough motivation to start exercising in the first place, as Christiane described that "*[she feels] good and energized after [exercising], but it's to get [her] to start it, that is kind of hard*." In this case, the pleasure from PA might not be a sufficient motivator, whereas creating commitment could be a feasible approach (see 4.2). Overall, our participants had diverse motivations for engaging in PA. In particular, participants who disliked PA relied more on the benefits associated with PA than exercise itself, suggesting the potential of combining other activities with exercise and leveraging environmental peripheral stimulators in motivating PA engagement for this group.

4.2 Social Commitment Was Both a Motivator and a Barrier to PA

Many participants were motivated by social interaction because it enabled them to turn their commitment to exercise into a social obligation that they found easier to keep. Such commitments seemed especially important for less motivated participants who found that "*only being accountable to yourself isn't good enough*" (Nancy) and that they "*need some push from somebody from something*" (Christiane) to achieve their PA goals. These commitments took different forms. For instance, registering for classes was a "*commitment to a set time*" (Christiane) and the people involved:

> Christiane: When I register [classes], I kind of commit myself. And when I'm committed, I do what I have to do.
> Nancy: When it's with other people, you're more inclined to show up. Like if I go to yoga class, this involves other people. And I won't skip it.

Commitments could come from people such as family members, whose encouragement and push could motivate participants to stick to their activity routines. For example, with his daughter signing him up for events, Norman started to step out of home and join group activities:

> Norman: [Before my daughter signing me up] I was just doing nothing at home. I wasn't seeing anyone. I wasn't talking to anyone. I didn't have any friends like people I can go out and talk to. So this offered me a lot of

> [opportunities], being able to meet people and come to a function or whatever that we are able to meet people and play games or something.

Not only was exercising with friends a commitment to them but it also stimulated mutual encouragement, making the PA process more engaging and "*easier*" (Ann), "*[giving] body more strength, pushing you and encouraging you to do [exercise]"* (Josette). However, many participants found it very difficult to find someone to exercise with, a buddy "*who would be walking at [their] level*" (Sandra) and ideally who had mutual interests to "*share their observations and experience*" (Helen). Yet, despite the motivation an exercise partner could bring in, some participants worried that such commitments would become so strong "*an obligation*" (Sandra) that they might interfere with their own routines. For instance, Sandra thought that walking with a partner could be motivating, but she was not that flexible to match to other people's schedules, while maintaining her own life routines. This suggests that participants were aware that having exercise partners could support them engaging in PA, but finding partners became a problem because it is related to other considerations such as exercise level, hobbies, and schedules.

> Sandra: There's nobody at my level that I know of, that I can go walk with. […] [Walking with a friend] would be like an obligation, if there was an obligation that I had to do this. […] But then there are also so many interruptions. There's always, how can I say it… not an impediment, but an event, something that happens, that interferes with that, maybe a plan or regularity of doing something. And not everybody's very flexible.

Given the key role of social interaction in creating commitments to PA engagement, living alone could be a barrier to maintaining exercise routines for some participants in that it loosened their motivation and self-discipline. For those who didn't enjoy exercising in itself, they were likely to "procrastinate" (Christiane) or didn't exercise at all, since there was no one observing and critiquing them, as Nancy mentioned, "*it's much easier when you're by yourself to do nothing*". Even for those who enjoyed exercising, exercising alone tended to lower their performance. For instance, Donna felt "*not disciplined and lazy at home*" and did less exercise on her own compared to attending exercise classes, while Norman became inactive because of living alone:

> Norman: I'm supposed to have more time to exercise. But you also get very lazy when you live alone. And I fell into that trap, not doing, not being active.

What is more, participating in this study along with filling out the activity diary before the interview was a vivid example of the impacts of commitments on maintaining routines. According to the collected diaries, most participants (13/17) reported higher PA levels during the week of completing the diary, compared to their regular PA level as filled in the background questionnaires. The motivating effects of the study participation on PA promotion were obvious, so much so that Josette was surprised to feel an "*improvement in the strength of [her] legs*" during that week. When asked what accounted for this improvement, many participants pointed out that the commitment and accountability created by joining this study mattered.

> Nancy: Because I knew you were coming, and I knew I had to fill this in. Accountability really matters in so many things.

