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Development and usability testing of an integrated geriatric care model (SMART system) to promote integrated home-based geriatric care

Rongrong Guo[1†], Huan Fan[1†], Shuqin Xiao[1†], Ziling Zheng[2], Fangyu Yang[1], Yanyan Xiao[2], Xue Yang[3] and Ying Wu[1*]

Abstract

Background Although integrated care has been proposed as a promising approach to the challenges of fragmented geriatric care, a universally accepted implementation framework for integrated care for older adults living at home remains elusive. This study aimed to address the gap by developing an integrated geriatric care model (SMART system) using a knowledge-based clinical decision support system (CDSS) architecture inspired by the principle of neural reflex and evaluate the usability of the SMART system.

Methods The development of our SMART system was guided by the knowledge-based Clinical Decision Support System architecture and the principle of neural reflexes, which included 5 phases: (1) functional design; (2) architecture and database design; (3) security measures design; (4) user interface and visualization design; (5) prototypes development and iteratively testing. Subsequently, a cross-sectional study was conducted from December 2020 to February 2021, collecting older Chinese adults aged 60 years old and above consecutively to evaluate their usability perception of the Care Receiver App within the SMART system via the Health Information Technology Usability Evaluation Scale (Health-ITUES) version designed for older adults.

Results The SMART system consisted of a Care Receiver App, a Professional Care Provider App, and a Cloud Platform. According to the assessment results and daily monitoring data, the SMART system can diagnose care problems and tailor interventions and implementation approaches to address the multifaceted care needs of older individuals. The personalized interventions and implementation approaches generated by the SMART system, after being reviewed and adjusted by professional geriatric nurses, will be sent to the corresponding care providers to facilitate coordinated care services. A total of 110 eligible older individuals were included in the usability testing. The Care Receiver App was perceived as useful and acceptable among older individuals with the mean scores for each item of the Health-ITUES version designed for older adults exceeding 3.00.

†Rongrong Guo, Huan Fan and Shuqin Xiao contributed equally to this work.

*Correspondence:
Ying Wu
helenywu@vip.163.com
Full list of author information is available at the end of the article

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Conclusions This study successfully developed an integrated geriatric care model using a knowledge-based CDSS architecture inspired by the principle of neural reflex. Furthermore, the study indicated acceptable usability perception of the SMART system among older population.

Trial registration The study was registered in the Chinese Clinical Trial Registry (Registration number: ChiCTR-IOR-17010368) on 12/01/2017.

Keywords Clinical Decision Support System, Home-based, Information and communication technology, Integrated care, Neural reflex

Background

Population aging is a global phenomenon that poses significant societal challenges. In 2021, approximately 963 million individuals worldwide were aged 65 or older, representing 12.2% of the global population, with projections suggesting this number will reach 1.65 billion by 2050, comprising 16.4% of the global population [1, 2]. As people age, the risk of frailty, chronic diseases, cognitive decline, and disabilities increases, creating complex care needs that span both medical and social care (mostly daily living assistance and other) domains [3]. The involvement of multiple care providers across different institutions results in fragmented and inconsistent care for older adults, diminishing care quality and potentially posing safety risks [4]. This fragmentation burdens caregivers, who may experience increased stress, emotional strain, and financial pressure from the need to coordinate care, manage complex health needs, and navigate various healthcare systems [5]. At a societal level, fragmented care can lead to redundant treatments, delayed interventions, and inefficient use of resources, which in turn drives up healthcare costs and affect economic well-being [6, 7].

Integrated care has been proposed as a promising solution to address these challenges by linking all stakeholders and promoting continuity in care delivery [8, 9]. The World Health Organization (WHO) defines integrated care as an approach to provide a coordinated continuum of services across different care levels and sites within and beyond the health sector, encompassing health promotion, disease prevention, diagnosis, treatment, disease management, rehabilitation, and palliative care, all tailored to individual's needs and resources [10]. This model emphasizes the seamless integration of both medical and social care, making it particularly suitable for addressing the multifaceted needs of older adults living at home. By coordinating efforts of healthcare providers, social workers, and family caregivers, integrated care reduces redundancies, improves health outcomes, and optimizes resource allocation, thereby enhancing the quality of life for older people [11]. For instance, programs like the Program of All-Inclusive Care for the Elderly in the United States, which integrates medical care with social support, demonstrated the effectiveness of this model in providing holistic, person-centered care for home-dwelling older adults [12]. Similarly, the Embrace program in Netherlands and the Sustainable Tailored Integrated Care for Older People in Europe are other examples where integrated care models have been successfully applied to support older adults in community settings [13, 14].

