SAIF: a System for Long-term Assessment and Intervention of Frailty with Gamification

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Abstract

Frailty refers to a state of high vulnerability to adverse health-related outcomes, in particular, disability, hospitalization, institutionalization, and mortality. It is a common condition in the ageing population that is increasingly prevalent and represents a public health priority for multiple reasons. Besides affecting the quality of life of the individual, frailty also severely threatens the long-term sustainability of health care systems. It is necessary to redesign models of care to render them more responsive to the unmet clinical needs of the growing frail population worldwide.

Frailty may represent a transition phase between successful ageing and major negative health-related outcomes, and a condition to target for restoring robustness in the individual at risk. Early intervention has the potential to improve frail individuals' quality of life, and reduce healthcare and social costs. Given its syndromic nature, targeting frailty in its early state at a population-level requires a comprehensive approach. However, most current frailty assessment and intervention programs are conducted in clinical settings, which is neither scalable nor sustainable. Their costs may also be unaffordable to a significant portion of the older adults.

In this paper, we propose a first-of-its-kind System for Assessment and Intervention of Frailty (SAIF) to reduce the risk, and at the same time delay or decelerate the progress of frailty. SAIF is an end-to-end system that covers both frailty assessment and intervention. It provides a range of multi-domain computerized assessments, which can help to unobtrusively assess the potential risk of prefrailty and frailty in home and community environments. Based on the risk assessments, SAIF delivers holistic and individualized interventions, including physical exercise, nutrition recommendation, and polypharmacy management. In interviews and focus group studies conducted with health professionals, caregivers, and older adults, we received positive feedback on the design of the SAIF system. We plan to evaluate its reliability and effectiveness in real-world community settings in subsequent studies.

Keyword: frailty; early detection; intervention; computerized tests; gamification.

I. Introduction

Frailty refers to a multi-dimensional syndrome which may include physical, psychological, cognitive, and social impairments. It is a strong predictor of major negative health-related outcomes in older adults, in particular, disability, dependency, hospitalization, institutionalization, and mortality [14]. The challenges in finding a generally accepted definition for frailty makes it hard for estimating its accurate prevalence. However, the American Medical Association has reported that more than 40% of adults aged 80 years and older are frail [1]. The prevalence of prefrailty and frailty among community-dwelling older adults worldwide is reported to be 42.3% and 17%, respectively [4]. There is consistent evidence across studies for an increasing prevalence of frailty with older age [27]. The number of frail people is expected to rise rapidly due to population ageing, highlighting its salience as a public health priority.

Frailty is believed to represent a transition phase between healthy ageing and adverse negative health-related outcomes, and is therefore an attractive target condition for restoring robustness in at-risk individuals [4]. Early intervention has the potential to improve the quality of life of frail individuals and to reduce healthcare and social costs [10]. Prior studies have demonstrated the effectiveness of intervention programs to improve health outcomes in prefrail and frail patients [3, 5, 17, 25]. However, many of the current frailty assessment and intervention programs are conducted in clinical settings, which is neither scalable nor sustainable. Their costs may also be unaffordable to a significant portion of the older adults.

In this paper, we propose an end-to-end System for Assessment and Intervention of Frailty (SAIF) to reduce the risk, and at the same time delay or decelerate the progress of frailty. Leveraging on Internet-of-Things (IoT) devices and human-machine interactions to gather user behavior data as well as data-driven artificial intelligence (AI) technologies, SAIF can help to unobtrusively assess the potential risk of prefrailty and frailty in home and community environments, which can complement existing clinical assessments. Based on such risk assessments, SAIF can then produce customizable, adaptable, and personalized intervention plans, including physical exercise, nutrition, and polypharmacy management, to maximize their effectiveness. As the first step in evaluating SAIF, we conducted interviews and focus group studies to evaluate it. The participants include professionals, caregivers, and older adult users. The participants generally hold positive attitudes towards the SAIF and believe that it has the potential to help predict the risk of frailty and decelerate the progression of frailty.

To the best of our knowledge, the proposed solution is the world's first community- and home-based system for both assessment and intervention of frailty. Owing to its cost-effectiveness, SAIF is more accessible and affordable, enabling frailty assessment and intervention at home and in communities in a scalable manner. It can also help to deliver more personalized interventions and introduce a paradigm shift from traditional reactive intervention to predictive and proactive intervention.

The rest of the paper is organized as follows. Section II reviews the relevant background on frailty and existing assessment tools and interventions for frailty. Section III introduces the design of SAIF and the modules in it. Section IV outlines the plans to evaluate SAIF and presents the results from interviews and focus groups. Finally, section V concludes the paper.

II. Literature Review

Despite attracting great attention in the geriatrics field, there is no generally accepted definition of frailty [2]. Frailty, a state of high vulnerability for adverse health outcomes, is not considered a disease, but rather a syndrome requiring a multidomain and multidisciplinary approach. This is because the presence of frailty may represent the manifestation or consequence of multiple concurrent factors rather than resulting from a single cause [4]. Fried et al. proposed a definition of frailty that characterizes it as an independent phenotype differing from co-morbidity and disability [15]. According to their definition, frailty is a clinical syndrome constituted by the co-occurrence of at least three of the following five criteria: unintentional weight loss, exhaustion, weakness, slow walking speed, and low physical activity.