While being aware of the importance of PA, many participants did not actively implement their PA plans. This commitment helped lift the priority of exercise in participants' daily lives and encourage them to implement their awareness towards exercise, because "*when you think about something often enough, you really get closer to the thought of doing it*"

(Norman). Moreover, having someone to follow up reinforced the effects of the commitment, as some participants emphasized that the personal contact with the researcher made a bigger difference than recording their daily activities in the diary, which might result from the psychological support and encouragement stemmed from the personal contact and social interaction. This highlights the power of social support, particularly human contact, in stimulating and maintaining motivation for PA.

> Nancy: It's the personal contact with you. If it was just filling in papers, I think it might influence me a little bit in a positive way, but when there's a person involved, you're more inclined to hold yourself accountable. It's like writing an exam at school. You'll study because you're going to write an exam.
> Josette: I wouldn't be motivated just to fill out the books for filling out the books. I'm motivated for the fact that I have to give it to you, otherwise I wouldn't do it.

4.3 Defining Own PA Routines

Our participants had their own perspectives regarding what counted as exercise and thus their own ways of maintaining exercise routines. Apart from engaging in PA specifically for pleasure (as stated in 4.1), PA was embedded in participants' everyday life routines. For instance, Nancy used to have a decent level of PA because walking was involved in her work:

> Nancy: Before the pandemic, I worked, so I didn't worry about exercise. I was working at […]. And I had to go down and then it involved quite a bit of walking that involved moving around.

Moreover, some participants regarded "*life activities as exercise*" (Carolyn), including doing housework and errands, because it was not only an essential part of "*managing [their lives]*" (Doris) but also a way of showing their capabilities of managing their lives.

> Doris: Managing my life is my exercise because it's completely physical and mental. But if I couldn't do it, that means I've gotten old and the body is broken down and I can't do it. But I can do it. […] And I do my own errands. I do my own housekeeping, like vacuuming, washing with the scrub board, kneeling down to polish my floors. […] I do my own grocery shopping and I walk to the grocery store, about ten blocks.

When it came to maintaining routines, a few participants believed that living alone was beneficial because they could follow their own preferred routines, whereas living with others might introduce additional disruption because they "*had to coordinate [different routines]*" (Doris). Living alone also allowed for more control over and flexibility of their exercise, in terms of schedule, location, and pace.

> Elizabeth: I can choose my own time to exercise, like to go out. Do I go out in the morning or shall I wait till I've done the ironing and go out in the afternoon or, that sort of thing. I'm more in control of the timing of my exercise, the pace of my exercise.

However, changing circumstances often hindered participants from maintaining their PA routines. Schedule conflict was a common barrier to engaging in PA, as some participants had to put off or cancel their exercise because they prioritized other more important things. For instance, Donna "*[didn't] have choice*" but having to miss her exercise class due to her doctor's appointment. Similarly, busy schedules kept Kathleen from maintaining her exercise routines:

> Kathleen: I didn't do [exercise] because I had so many things appointments that had to do. […] It's funny because you think when you're older, you'd have more time when you're retired, but it doesn't work that way.

Fluctuating health condition (e.g., fatigue, leg pain, etc.) was another frequent and unavoidable barrier to maintaining PA routines for most participants. Participants described not being able to do anything except suspending their PA plans until they felt better. Those with higher motivation and discipline for PA seemed to be particularly impacted by these unavoidable disruptions. For instance, Paul encountered such a situation during the week of filling out the diary—his sore hip joint restricted him from keeping his PA routine because "*even walking in the house was a problem*," to the extent that the interview location needed to be changed from the first author's office, which is up a steep hill with limited transit or parking options, to a more accessible location.

> Paul: … the other time when I came to see you, like a week ago, when I was walking up the hill was no problem. […] But this time, if I had to walk up the hill, it's… This is why I asked if we could have a meeting place somewhere else. I would have had a lot of trouble going up the hill. So each day is different. Each week is different. Circumstances change.

On top of managing fluctuating health conditions, participants were also very cautious of environmental changes, especially the weather, which created additional barriers to maintaining PA routines. Concerns over losing balance and falling prevented participants from walking outside on slippery days, including most of winter.

> Josette: When you lose strength, it makes it worse when you have to go in the snow, and also becoming very, very scared about the ice.

Since PA took different modalities and meanings for individual routines, coupled with intermittent disruptions out of the changing personal and environmental conditions, some participants emphasized that they would like to take control over their own exercise routines, rather than being told by other people or technology. That is, "*doing [their] maximum, not somebody else's maximum*" (Nancy). Yet, the changing circumstances and older adults' autonomy were not adequately considered in the design of activity promoting technologies, which was one of the reasons that those technologies were less adopted by older adults, as in Paul's experience with Fitbit. This illustrates a pitfall of current PA promoting technologies for older adults, i.e., assigning universal PA goals to all the users, without respecting their varied conditions and physical capabilities. This also highlights that older adults would like to define their own PA routines, in terms of both what PA means and what successful PA means.