Despite these efforts, large-scale implementation and widespread adoption of integrated care models remain challenging, particularly for older adults living at home. This challenge primarily arises from the complexity and progressive nature of health conditions in older adults, which necessitate continuous and personalized care delivered collaboratively by multiple institutions across various care systems. This approach requires real-time monitoring of older people's overall health status and timely identification of their care problems [15]. Additionally, insufficient collaboration between social and healthcare institutions hinders information sharing and seamless coordination, resulting in fragmented care that fails to address the holistic needs of older adults [16, 17]. The lack of a set of tools and strategies for community-based integrated care for older people exacerbates these challenges, necessitating further research and innovation in this area [18].

Information and Communication Technology (ICT) is a crucial enabler for implementing integrated care by providing platforms for continuous monitoring, resource integration, information sharing, team communication, consultation, and timely feedback [19]. Previous research has explored ICT-based integrated care solutions. For example, Kouroubali et al. [17] developed an artificial intelligence (AI)-enabled platform to support multidimensional, coordinated, and timely care for older adults with frailty, enabling early detection of frailty, preventing disability and adverse events, and minimizing hospital admissions. Similarly, Chouvarda and colleagues [20] developed WELCOME platform for older adults with Chronic Obstructive Pulmonary Disease. WELCOME focuses on early detection and prevention of comorbidities through continuous monitoring and decision support. Another example is ProACT, a European digital health platform that supports integrated care for older adults with multi-morbidity by incorporating monitoring, intervention gcustomization, and data sharing within a care network [21].

However, AI-based solutions are not without limitations. In vital fields like healthcare and nursing, where accuracy and consistency are paramount, decision-making errors can have severe consequences. While AI based on machine learning and deep learning is promising, it often suffers from the "black box" problem, which obscures the traceability and comprehensibility of its reasoning processes, as well as the hallucination phenomenon, where the AI may produce inaccurate or misleading information. The "black box" and hallucination problems can lead to inaccurate or conflicting recommendations that may not align with established guidelines [22]. Given these unresolved challenges, knowledge-based clinical decision support systems (CDSSs) emerge as a more reliable option [23]. CDSSs are defined as technology-driven systems to improve healthcare delivery by facilitating medical decisions through the use of targeted clinical knowledge, patient information, and other health data [24]. Based on decision-making mechanisms, CDSSs are typically categorized into knowledge-based and data-based CDSSs. A comprehensive knowledge-based CDSS architecture includes a knowledge base, inference engine, and user interface, which function collaboratively to support decision-making by relying on explicit, predetermined knowledge rules or guidelines, thereby augmenting clinicians in the complex decision-making processes [25]. Although it may not possess the same predictive capabilities as deep learning models, the knowledge-based CDSS provides transparency and ensures that its recommendations are based on established clinical expertise and guidelines [26, 27]. This feature reduces the risk of critical errors, making it a safer and more effective tool for promoting consistent and accurate integrated care, particularly for home-based geriatric care.