The predictive value of frailty for negative outcomes is consistently confirmed across assessment instruments, target populations, and settings. The increased risk of negative health-related events includes falls, hospitalizations, disability, institutionalization, and mortality [6, 13]. However, the progression of frailty varies from individual to individual and it is capable of change. Evidence from previous studies suggests that frailty (especially at its very earliest stages) might present characteristics of reversibility. In a study by Gill et al., among the 754 participants, 57.5% had at least 1 transition between any 2 of the 3 frailty states (robust, prefrail, and frail) during the 54-month follow-up period [17]. In the first 18 months of the study, among participants with frailty at baseline, 63.9% remained frail, 23.0% improved to a state of prefrailty, 13.1% died, and none reversed to robustness; 11.9% of prefrail participants at the baseline regained a robust state by the end of the follow-up. Similar findings were reported in another study by Borrat et al. [3], where 32.4% of prefrail participants recovered to a robust state after 2 years of follow-up. These study results support that the identification of frailty at its early stage is pivotal for implementing effective interventions to restore robustness in the individual at risk.

We first review existing approaches to the assessment and identification of frailty. Nowadays, a plethora of frailty assessment tools exist, from short screening instruments to sophisticated, time-consuming assessments. Despite a lack of agreement on reference standards for measuring frailty [7], there are some instruments that are more commonly adopted than others. The landmark Frailty Phenotype instrument was devised by Fried et al. [15]. It assesses frailty by measuring five components in the definition of frailty: unintentional weight loss, exhaustion, weakness, slow walking speed, and low physical activity. Another rapid screening tool is the FRAIL, which screens for frailty using 5 simple questions [24]. Another popular tool is the Frailty Index (FI) of accumulative deficits by Rockwood, Mitnitski and colleagues. FI incorporates the multi-dimensional nature of frailty into an operational definition [23]. Although widely used for research purposes, it requires information from a fairly comprehensive geriatric assessment to compute the FI and hence may not be feasible in certain settings. An alternative to the FI which was developed by the same group is the Clinical Frailty Scale (CFS) [26]. This is a well-validated global assessment scale that allows frailty to be graded using simple clinical descriptors synthesized from routine clinical assessment. Another simple yet effective predictive tool for frailty proposed by Verghese et al. is the Walking While Talking (WWT) test, which is a motor-cognitive divided attention task requiring individuals to walk while reciting alternate letters of the alphabet [29].

There are a number of issues with existing frailty screening and assessment tools. First, most of them are conducted by medical professionals in clinical settings such as hospitals or outpatient clinics, which are resource intensive. Second, most tools are reactive rather than proactive, i.e. the assessments are only conducted if the elderly is already exhibiting some symptoms.

Once a prefrailty or frailty diagnosis is confirmed, different interventions can be offered to the patient. The critical time window for interventions that target frailty has not yet been clearly established. On a spectrum from prefrailty through frailty to disability, it is often assumed that early intervention to prevent the onset of disability is crucial and optimal; however, that is not to say that established disability cannot be reduced, or its progression slowed, or its impact on the older person and his or her caregivers mitigated [4]. In the past, many studies have shown consistent evidences that different interventions can improve health outcomes in prefrail and frail patients [3, 5, 17, 25]. However, there is still a lack of scientific agreement on ``gold standard" interventions for frailty. A first step towards that was made through the recently released Asia-Pacific clinical practice guidelines for the management of frailty, in which five evidence-based interventions are recommended: (i) physical exercise (including resistance training), (ii) reduction of polypharmacy, (iii) screening for reversible causes of fatigue, (iv) caloric and protein support, and (v) vitamin D supplementation [7].

However, these interventions still mostly rely on the medical professionals' instructions and guidance. One exception is Geraedts and colleagues' personalized home-based exercise program for frail elderly [16]. This continues to be an active area for research, exploring the role of home- and community-based models of care, individual-tailored multi-component interventions, and various approaches to integrated case management.

Based on our literature review, we summarize the key desirable characteristics of an effective frailty assessment and intervention system as follows:

- Providing multi-domain and multidisciplinary approach assessment: since it is unlikely that a single cause underlies the presence of frailty, a comprehensive assessment should follow the initial suspicion to identify and treat the underlying causes of frailty.
- Providing personalized intervention: the progression of frailty varies from individual to individual and it is capable of change. Interventions for frail older adults need to include treatment of progressive weakness, weight loss, decreased exercise tolerance, slowed task performance (i.e., walking speed), and/or low activity. Training activities, such as resistance and muscle strength exercises, often involve physical components, which needs to be individualized to ensure safety and effectiveness.
- Supporting long-term and self-administered assessment and intervention: frailty is characterized by wide fluctuations of health status and high risk of acute complications that can interrupt the

recovery program and negatively impact the functional progress. Intensive and frequent assessments in long-term, aimed at monitoring acute fluctuations in health status, may allow more effective intervention and strongly affect the prognosis of frail older adults.