> Paul: [Fitbit] was trying to keep me doing things at a certain rate at a certain pace, which didn't suit me. I didn't want to be controlled by this gadget. In other words, I wanted to keep my control, do my own regiment, my own routine.

4.4 Challenges of Reconstructing PA Routines

4.4.1Experiencing Permanent Disruption

Major life changes disrupted almost all the participants' exercise habits, limiting them from maintaining the exercise routines they used to have. Retirement was one type of life change influencing some participants' PA routines and overall lifestyle. For instance, Linda used to be physically active and "*constantly going*" during her work, but she lost her activity routine and "*rhythm*" since retirement.

Age and its related deteriorating health appeared to be the most prominent change. Some participants were very physically active when they were younger, but now had to give up exercises they had liked due to age-related changes in their abilities. Facing these irreversible changes and permanent disruptions was difficult, with some participants describing

a lingering attachment to their previous routines, as Claudine explicitly expressed "*[missing] the life [she] used to have*." Others echoed these feelings of loss:

> Kathleen: When I was young, I used to ski, but I had to give it up because it was too hard on my back and my neck.
> Paul: I've been active most of my life, all my life. But as you grow older, this is not new, but you grow older, you get slower, right? And you get starting to get restrictions.

These disruptions also appeared in the form of limitations in the type of PA that older adults were able or felt safe to do. Some participants had to avoid intense exercise and "*limit [themselves] to what [they] can do at [their] age*" (Claudine), choosing mild activities like walking to prevent from hurting themselves.

> Paul: The only thing that I can do right now is walk. Like I don't really, I'm not looking at other options. I can think of other things that I'd like to do, but right now I don't have that flexibility. […] This is the only option that I have. Walking is the least problematic.

Disruptions were also shown in when and where older adults felt safe to engage in PA. Due to their slowing reaction speed, some participants felt insecure biking or walking near heavy traffic. Claudine talked about being hit by a car when biking outside as well as her experience of feeling unsafe when walking across the street.

> Claudine: I used to bike a lot outside, but now I don't feel secure enough. The last time I used my bike, I was hit by a car. And I don't feel like my reflexes are as good as they used to be. […] If you go walking in the street where you have to cross streets, you have to always be on your guard. You cannot have an easy 30-minute walk on the streets. You have people, you have cars and bikes and all kind of things.

Because of these concerns, some participants started to change their perspectives on PA and establish new PA routines that they felt both safe and suitable to their capabilities. For example, though indoor gyms were never attractive to her, Claudine was thinking of going to a gym which would be safer than walking outside. Similarly, Nancy started to regard walking as a proper type of PA for her age.

> Nancy: As a younger person, I don't think I would see [walking] in a positive light at all […] because I would see going to the gym and running on the treadmill as something more valuable. Where now I know my limitations, so I'm content to see that walk in the mall in a positive light.

Evolving health conditions made our participants more sensible, vulnerable, and thus cautious to the environment and the changes thereof. As a major change in recent years, COVID posed multiple barriers for participants to maintaining their PA routines. More specifically, COVID substantially restricted where and how people could exercise. Since they were afraid of getting infected, many participants stopped using public exercise facilities and avoided enclosed public places such as exercise classes and gyms, and some relied more on following online exercise videos at home.

> Elizabeth: I like swimming, but since COVID I won't go to the gym. […] I don't think it's a good idea to be undressing in these places and breathing, and there isn't much ventilation at the Y. […] So I feel very unsafe going to swim at the Y or use their gym, so yes, COVID now has influenced where I can exercise.
> Ann: [Following online exercise videos] is more during pandemic. I feel pandemic is still here. It's still risky.

COVID also greatly restricted social interaction and its related commitment, leaving some participants less opportunity to engage in PA. For example, Michele often went out with friends but "*now all that has changed because of COVID*." Similarly, until the pandemic Nancy "*didn't worry about [her] exercise*" because she had work to do "*that involved moving around, [but] then that stopped.*" The limited social interaction had psychological impacts on some participants by diminishing their "*ambition to do anything*" (Nancy), including their motivation for PA. Gradually, they started to "*get in the habit of not exercising*" (Nancy) and thus their PA levels dropped substantially, which led to deteriorated physical health conditions, for example, their "*muscles got weak*" (Doris). In particular, this problem was exacerbated by the situation of living alone, where some participants were more isolated and felt "*lonely*" and "*depressed*" (Ann) and even lost "*ability to engage in life*" (Nancy).