Hence, this study aimed to address these gaps by developing an integrated geriatric care model by using a knowledge-based CDSS architecture inspired by the principle of neural reflex. The foundational knowledge base and operational algorithms have been developed in the initial stages following the first three steps of the Intervention Mapping (IM) framework, as detailed elsewhere [28]. In brief, to identify the home-based care needs, functionality and user interface preferences, as well as the expected information presentation formats, we conducted semi-structured in-depth interviews with older adults and their daily caregivers. Grounded in the needs assessment findings and informed by the latest literature, guidelines, and expert opinions in relevant fields, we clearly articulated care problems, risk factors and/or causes, diagnostic criteria, long-term and short-term care objectives, evidence-based interventions, specific implementation approaches, as well as trigger rules from a total of 11 domains (decreased or lost self-care ability, falls, delirium, dysphagia, urinary retention, constipation, incontinence, cognitive decline, depression, impaired skin integrity, and common diseases) in the knowledge base. Our integrated geriatric care model relies on this knowledge base and associated algorithms to realize integrated care in the above-mentioned eleven domains for older adults living at home. Similar to how the neural reflex functions in biological systems, where receptors collect information and transmit it to the central nervous system for processing before commands are sent to effectors, our integrated geriatric care model was designed to function as the "neural reflex" [29]. The model consists of *S*ensors and Scales (servers as the receptor), a *M*obile Phone *A*utonomous Response System (serves as the central nervous system in the spinal cord), a *R*emote Cloud Management Center (serves as the central nervous system in the brain), and a *T*otal Care System (severs as the effector, where various care institutions are incorporated to assume responsibility for specific types of care services for older people, thus promoting the integrated and consistent care), collectively referred to as the *SMART* system. Additionally, Wifi and 5G networks serve as Afferent Nerves or Sensory Nerves and Efferent Nerves or Motor Nerves. Our secondary objective was to evaluate the usability of our SMART system among older adults.

Methods

Based on the knowledge base previously developed for the integrated geriatric care model [28], the current study progressed by employing the subsequent step of the IM framework: program production. The SMART system was designed to tackle 138 care problems spanning eleven domains (e.g., risk for falls, related to environmental hazards) and generate personalized interventions (e.g., guidance on age-appropriate home environment modifications) in accordance with the characteristics (e.g., preferences, living situations) of older people. For instance, if the SMART system detects that an older adult has been bedridden for extended periods and remains in a single position for over 4 h (risk factors), it will diagnose a care problem of "Risk for pressure ulcers, related to prolonged periods of unrelieved pressure". The corresponding short-term and long-term care goals would be to reduce the duration of pressure on bony prominences and maintain skin integrity, respectively. Based on the comprehensive assessment results, if the individual is unable to reposition by himself/herself and is primarily cared for by the daughter, the personalized intervention would be