III. The Components of SAIF

In this paper, we propose an end-to-end system, named System for Assessment and Intervention of Frailty (SAIF), to reduce the risk and to delay or decelerate the progress of frailty. Specifically, SAIF provides a set of comprehensive multi-domain assessments. By performing predictive analytics on performance trajectory data collected from the assessments, SAIF would predict the risk of an older adult in transiting between any 2 adjacent frailty states, i.e. transitions from robust state to prefrail and/or from prefrail to frail. Based on the identified risk, SAIF would subsequently formulate personalized adaptive intervention plans based on best medical practices and patient profile. SAIF explores a new model-of-care for at-risk and frail older adults, through providing assessment and intervention at home and in the community, thereby reducing the burden on existing healthcare infrastructures.

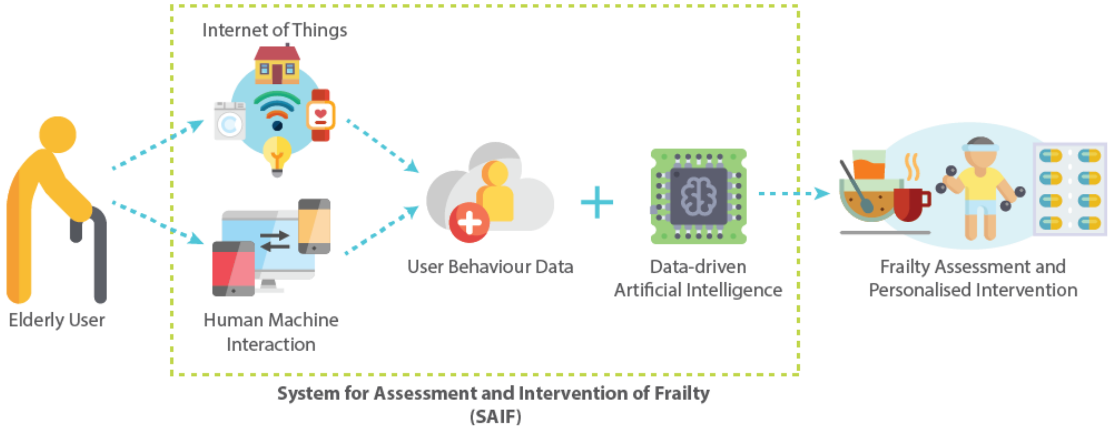

Figure 1 Key technologies powering SAIF

Figure 1 provides an overview of the key technologies employed by SAIF. SAIF makes use of Internet-of-Things (IoT) devices and human-machine interaction technologies to gather user behavior data. Such data would then be analyzed with data-driven artificial intelligence (AI) technologies, enabling SAIF to unobtrusively assess the potential risk of frailty and prefrailty and to provide personalized interventions.

SAIF comprises 8 modules, as shown in the conceptual diagram in Figure 2, which are split across three overarching categories: interface modules, assessment modules, and intervention modules.

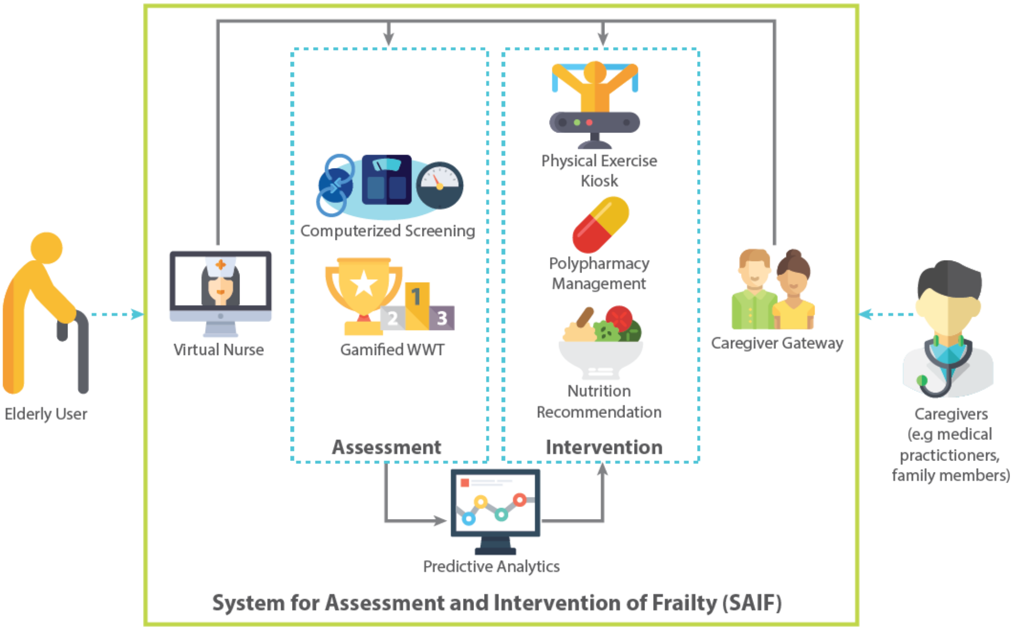

Figure 2 Conceptual framework for the proposed SAIF

The **interface modules** act as the gateway between users and other modules. The *Virtual Nurse* module, acting like a human nurse, interacts with older adults to schedule assessments, deliver interventions, provide all-round care, and offer suggestions. The *Caregiver Gateway* module interacts with caregivers, including medical professionals, family members, and community workers, as a tool for monitoring the status of older adult users and managing their intervention plans.