> Norman: COVID dampened my spirit. And I wasn't encouraged to do any exercise or anything like that. […] It puts you in a in a bad state. I didn't get COVID, but it's the feeling that not being able to go out and walk around. And I didn't do anything. I stayed at home and watched TV every day.
> Ann: Because of COVID-19, I don't feel like doing anything. Especially when you live alone, you don't feel motivated for anything. And you cannot even have friends at your place because of COVID. You never know the risk of having visitors, so it's really lonely. It's…I feel lonely.

Notably, this process of recovering from a permanently disrupted activity routines to successfully forming a new one was a long and difficult process for our participants, requiring both physical adaptation and psychological preparation. They had to give up preferred exercises and established routines and then work to identify, select, and establish new routines with a more suitable PA type and location, while mentally preparing themselves for those changes. Yet, most participants did not have access to the resources that could navigate them through this reconstructing process.

4.4.2Limited Access to Resources

As they were rebuilding new PA routines from the aforementioned disruptions, many participants found that easily accessible PA resources were limited if taking suitability, location, and costs into consideration.

There was a limited access to professional support that could navigate them in finding and learning suitable activities. Doing unsuitable exercise and lack of instruction often led to injuries among participants, which became more apparent when some participants shifted to online exercise during COVID. For instance, Elizabeth attended online yoga classes during the pandemic but discontinued after a few classes because her shoulders and joints were hurt by the exercise that was "*obviously not for [her]*". Josette had similar experience and "*since then [she didn't] want to do any exercises alone on the web*;" she specifically expressed "*[preferring] to be in the same room as the teacher*" to know "*exactly what to do and how to do it*." Due to the restrictions of age on their muscles and joints, many participants would like to have professionals' instructions to show them which exercise was suitable for them and how to move their body properly. However, resources such as instruction videos were "*hard to find*" (Kathleen) for many participants, not to mention those matching their current PA capabilities.

In-person exercise classes usually provide professional instructions, but location and cost posed additional barriers for many participants to accessing these resources. Some participants, including Kathleen, stopped attending exercise classes because of the time cost and effort for travelling, especially in the winter. If coupled with the financial cost of joining classes or gyms, accessible resources became even scarcer. Because many participants tend to "*have a more modest and contained income*" (Helen), they became cautious of spending money on expensive PA programs.

> Linda: If you look in your area like at the local community center, forget it, I can't afford to pay the prices they're asking to teach us a small class. You know, things are expensive.

Although most online exercise programs were low-cost and convenient, accessing them required some level of familiarity with technology, which some participants did not have. For example, Claudine wanted to join online exercise courses but gave up because she found "*it was very complicated*" to get on to Zoom. Similarly, Carolyn could not find the exercise resources she wanted because of the lack of skill of searching online:

> Carolyn: I'm sure you, as an information technologist, know how to zoom in by saying the keyword that you need to save through the tablet for the Internet to find that, but I don't have that skill. So I find myself forever winding up at a ballet site with different ballet companies doing different dance routines, rather than exercise routines.

This suggests that our participants needed not only the convenient environment and facilities that allowed them to safely engage in PA but also the intangible knowledge that guided them to find suitable activities and access available resources. However, such resources were very limited. Regarding this issue, some participants expressed their views towards the government and remarked that more policies and work were needed on a societal level to accommodate older adults' PA needs, rather than just "*[doing] little tokens*" (Linda).

> Josette: I think it's because of my age, because the society and part of the medical field […] consider that at my age it's not worth it. […] At my age, wherever we go, we're not very much considered because we're not, what I've seen for many in our society, as a long-term potential.

5 DISCUSSION

Our findings reveal that older adults living alone had diverse motivations for PA that went beyond simply maintaining health. However, their established exercise routines were disrupted, both intermittently and permanently, by a series of barriers, including fluctuating health conditions, changing environmental conditions, lack of commitment to PA from social interaction, and limited access to suitable PA resources. These barriers were multidimensional and often intertwined, which further hindered their ability to recover from disrupted exercise routines. In this section, we discuss how future technology could be designed to support older adults in establishing and maintaining activity routines.