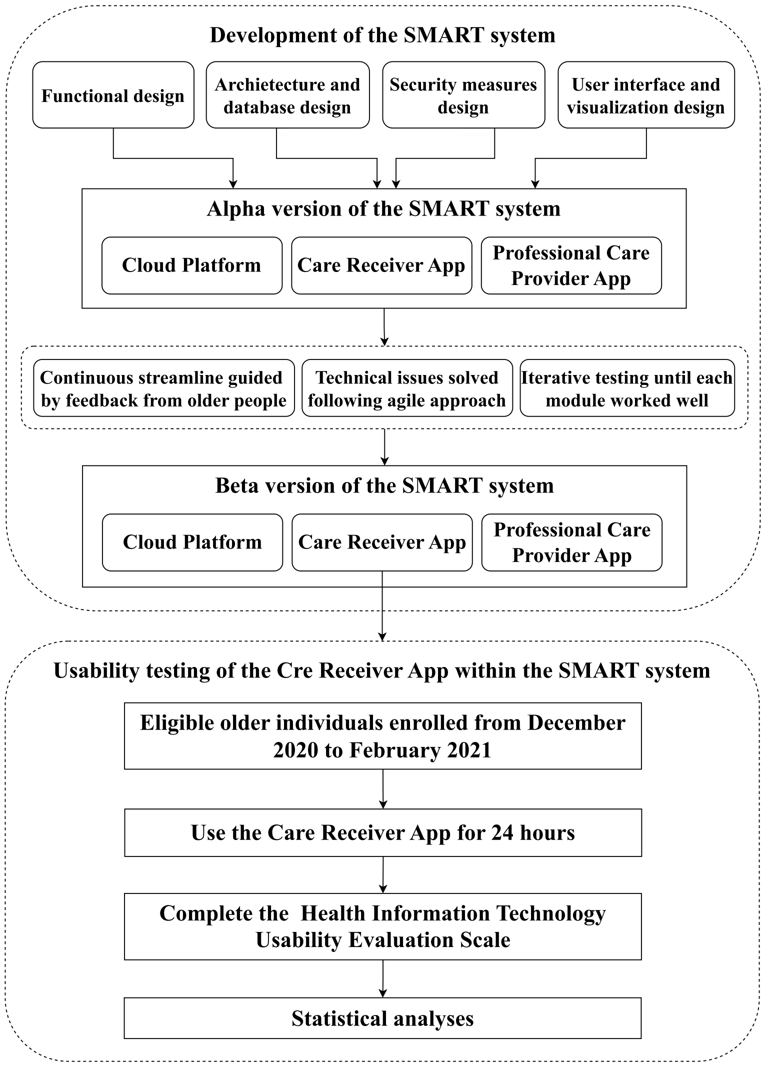

Fig. 1 The flow diagram for the development of the SMART system and usability testing

"Frequent repositioning" with the specific implementation approach being "Remind the caregiver to reposition the older individual every two hours". A summary of the 138 care problems and examples of care problems along with corresponding personalized interventions were provided in Additional Tables S1 and S2, respectively.

A multidisciplinary team comprising professionals in nursing informatics, nursing research, gerontological care, software engineering, and interface designing was established to collaboratively advance the development of the SMART system. We held weekly meetings throughout all phases to promptly resolve problems and issues raised during the development phase to ensure smooth ongoing progress. The study, encompassing both the system development and usability testing, obtained approval from the Institutional Review Committee of the Capital Medical University (Approval No. 2015SY49). The flow diagram for the development of the SMART system and usability testing was presented in Fig. 1.

Phase 1: development of the SMART system

Functional design

According to human neural reflexes, the Sensors and Scales collected data from older individuals through wearable devices, periodic self-assessments of older people, and assessments by others (e.g., family members, nannies, community nurses, etc.). The collected data were uploaded automatically to the Remote Cloud and Management Center via Wifi or 5G networks for comprehensive analysis to diagnose care problems and formulate customized interventions, which were subsequently distributed to daily caregivers (mainly family members and nannies) or professional care providers (e.g., doctors and