The **assessment modules** provide a range of multi-domain assessments, aiming at assessing each and every physical component of frailty. The *Computerized Screening* module digitalizes well-established frailty screening instruments for easy self-administration. It comprises a number of assessments, such as weight measurement, grip strength, and activity questionnaires. The *Gamified Walking While Talking* is a self-administered version of the Verghese's Walking While Talking (WWT) test. The user can perform this test alone instead of being assessed by a medical professional. The data collected by *Computerized Screening* and *Gamified WWT* is used by the *Predictive Analysis* module to generate frailty risk predictions.

The **intervention modules** deliver holistic interventions from different aspects, including physical exercises, medication management, and nutrition recommendation. The *Physical Exercise Kiosk* module is a kiosk housing two serious games, Taichi for exercising upper limbs and balance and Cycling for training strength of lower limbs. The *Nutrition Recommendation* module helps to record users' daily nutritional intake and provide individualized nutrition recommendations. The *Polypharmacy Management* module helps users to manage their medication and supplement intake, aiming at improving medication adherence and monitoring adverse drug events. In the remaining part of this section, we will introduce each of the modules in greater details.

A. *Interface modules*

Virtual Nurse

The Virtual Nurse module is the main interface for interactions with the older adults. Through its embodiment as a human-like virtual nurse, it provides more natural, familiar, and elderly-friendly human-agent interactions. This module is in charge of coordinating and facilitating the assessment and intervention offered by the other modules in SAIF. To maximize overall effectiveness of SAIF, the Virtual Nurse employs AI planning strategies [8] and is equipped with situation awareness capabilities [9]. Based on motivation and persuasion theories such as Elaboration Likelihood Model (ELM) [18], the Virtual Nurse also acts as a motivating companion to provide positive and encouraging messages to promote participation in the assessment and intervention plans. The Virtual Nurse is also empowered by artificial curiosity [31] to detect unusual interaction patterns and behavioral abnormalities, and to delve deeper into identified problems (e.g. inquiring about potential reversible causes of fatigue).

To support smooth and effortless human-agent interactions, the Virtual Nurse is designed with consideration of important human factors such as familiarity [28] and age-friendliness [22]. One major challenge is to design user interfaces the older adults can comfortably interact with, including to provide suitable communication medium and language support. Following the advises from healthcare professionals, speech is used as the primary medium and text as the secondary medium due to the relatively low literacy among the local older adults. All conversations are conducted in speech, accompanied by the corresponding text displayed on the screen of smartphones and tablets. In addition, users can press buttons and type text (optional) on the screen to interact with the Virtual Nurse. In terms of language support, the Virtual Nurse supports Mandarin in addition to English.

Caregiver Gateway

The Caregiver Gateway module is the main interface for caregivers (including medical professionals, community caregivers, and family members) to interact with the platform. It has three main purposes: 1) enable caregivers to view information about a patient (e.g. intervention regimen adherence, assessment results, etc.), 2) enable caregivers to input parameters for intervention planning purposes (e.g. a medical professional may wish to specify parameters based on a patient's particular condition, or a family member may wish to include objective information about a patient's routine), and 3) automatically provide alerts to caregivers in case an abnormal situation is detected (e.g. a patient is suspected of suffering from frailty). Data visualization techniques [30] are used to clearly display relevant data in a simple and informative manner.

B. *Modules for Frailty Assessment*

Computerized Screening

The Computerized Screening module aims to transpose standard frailty screening instruments into a self-manageable process. Following the Frailty Phenotype and FRAIL instruments [24], it measures six distinct physical components of frailty: fatigue, weak strength/resistance, difficulty in ambulation, illnesses, low physical activity, and loss of weight.

By leveraging both the literature review findings and discussions with healthcare professionals, a set of multi-domain assessments are carefully selected and designed for the Computerized Screening module, as shown in Table 1. For objective measures such as weight and grip strength, smart Internet-of-Things (IoT) devices are designed and developed to automatically send measurements to the back-end server. These IoT devices are placed in home and/or community settings to ensure ease of access as well as automatic and reliable data collection. For walking time measurement, a mobile application tapping into the device's embedded sensors is designed and developed to track the walking time within a designated distance.

Table 1 Design of the Computerized Screening Module

Component of frailty	***How to evaluate***
Shrinking, loss of weight	Smart weight scale
Weakness, resistance	Smart grip scale
Poor endurance, fatigue	Questionnaire by Virtual Nurse
Slowness, ambulation	Mobile App with sensors
Low physical activity level	Questionnaires by Virtual Nurse
Illness	Questionnaires by Virtual Nurse

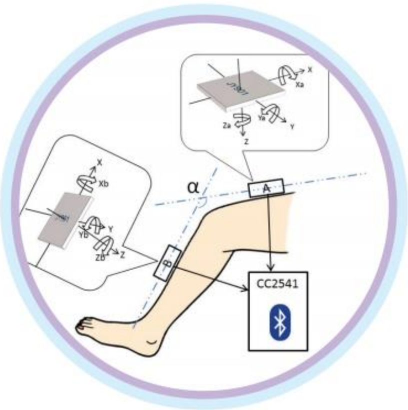

Figure 3 Wearable system designed for Gamified WWT

For subjective measures such as fatigue, physical activity level, and illness, relevant questions will be intelligently delivered through the Virtual Nurse. The older adults could answer questionnaires using traditional methods (e.g. text-based entry) but also using natural language (through speech processing powered by Natural Language Processing techniques) as if talking to a human nurse. Moreover, to make the evaluation procedures less tedious and more entertaining, all assessments are wrapped into a game scenario, which can transform the repetitive and tedious evaluation procedure into a more entertaining and engaging experience.