5.1 Design for Flexibility

Our findings show that participants had diverse motivations for engaging in PA, whether for the benefits brought by PA, such as health and socializing, or the pleasure associated with PA, such as exercise itself and sensory experiences from the environment. However, these motivations changed as participants had reestablished or were reestablishing new PA routines following a permanently disrupted routine due to age-related changes to their physical abilities. Yet, transferring from their "younger" routines to new "older" ones was experienced as a long and challenging process, both physically and psychologically.

Age-related health problems pose physical impacts and restrictions on older adults' exercise habits, in terms of activity type and location, leading to a decline in voluntary PA [47]. Out of concern about falling and injury, an outcome that is of particular concern for community-living older women [58], many participants chose safe activities that they felt were suitable for their current capabilities, abandoning activities that they had previously enjoyed such as cross-country skiing and outdoor biking. Giving up their favorite exercise also meant giving up the pleasure they could get from doing the

exercise, which partly limited their motivation for exercising. It is totally understandable for older adults to make such a compromise, but deep down it is the lack of accessibility in some exercise that forces older adults to choose other safer activities instead. If those exercise could be designed to fit people with varying body conditions, older adults would be able to maintain their exercise routines that they have kept for decades, without having to go through reconstructing motivations and routines for remaining physically active.

Compared to those physical challenges, psychological challenges were subtle, mostly invisible, and thus often-neglected barriers in the process of routine reconstruction. Reestablishing routines often required a shift in expectations, redefining success from performance improvement to a more subtle slowing of decline. Except that both older and younger adults could be motivated by enjoying PA and feeling good after PA [32,60], their specific motivators varied. While research has found younger adults to be motivated by appearance [38,60] and stress management [32,38], our findings suggest older adults may find more encouragement in the aesthetic experience created by peripheral stimulators in the environment, such as visual stimulations including scenery of nature and street views as well as auditory stimulations including music. From the pursuit of enhancement among younger people to the preferences toward aesthetic experience in PA [65], the changes of motivation across age groups imply that some older adults have to relinquish a part of their earlier primary motivators such as enjoying their preferred exercise and rely more on secondary motivators. It requires additional mental efforts not only to bid farewell to favorite activities and old "younger" routines but also to restore motivations and establish new "older" routines. More often than not, their secondary motivators may not be strong enough to sustain their reconstructed routines. As their routines and motivations changed, participants' perspectives also changed as to what counted as PA. Some participants began to accept walking as a form of exercise, while others adopted a more holistic view that included managing daily life and doing housework as exercise. Regardless of the type of exercise, what is beneficial for health is moderate- to vigorous-intensity aerobic activity that increases heart rates and makes people breathe harder, as suggested by PA guidelines for older adults [62]. Thus, it is important to guide older adults to choose appropriate activities based on both older adults' preferences and activities' potential health benefits.

Given that later life was experienced as a transformative stage where PA routines, motivation, and perspectives needed to be renegotiated, participants experienced difficulty navigating this process and required more support to guide them in identifying, selecting, and learning suitable activities. Activity promoting technologies should have the flexibility of adapting to the shift of perspectives and motivations, allowing older adults to define their own PA routines, in terms of what it means to be physically active. Since older adults tend to assign different meanings to PA engagement, it is important for technologies to respect older adults' views towards PA and the part PA plays in their lives. Given that a wide range of activities, from attending exercise classes to doing housework, is regarded as exercise by this group, technologies need to provide such diversity of options. Yet, current technologies tend to be tailored to a narrow set of activities of the sort prioritized by younger users (e.g., running, cycling, swimming) and are unable to accurately track some of the 'safer' activities chosen by our participants. Even for walking, systems tend to be less accurate in tracking data from disabled users [72] and thus may underreport activity for older adults. Thus, more work is needed to investigate how to not only accurately measure specific activities but also comprehensively measure a variety of activities.

Due to the difference in goals and motivations for PA between younger and older adults, some PA promoting approaches preferred by the former may not work for the latter. We suggest that technologies for older adults could employ more defensive and neutral behavior change strategies rather than more offensive ones. For example, social comparison and competition strategies could encourage younger adults to engage in more activities, but those strategies may be too aggressive to match to older adults' physical capabilities and goals. Because of the vast diversity of PA levels among older adults, comparing performance or competing with other people might push individuals out of their PA comfort zones and

cause anxiety or injury. Past research has pointed out that social comparison is regarded by older adults as demotivating and may provoke feelings of embarrassment and distress if lagging behind others [33]. Rather, it would be safer and more encouraging for older adults to compare with themselves and improve based on their own capabilities, instead of others'. Accordingly, technologies could use strategies such as self-monitoring and personalization to remind older adults of their progress, along with reward and praise to celebrate their completion of activity routines.