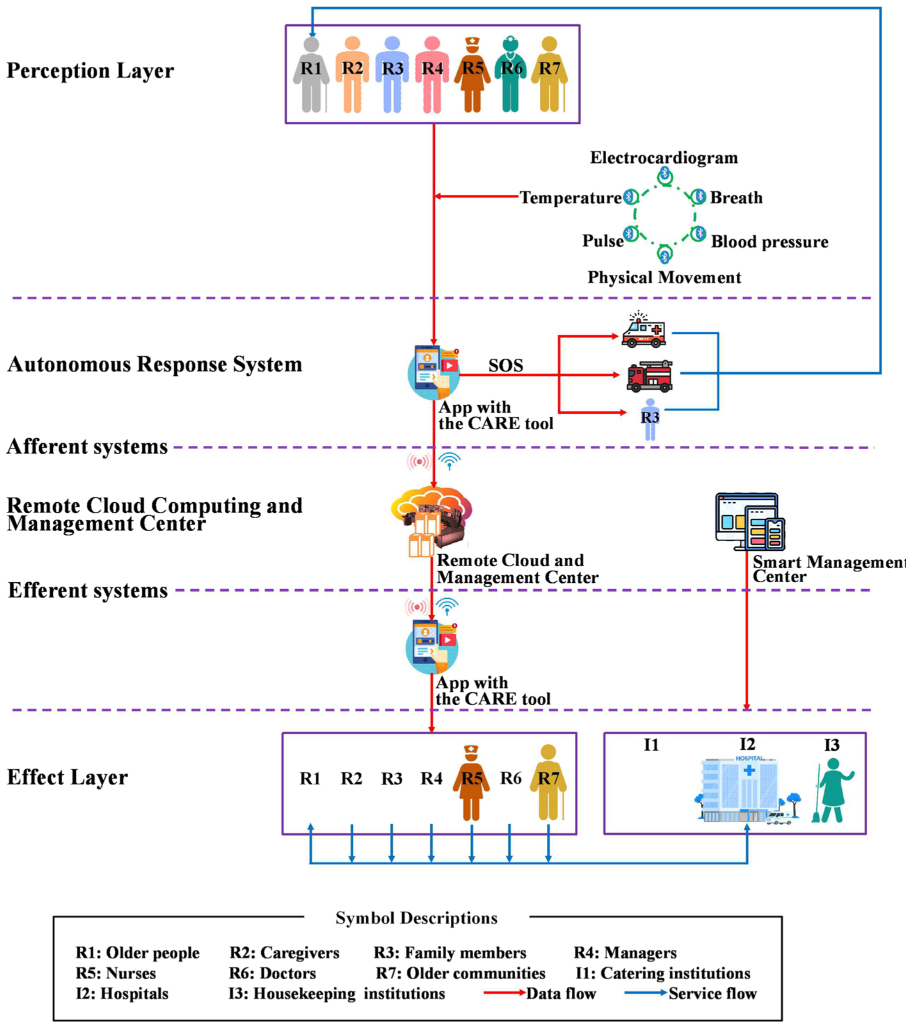

Fig. 2 The overall architecture of the SMART system. App, application; CARE, Continuity Assessment Record and Evaluation

nurses in the medical care system who are responsible for medical assistance, domestic workers in the social care system who mainly assist with daily living activities) within the Total Care System as appropriate. The Mobile Phone Autonomous Response System was a set of simple algorithms that were pre-integrated into the SMART system to deal with simple but urgent care problems, similar to the coordinate reflex actions within the spinal cord, such as the withdrawal reflex from a painful stimulus. The process could enhance coordination among various caregivers and professional care providers and ensure high-quality, coordinated, and integrated older care (see Fig. 2).

According to the overall objectives and functional design of the SMART system, the research team drafted key functions and modules for the Cloud Platform, Care Receiver App, and Professional Care Provider App using XMind software version 8 (XMind, Ltd). Based on the initial draft, the multidisciplinary team collaborated in brainstorming to produce a more detailed document to guide the development of the SMART system (see Additional Table S3).

Architecture and database design

To enhance the flexibility, scalability, and maintainability of the SMART system, we adopted the MicroService architecture for development. The approach allowed us to decompose the SMART system into small and single-responsibility units that can be developed, operated, deployed, scaled, and managed independently [30]. The MicroService architecture not only can reduce task complexity and improve development efficiency but also enable zero-downtime releases in satisfying older people's evolving care needs [31].

The Cloud Platform was designed to be compatible with mainstream browsers following a Browser/Server