Gamified Walking While Talking (Gamified WWT)

The Gamified WWT module is a gamified version of the Verghese's Walking While Talking (WWT) test for predicting frailty conditions. It aims to embed the Verghese's WWT test within a game scenario and environment, thereby enabling unobtrusive assessment of the potential risk of frailty and pre-frailty in the community settings, instead of clinical settings, in a fun and engaging manner. The Verghese's WWT normally comprises two trials. The test subjects first walk at a normal pace through a walkway of at least 5 meters, after which walk through the same walkway again while performing a cognitive task, such as counting numbers or naming animals. The Gamified WWT is also designed with these two trials.

The Gamified WWT uses wearable sensing devices together with a smart phone to measure and record the performance of both walking and cognitive tasks. The wearable sensing devices form a wearable system which is embedded in a pair of knee sleeves and can be worn on the legs. The system measures the motion of lower limbs in high accuracy and frequency to obtain the users' gait patterns. More specifically, the wearable system comprises 2 three-axis accelerometers and three-axis gyroscopes on each leg as in Figure 3 and measures angles and speed of joint movements of each leg. The smart phone provides detailed instructions for users to perform the Gamified WWT. Moreover, the smart phone measures the walking distance in real-time using Near Field Communication (NFC) chip sensors and records voice input when elderly users provide answers to the given cognitive tasks.

To cover both entertainment and assessment purposes, serious game design methodologies [21] are adopted for designing and developing the Gamified WWT module. Over time, multi-dimensional in-game data will be collected and fed into the Predictive Analytics module for predicting frailty status.

Predictive Analysis

The Predictive Analytics module aims to predict the risk that a user would progress from a robust state to pre-frail and/or from pre-frail to frail. To increase the accuracy of the predictive analytics, we adopt a hybrid model that combines the domain expert knowledge provided by medical professionals and advanced AI analytic techniques such as deep learning [20] and explainable AI [11, 12].

The inputs to this module include the following four data sources: 1) users' activity data captured by the Internet-of-Things (IoT) devices and through self-reports, 2) users' health-related data captured by the Computerized Screening module and through self-reports, 3) users' game-play performance captured by the Gamified WWT module, and 4) the domain knowledge adopted from healthcare professionals.

After data collection, the Predictive Analytics module first cleans the heterogeneous and conducts data fusion. Furthermore, high-level features will be extracted and used for the identification of differences in stratified user groups. Such stratification is not predefined (such as robust, pre-frail, and frail), but autonomously performed using unsupervised clustering techniques by comparing the individual difference. Supervised classification methods will also be used to build the frailty prediction model. The importance of different data sources in the generated frailty prediction model will be studied. In addition, we also plan to incorporate doctors' domain knowledge into our frailty prediction model to improve its accuracy. To help users, health professionals and caregivers better understand the prediction results, explainable artificial intelligence (XAI) techniques will also be integrated into the predictive analytics framework.

C. *Modules for Frailty Intervention*

Physical Exercise Kiosk

The Physical Exercise Kiosk module is a kiosk housing two serious games, Taichi for exercising upper limbs and balance and Cycling for training strength of lower limbs. The kiosk is designed to be used in community settings with minimal supervision. The game themes have been carefully selected to cover comprehensive physical exercises purposes and designed to provide both fun and therapeutic efficacy. Moreover, various human factors design elements, such as popularity, familiarity, efficacy, motivation, and preference, have been considered during game design. The kiosk also supports multi-player modes to promote social engagement and peer competition, thereby increasing user engagement and enjoyment.

Taichi is a Kinect-based game promoting resistance and aerobic physical exercises. TaiChi is popular among older adults with Chinese cultural background. More importantly, it is an appropriate and safe balance exercise for frailty intervention. Kinect is a camera-based motion sensor which can sense the position and motion of different body parts and support full-body gaming experiences.

Kinect provides a more friendly game interface to the older adults and powerful motion capture capability that allows rich body motion data to be collected. The users practice Taichi movements by following the virtual Taichi master in the game. Users' movements are captured by Kinect and used to provide feedback and determine their game performance. The resistance exercises are carried out with the assistance of weights and elastic bands.

Cycling wraps cycling exercises into a tablet-based game, which provides virtual contexts for the cycling activity. The user is represented by an avatar in the game environment and can navigate the environment by paddling the exercise bike, e.g., a fox wandering in an exotic desert landscape. Sensors are mounted on the exercise bike to track the speed of cycling, which controls the speed of navigation in the game environment. The tablet-game provides an interactive virtual environment which allows the user to received immediate feedback (e.g. paddle faster to navigate faster in game) and makes cycling less tedious but more interesting (e.g. changing landscape, picking game items).