Flexibility in those higher-level strategies requires lower-level system features to be individualized according to older adults' motivations for PA. Rather than measuring users' PA by step counts, the distance walked, and the time used as prevalent activity trackers do, future technologies could integrate PA into visual and auditory stimulations and then measure users' achievement by the pleasure enjoyed, e.g., how many interesting blocks they have walked and how long they have listened to music. By focusing more on the pleasure associated with activities than individual performance, personalized metrics could be helpful especially for those with little interests in PA. Prior research has looked at how pleasure could be implemented throughout the visualization of PA data [70], which might motivate older adults to engage in more activities and thus enhance the PA performance. Here our findings highlight that pleasure as a catalyst to PA engagement may not be sustainable and would gradually fade away, leading to reduced exercise. This suggests that older adults need sustained interests and pleasure to maintain their exercise routines in the long run. Thus, future technologies need to not only emphasize the pleasure associated with PA but also update the pleasure from time to time to sustain older adults' motivation. For example, music playlists need to be frequently updated if a system measures PA by how many songs users enjoyed while exercising.

5.2 Design for Resilience

Our findings show that participants frequently encountered intermittent disruption to their routines due to changes in personal and environmental circumstances. Older adults tend to have established life routines, where other important things would be prioritized over exercise when schedule conflicts occur. On top of that, older adults' activity plans and needs change as their health conditions change frequently and often unexpectedly. Because of their evolving health, older adults tend to be more cautious of the potential detriment from the environment to their health, and their PA routines are often influenced by season and weather. This is particularly true for our participants who all lived in Greater Montreal, a region with long and snowy winters, with some participants reporting little PA engagement in the winter and being limited to home-based exercises, a finding that has been reported by others as well [49]. COVID was also a source of disruption from the environment. While the study was conducted after COVID-related restrictions were relaxed, participants still carried lingering concerns. Many were still avoiding public exercise facilities and equipment (e.g., swimming pools and treadmills) due to the fear of infection but had not found safe and convenient alternatives. Some shifted to exercising at home but couldn't find suitable exercise or lacked the ability to purchase equipment to maintain a successful home-based routine, as shown in past work as well [54]. The duration of the pandemic had also led some participants to become habituated to an inactive lifestyle. In comparison, a prior study reported that older adults who used digital technologies to support PA during the pandemic were able to remain physically active because technologies helped them adapt to changing circumstances and physical conditions, which highlights the potential of older adults employing technologies to navigate the changes [30].

Therefore, PA promoting technology should be resilient in response to changing circumstances and needs, with the ability of adapting to changes and supporting maintaining PA routines. While past research also suggests design for resilience to support older adults' agency and competence of using learned knowledge to deal with encountered problems [52], here we focus more on how technologies could support restoring disrupted PA routines. Above all, reestablished PA

routines should be fitted into older adults' established overall life routines, instead of revolving other schedules around exercise. Hence, PA promoting technologies could be combined with personal calendars, for instance, so that they would be able to automatically reschedule when planned exercise has to give place to a more important appointment. When it comes to deciding specific PA routines, technologies need to be designed from an alternative perspective to enable older adults to take control over their own routines and change their daily PA goals easily, since only older adults themselves know how much PA would be appropriate for them on a certain day. This echoes with prior studies indicating that older adults prefer to listening to their own bodies and determine suitable PA types and amounts [71] as well as setting goals by themselves [15]. For instance, technologies employing goal-setting features could encourage setting flexible goals on weekly basis (e.g., lifting weights three times a week), rather than planning specific exercises on daily basis (e.g., lifting weights on Mondays). Moreover, technologies need to be contextual and sensitive to potential environmental risks. While past research suggests technologies to take contextual cues and nudge users to exercise [59], it is more important for technologies to tell older adults not to exercise or recommend alternative activity options when the environment is not appropriate for following regular routines, e.g., suggesting stretching at home instead of walking outside on snowy days.