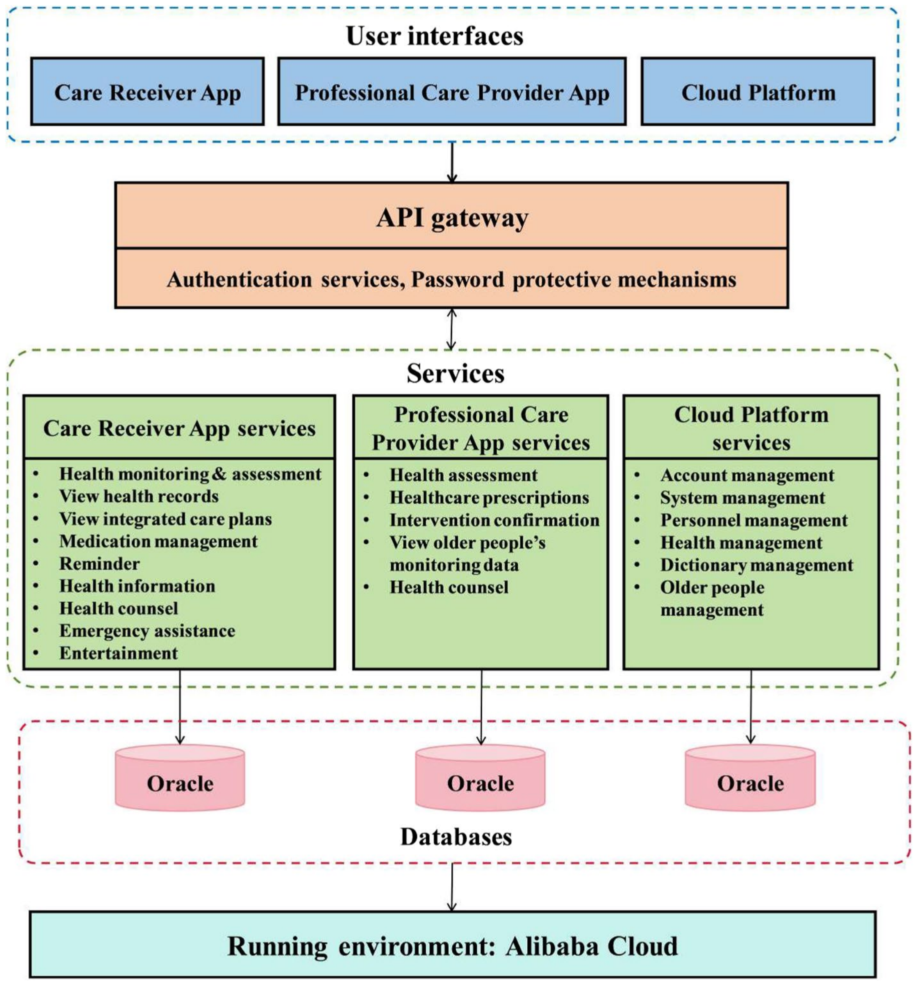

Fig. 3 The system architecture of the SMART system

(B/S) architecture [32], while the Care Receiver App and Professional Care Provider App adopted a Client/Server (C/S) architecture with the application programming interface (API) gateway for access [33]. Besides, both Apps were programmed to be accessible on Android-based mobile phones to ensure their widespread popularity and affordability in China [34]. Once stable on Android-based mobile phones, we will extend compatibility to iOS-based mobile phones.

SQL databases were used to store, process, capture, retrieve, and manage substantial amounts of fully structured data, while NoSQL databases were employed for semi-structured and unstructured data [35]. The SMART system stored information such as older people's basic characteristics and comprehensive geriatric assessment results, with data from each module stored in either Oracle or MongoDB as appropriate (see Fig. 3).

Security measures design

The SMART system transmits sensitive data, such as personal identification and health information, making it susceptible to external and internal threats. Multiple protective measures were therefore applied to ensure system security. Data access control was achieved through user authentication services and password protective mechanisms, including verifying password strength, limiting login attempts, and periodically changing passwords [36]. To secure data transmission and storage, mutual authentication HTTPS were employed to encrypt all sensitive data [37]. Additionally, database backup and recovery functions were included to ensure data availability at any time. The development of the SMART system adhered to international and national data standards (Additional Table S4).

User interface and visualization design

The user interface (UI) of the Care Receiver App was meticulously crafted based on six user-friendly design principles (structure, simplicity, diverse presentation, feedback, consistency, and tolerance) to improve older people's perceived usefulness and ease of use with the Care Receiver App, following the Technology Acceptance Model [38]. Axure RP8 (Axure Software Solutions, Inc., USA) was employed to draft the module interfaces with functional buttons annotated to assist interface designers in understanding the functionality of each icon. Subsequently, the interface designers used Flinto version 26.0.5 (Flinto Inc., Australia) to document the planned UIs and their interactions. Distinctive design elements such as contrasting color blocks, large fonts, prominent functions, and unique icons, were used to signify various functions.

Prototypes development and iteratively testing

The SMART system was developed using Java/. Ne for its popularity, power, verbosity, and ease of maintenance, with Linux and UNIX as the operating environment. The software engineers used Android Studio to develop the alpha version of the SMART system based on the functional design and system architecture provided by the research team [39]. The research team then randomly invited ten home-dwelling older individuals from the preliminary needs assessment [28] to test the alpha version within an iterative design framework. Details of inclusion and exclusion criteria as well as the characteristics of the ten older adults are summarized in Additional Method 1 and Table S5. Through ongoing feedback from older people, the team continuously streamlined the delivery of care problems and personalized interventions. Following the agile approach, software engineers iteratively identified and solved technical issues throughout the development process to promote adaptive planning, evolutionary development, high-quality delivery, and continuous improvement [40]. After fixing technical issues in the alpha version, a beta version was formulated and tested within the research team until all modules worked well.