Nutrition Recommendation

The Nutrition Recommendation module aims to provide suitable dietary health suggestions to users based on the analysis of their daily food intake and the nutrition intake recommended by health professionals. Users' food preferences are learned by the module and subsequently used to make personalized food recommendations that may simultaneously appeal to their palate and satisfy nutritional expectations.

The Nutrition Recommendation module is divided into three sub-modules according to the data flow pipeline, namely data inputs, recommendation model and recommendation results. Data inputs can be both internal and external data. Internal data include but not limited to 1) users' personal profiles, 2) users' food intake history, 3) unobtrusively collected daily living and behavioral data, and 4) frailty assessment data collected from Virtual Nurse, Computerized Screening and Gamified WWT modules. External data mainly comprise well-established relevant datasets. The major benefit of using external data is that the recommendation model can be built based on ample training samples instead of having a cold start.

In the recommendation model, the rule-based approach and the knowledge graph approach are combined to make nutrition recommendations. In addition, the domain knowledge provided by health professionals will be added to the recommendation model as prior information.

As for the intermediately obtained nutrition recommendation results, they are in the raw format such as a list of ranked nutritious food for individual users. Moreover, Explainable Artificial Intelligence (XAI) techniques are used to provide more natural and hopefully more persuasive recommendations.

Polypharmacy Management

The Polypharmacy Management module is a personalized system for managing medication and diet supplement intake. It comprises a software-based smart pillbox solution for tracking and managing adherence, as well as a diary function and a query engine for monitoring and managing side effects and inappropriate medication.

A software-based smart pillbox solution is designed to help users manage their medication and supplement regimen. Instead of relying on a single smart medicine dispensary machine, RFID technology is used for convenient tracking of medication consumption. To cater to the problem of unintentional non-adherence, a prospective memory agent is designed to provide personalized reminding services. It can autonomously determine the optimal settings for important aspects and variables in the process of reminding (e.g., the frequency of reminders, the type of messages to display, and the lead time before the event by when the first reminder should be initiated). To reduce intentional non-adherence, a persuasive agent [19] and an incentive agent are designed to motivate and persuade users. The reminders, persuasive and motivating messages generated will be delivered through Virtual Nurse.

The Polypharmacy Management module also includes an app-based diary for the users to record and self-report any side effects they experience before/after taking their medication and/or diet supplement. A comprehensive polypharmacy database is constructed based on information pooled and extracted from various common medicine and diet supplement databases. This polypharmacy database serves as an information repository, which archives necessary but simplified information understandable to older adult users. The users can initiate queries to check for possible contraindications between medications and/or diet supplements. Information collected by the diary and user queries could be shared with the associated healthcare professionals for their advice and guidance.

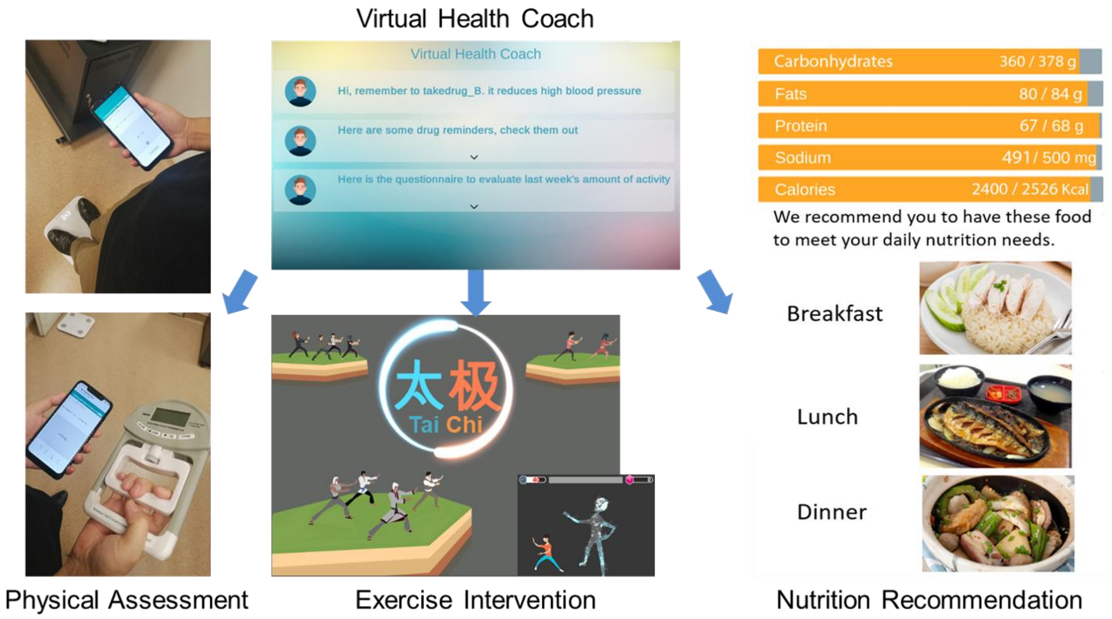

Figure 4 Interfaces of the SAIF modules

IV. User Study

A. Study Design

As our primary aim is to reduce the risk and delay and/or decelerate the progress of frailty, the main target population for the SAIF system is pre-frail older adults. Such a population is at risk of transitioning to a frail state and can thus benefit from predictive assessment and proactive intervention tools. Frail older adults may also use the SAIF system, provided that they are mobile, which is a necessary condition to be able to interact with the system. In their cases, the game performance collected by the assessment modules would not be used to predict the risk of frailty, but rather to track improvements following interventions. Finally, robust older adults may also benefit from using the proposed system, especially those who are close to clinical pre-frailty, as it can predict the risk that they would transit to a pre-frail status, and provide them with interventions in order to avoid such undesirable outcome.