5.3 Design for Connection

Our findings demonstrate the role social interaction can play in facilitating PA engagement for older adults through the creation of commitments to and motivations for PA, which are especially needed for those living alone who could be less motivated to engage in PA. Commitment in this context is an external stimulus from something or someone to sustain motivations, such as exercise classes, encouragement from others, socializing with friends, and having partners to exercise with. Furthermore, having other people to follow up the progress could reinforce the commitment, in that it could not only prioritize PA in participants' daily lives but also provide psychological support through personal contact. For example, participating in this study was regarded by most participants as a commitment; taking notes of their daily activities helped them be more conscious of their own routines; and returning the diary to the researcher motivated them to stick to this commitment. Just being aware of that someone was there observing their activity routines could strengthen the power of the commitment and motivate most participants, especially those with less interest in PA, to maintain physically active, suggesting the potential of applying social commitment to PA promotion.

The diary study illustrates how a combination of different motivators and behavior change strategies—joining a program as a commitment, diary as a tracking tool (i.e., self-monitoring), and personal contact as a reinforcer (i.e., social support)—work together in real life. It needs to be noted that the social support from personal contact in this case goes beyond the seven design principles (i.e., social learning, social comparison, normative influence, social facilitation, cooperation, competition, and recognition) included in the social support category of the Persuasive Systems Design framework [55], since the researcher was more like a neutral observer, without getting involved in participants' activity routines or providing any active support in the sense of the framework. Rather, the effects of social support in this case are closer to the principle of surveillance included in Fogg's persuasive technology tools [21], though it was not our original intention to use this principle. Given its obvious social characteristics, here we regard the commitment as a specific type of social support.

However, the lack of commitment is found to be a barrier to PA for many participants, especially for older adults living alone during the COVID-19 pandemic. The restricted social interaction during the pandemic had limited creating a variety of social commitments, reducing the opportunities of PA associated with it, posing negative impacts on our participants both physically and psychologically. Some participants seemed to experience social isolation, in the form of social disconnectedness (e.g., small social network, infrequent participation in social activities) and/or perceived isolation (e.g.,

loneliness, perceived lack of social support), both of which are associated with worse physical and mental health [16], resulting in reduced everyday physical activity and increased sedentary time among older adults [64]. The deterioration of physical conditions and the presence of psychological symptoms were prevalent among the older population during the pandemic [43], partly because disruption in the access to social support could worsen mental health [67], which is particularly true for those living alone [27].

To enhance social interaction, technology has shown the potential to cultivate relationships among older adult through offering different ways and opportunities of social engagement, alleviating loneliness and social isolation [4,13,36]. In particular, prior research suggests using technology to strengthen existing meaningful relationships, rather than fostering new friendships towards which older adults are less motivated [45]. However, this may not hold completely true for those living alone, as some participants explicitly expressed the need of building new exercise-partnership and developing social commitment, where technology can also play a part by helping older adults build new social connections [74].

The importance of social support in PA promotion and maintaining exercise routines has been manifested in prior research [54]. Through interacting with others (e.g., fellow exercisers, health practitioners, and researchers), older adults could foster a sense of belonging and togetherness which contributes to adherence to PA [10,37] and decreasing perceived feelings of loneliness or social isolation [31]. Moreover, incorporating social support features such as engaging with friends in technology is suggested to be a promising approach to promoting PA for older adults [26]. Since both our diary study and prior research show the key role of human contact in older adults' communication preferences, it is recommended to supplement technologies with face-to-face contact [24]. Hence, we suggest that future PA promoting technologies could exploit older adults' current social network and involve their friends and family members in creating commitments to PA engagement, for example, inviting their friends to follow up with their everyday activities. Future technologies could also support older adults in expanding their social connections and finding exercise partners based on location and exercise levels. When new virtual connections are established and potential exercise partners are found, technologies could encourage them moving from online to offline interaction and exercising together in person.

Despite its stimulating effects on maintaining activity routines, social commitment might introduce additional disruption to older adults' life routines. Although many participants would like to have exercise partners and agreed the motivating effects of exercising with others, they also worried that such commitment might be so strong that it would interfere with their planned schedules. In particular, some participants highly valued the benefits of living alone such as taking control over their own lives, without having to coordinate with others' routines. Such attitudes towards finding exercise partners echo older adults' communication preferences that they wish neither being burdensome and intrusive to others nor others intruding on them [45]. This highlights that when employing the social commitment strategy, technologies need to balance between the rigor of commitments and the (in)flexibility of users' schedules and fit new activity routines into older adults' overall life routines, aiming for greater resilience in response to other disruptions (as discussed in 5.2).

5.4 Design in a Holistic Approach

During the process of reconstructing and maintaining PA routines, our participants frequently encountered a series of barriers from personal, interpersonal, environmental, and social factors. These multidimensional barriers are often intertwined and interrelated with each other, which makes it a more complex problem than it seems to be. In some cases, as exhibited in our findings, participants knew the answer to the problems of how to get themselves more motivated to engage in PA, but the answer itself became another problem because it gave rise to other problems that would be hard to solve. For instance, some participants were aware that having exercise partners could encourage them to exercise more, yet they worried whether the partners would have similar exercise level as them, whether they would have mutual interests

to chat about, and whether such commitment would lead to schedule conflicts and interfere with their established life routines. Some participants would like to engage in exercise, but they had limited budget to have access to suitable programs nearby. Some participants were aware of online exercise resources, but their limited technology knowledge and skills prevented them from accessing those resources. In other words, older adults have to persistently overcome a series of interrelated barriers, rather than individual barriers, to maintaining their PA routines. It is the interplay of those multidimensional barriers that makes remaining physically active a big challenge.

However, current PA promoting technologies tend to focus on addressing individual barriers, while overlooking the interplay between different barriers. Self-monitoring, for example, is a primary feature of activity trackers and can help increase older adults' awareness of their own PA behavior [18]. It is true that awareness of PA is essential for promoting motivation for PA, but it is not sufficient for older adults to actually engage in PA, since other disruptors, such as bad weather and busy schedules, are very likely to become additional obstacles preventing older adults from realizing the motivation. Similarly, prior study showed the potential of technology leveraging social support strategy through coordinating activities with close friends [26], but close friends may not be suitable exercise partners for older adults because their exercise levels might vary greatly. When designing technologies and evaluating designed technologies, past research tends to focus on whether and how their proposed solutions can solve individual problems (e.g., [20]). This simplified approach may account for why current technologies are limited in meeting older adults' multidimensional needs with respect to maintaining PA routines.

Therefore, we suggest that future PA promoting technologies should be designed in a holistic approach. During the design process, designers could employ participatory design method [46] to uncover and prioritize potential barriers pertaining to a specific problem scenario, instead of focusing on a single barrier, before incorporating all the important disrupting factors into design. For example, when it comes to supporting older adults finding suitable PA resources, online databases aggregating senior-oriented PA programs and information could be categorized by health condition [48], location, and costs [29], which are potential barriers to PA engagement for older adults. Furthermore, convenience and inexpensive access to PA programs may be not enough, as older adults often need more incentives to take the next step of enrolling and regularly participating in the programs [6]. To this end, creating social commitment, whether to health care providers [6] or family members, would help older adults sustain their motivation of attending programs. In addition, we acknowledge that a holistic design approach cannot address the PA promotion issue comprehensively, since it requires multidimensional efforts, particularly at the environmental and social levels (e.g., through the development of free exercise facilities and safety focused enhancements to the built environment), to solve multidimensional barriers.

5.5 Limitations and Future Work

Since the study was conducted in the winter when COVID and flu were prevalent, the impacts of winter weather and COVID on participants' activity routines were more frequently mentioned than they would have been if the study had been conducted earlier or later. Although our diary activity exhibited positive effects on improving participants' PA levels, it is uncertain whether such effects were sustainable as we did not include a follow-up to check for long-term effects. Also, our life experience might limit us from fully understanding older adults' concerns and challenges in terms of health and financial position. It is noteworthy that since our study focuses on older adults living alone, it remains unclear what influences living alone exerts on PA engagement. Hence, a comparative study using the same methods could be done in the future to focus on older adults living with others, understand their barriers to PA engagement, and examine whether the findings and design implications from this study could apply to older adults in general, especially whether social commitment is also needed by those living with others, who tend to have more social connections than our target group.

6 CONCLUSION

This study explored the barriers older adults living alone encountered to remaining physically active, uncovering design opportunities for future technologies to better support older adults' exercise needs. Our thematic analysis of interview transcripts and diary notes revealed that our older adult participants held diverse motivations for PA, but they experienced frequent disruptions, both intermittent and permanent, to maintaining their PA routines, due to evolving health circumstances, changing environmental conditions, a lack of stimuli to sustain motivations, and limited access to suitable PA resources. These barriers were multidimensional and often intertwined, which further hindered older adults recovering from disrupted exercise routines. We discussed how future technologies could leverage social support to develop commitments to PA. We also suggested that future technologies should be flexible to allow older adults to define their own exercise routines, resilient in response to changing circumstances, and designed in a holistic approach to take the interplay between those barriers into consideration to navigate older adults through establishing and maintaining activity routines.

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