In our study, participants will be recruited with the following inclusion criteria:

- Age 60 and above,
- Clinical Frailty Scale (CFS) [26] score of 4 or 5, or CFS score of 3 combined with a FRAIL score of at least 1.

CFS is a well-validated 9-point global assessment tool for frailty. A CFS score of 4 or 5 indicates that the screened subject is at the state of pre-frailty and mild frailty, respectively. A CFS score of 3 combined with a FRAIL score of at least 1 identifies robust subjects at higher risk of frailty. Selecting participants in this manner will ensure that we are targeting those who have the most to gain from our system, and thus more likely to demonstrate observable changes over a 12-month study. Robust participants (i.e. those with a CFS score from 1-3 and a FRAIL score of 0) may not demonstrate much change over a 12-month study. Similarly, frail participants (i.e. those with a CFS score of 6 or higher) may be too physically impacted to benefit from our system.

Table 2 Metrics used to evaluate the effectiveness of the SAIF system

Metrics	***Target***
Assessment: appropriate and efficient identification of pre-frail and frail older adults	
Concurrence with the Fried Frailty Phenotype instrument for identification of frailty and pre-frailty	Pearson's correlation coefficient of 0.8 or higher between SAIF and the Fried Frailty Phenotype for identification of frailty and pre-frailty
Concurrence with the Clinical Frailty Scale (CFS) instrument for identification of frailty and pre-frailty	Pearson's correlation coefficient of 0.6 or higher between our system and the CFS for identification of frailty and pre-frailty
Intervention: reduce the risk, delay and/or decelerate the progress of frailty	
Progression of frailty as measured by the Fried Frailty Phenotype instrument	The change in Fried Frailty Phenotype scores is at least 0.3 points higher in the intervention group compared to the control group on average
Physical performance as measured by the Short Physical Performance Battery (SPPB) instrument	The change in physical performance score measured by the SPPB instrument is at least 0.5 point higher in the intervention group compared to the control group
Cost-effectiveness: incurring fewer financial or manpower costs than traditional assessment and intervention tools	
Manpower savings for community screening	Reduction of time needed for community screening of frailty by 20% (with concomitant reduction in first-line manpower costs)
Quality: improving the quality of life of the target population	
Patient activation, measured using the Patient Activation Measure (PAM-13) instrument	Intervention group participants have an average improvement in PAM-13 scores of at least 4 points higher compared to control group participants
Health-related quality of life, measured using the EQ-5D-5L instrument	Improvement in quality of life measured through EQ-5D-5L of the intervention group is at least 4 points higher on average compared to the control group

In order to evaluate the effectiveness of the SAIF system, a number of metrics will be tracked at different phases of the system design and development, covering both objective and subjective measures. The SAIF system will be assessed in four aspects, as shown in Table 2: 1) assessment: appropriate and efficient identification of pre-frail and frail older adults, 2) intervention: reduce the risk, delay and/or decelerate the progress of frailty, 3) cost-effectiveness: incurring fewer financial or manpower costs than traditional assessment and intervention tools, and 4) quality: improving the quality of life of the target population. The scores obtained using well-recognized frailty assessment scales will be used as references to establish the reliability of the assessments made by SAIF and to measure the improvements in frailty conditions due to interventions in SAIF.

The proposed metrics will be collected through interviews and/or focus groups, a small-scale pilot study, and a larger-scale pilot study, as follows:

- At the end of the design phase, short interviews and focus groups were arranged to evaluate the proposed designs for each of the system's modules. The feedback was used to refine designs of the SAIF system before entering the development phase. 10 participants were jointly recruited by the Project Team and Implementation Partner, including medical experts, caregivers, and senior end users.
- A small-scale pilot study involving around 20 participants will be organized towards the end of the development phase. This pilot study will evaluate the system's usability and effectiveness in frailty assessment. Feedback gathered during this pilot study will be utilized to refine the developed system.
- A larger-scale pilot study involving no less than 100 participants will be conducted during the test-bedding phase. To validate the effectiveness of the developed system, participants will be divided into control and intervention groups. Control group participants will receive standard care as well as an educational package covering the Asia-Pacific guidelines for the management of frailty [7]. During the study, data for proposed metrics will be unobtrusively collected from all participants at baseline, 6 months, and 12 months. At the end of the study,

the data from the control group will be compared with the data from the intervention group for all valid participants.

B. *Results from interviews and focus groups*

As described in the previous section, short interviews and focus groups were conducted at the end of the design phase to evaluate the proposed designs for each of the system's modules. 10 participants were jointly recruited by the Project Team and Implementation Partner. Among the 10 participants, 5 were caregivers and older adult users aged above 60, among which 4 were females and 1 was male. The other 5 participants were healthcare professionals, including 1 nutritionist, 1 pharmacist, 1 physical therapist and 2 doctors from the Geriatrics department.

The 10 participants were interviewed for their opinions on whether and how they think the SAIF system would help with the assessment and intervention of frailty. The participants also rated the effectiveness of the modules in SAIF on a Likert scale of 1 to 7. The numerical results were briefly tabulated in Table 3.

Table 3 Interviews and focus group results

Contents	*Mean*	*SD*	*Median*
Healthcare Professionals	5.2	0.84	5
Caregivers and Older Adults	6	1	6
Overall	5.6	0.97	5.5

Generally, we received positive feedback on the design of the SAIF system. Using a 7-point Likert scale, the SAIF system received an average score of 5.6 from all the participants, with a standard deviation of 0.97 and a median of 5.5. The overall scores indicate that the participants generally hold positive attitudes towards the SAIF and believe that it has the potential to help predict the risk of frailty and delay and/or decelerate the progression of frailty.

The caregivers and older adult users seem to be more positive than the healthcare professionals. The average score of the caregivers and older adults' group is 6 (SD = 1, median = 6), slightly higher than that of the healthcare professionals' group which is 5.2 (SD = 0.84, median = 5). During the interviews, some healthcare professionals expressed concerns that older adults might have difficulty coping with the SAIF system and would need the support of a technical person in order to use it. While the healthcare professionals showed worries about leaving multi-domain assessments and interventions of frailty completely self-administered, the older adult users demonstrated their confidence that they can learn and use the SAIF system by themselves without hassle. Nonetheless, the concerns of the healthcare professionals highlight the importance of the usability of the SAIF system and should be considered in the subsequent development and testing of the system.

C. Discussion

Although positive feedback was received on the design of the SAIF system from the interviews and focus groups, there are some adaptations of the SAIF prototype to specific real-world contexts that merits consideration.

Our study results with the focus group participants may not be necessarily generalizable to other population groups with lower educational levels, less tech-savviness, and lower self-efficacy. Moreover, the acceptance and utilization of smart devices among seniors vary across different populations, while most of the modules of SAIF are in the form of a phone or tablet application. Hence, in terms of design, SAIF would benefit from simple and intuitive interfaces and clear instructions. It is recommended that SAIF should use simple and direct languages for instructions, augment textual instructions with audio, and provide realistic and detailed video tutorials for each module. In terms of modes of delivery, SAIF would benefit from supporting both centralized and decentralized assessment and intervention. These two delivery modes will be further elaborated in the discussion on the scalability of SAIF subsequently.

With the plans of conducting pragmatic effectiveness studies in broader Singaporean populations, it is important to appreciate that Singaporean populations are vastly heterogeneous with regard to language, culture, religious beliefs, socioeconomic status, and social setting. Multiple languages should be supported by SAIF, at least in full English and Chinese versions. Most assessments and interventions in SAIF can be deemed to be relatively ubiquitous and non-culturally-biased, for example, the physical assessments, WWT and polypharmacy components. In contrast, components pertaining to food and nutrition are more contextually dependent on the local culture. Representative cuisines for different ethnic groups should be included as food options in *Nutrition Recommendation* module.

To deploy SAIF in large-scale pragmatic studies and in broad populations, the combination of decentralized and centralized delivery modes in conjunction could be a viable strategy for home- and community-based frailty assessment and intervention. For seniors with better socioeconomic status and living with their children, SAIF could be installed on their personal devices to support assessment and intervention at home. Portals can be provided to their children for assistance and monitoring. On the other hand, SAIF could be deployed at central locations, such as community centers, senior homes, and geriatrics centers to provide centralized assessment and intervention. The devices at these locations could be centrally managed and shared, offering a cost-effective option for large-scale implementation.

V. Conclusion

Frailty is a highly and increasingly prevalent condition in the ageing populations. It not only deteriorates the quality of life of frail individuals, but also threatens the sustainability of existing health care systems. To confront this challenge at a population-level, early identification and intervention of frailty is pivotal. However, as discussed previously, there are a number of key problems with current model of care for frailty:

- Commonly used assessment tools are reactive and are not used to proactively predict the risk of frailty, thereby missing a window of opportunity for effective intervention;
- Existing assessment tools and intervention methods are mostly carried out by medical professionals, which is resource intensive;
- Frailty assessment and intervention costs may be unaffordable to a significant portion of the elderly population.

We propose, to the best of our knowledge, the world's first home- and community-based system for both assessment and intervention of frailty. The novelty and advantages of SAIF can be summarized as follows:

- It uses an **end-to-end** system architecture, enabling periodic (re)-assessment to track the individual's progress and personalized adaptations to the interventions to improve health outcomes.
- It is **cost effective**, enabling assessment and intervention at home and in the community in a **scalable** manner. Nonetheless, it does not aim to replace medical professionals' expert input in frailty management.
- It is **predictive** and **proactive** instead of reactive, using data to identify the risk that a person may go from robust to pre-frail and/or from pre-frail to frail, and proactively intervening to reverse such undesirable trends.
- It is **personalized**, using data-driven approaches combined with medical domain knowledge in order to customize interventions based on patients' profiles.

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