Phase 2: usability testing of the care receiver App within the SMART system

The usability testing of the SMART system's beta version adhered to the International Standards Organization (ISO) standard 9241–11, which defines usability as the extent to which users can use an App to achieve specific objectives with efficiency, satisfaction, and effectiveness in a specified context of usage [41]. The usability testing was registered in the Chinese Clinical Trial Registry (Registration number: ChiCTR-IOR-17010368) on 12/01/2017. Since older individuals are the core users of the SMART system, we only tested the usability of the Care Receiver App among older people.

Study design and participants

To improve sample-selection efficiency, we conducted a cross-sectional study in a geriatric ward of a comprehensive hospital in Beijing, China, which was accredited as a comprehensive facility with dedicated geriatric wards and capable of serving a diverse population of older patients, from December 2020 to February 2021. Older adults were included consecutively if they: (1) were aged 60 or older; (2) were about to be discharged from the hospital and return home; (3) possessed normal communication and interaction abilities; (4) obtained at least a primary school education; (5) had an Android-based smartphone for Internet access; (6) expressed willingness to participate. Older individuals with dementia or other mental illness were excluded. All participants provided written informed consent on enrollment.

Measures

Demographic information of the older participants was collected using a predefined questionnaire, encompassing age, gender, education, monthly income, mobile phone use experience, and daily mobile phone use time. The perceived usability of the Care Receiver App among older individuals was measured using the Health Information Technology Usability Evaluation Scale (Health-ITUES) [42]. The Health-ITUES comprises 20 items from 4 domains: impact (3 items), perceived usefulness (9 items), perceived ease of use (5 items), and user control (3 items). Each item is rated from 1 (strongly disagree) to 5 (strongly agree) on a 5-point Likert scale. The total scores range from 20 to 100, with higher scores indicating better usability. This tool supports customization at the item level to align with specific tasks and expectations of the health systems. The Chinese version of the Health-ITUES demonstrates satisfactory reliability with a Cronbach's α coefficient of 0.74–0.90 [43]. To accurately reflect the perceived usability of the Care Receiver App among older people, the Health-ITUES was customized and distributed to them after completing the assigned tasks.

Testing process

Once receiving approval from the relevant departments, we screened older individuals according to the predefined inclusion and exclusion criteria. After a detailed explanation of the study's purpose, significance, and procedures, we assisted the older participants in downloading and installing the Care Receiver App. Training materials, including instructional videos and user manuals, were

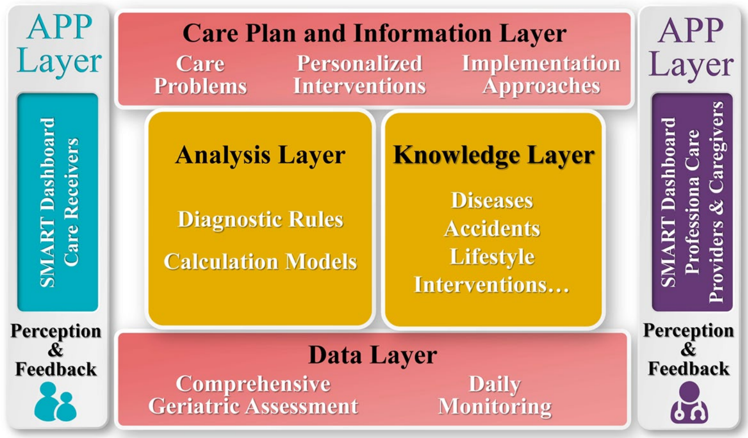

Fig. 4 The overall functional components of the SMART system. App, application

made available until they felt confident in using the App. Subsequently, the older participants were encouraged to use the App for 24 h to complete the assigned tasks before filling out the customized Health-ITUES. The tasks included independently viewing assessment reports at least once, inputting medication information at least once, recording blood sugar or blood pressure at least once, recording diet or exercise at least once, and accessing health information at least once. For paper questionnaires, we conducted thorough checks to identify any omissions and verify incomplete or ambiguous information on the spot, thereby ensuring data integrity. For electronic questionnaires, data completeness was verified within 12 h.

Sample size calculation

To achieve adequate statistical power, the sample size should be 5–10 times the number of items [44]. With a total of 20 items in the Health-ITUES version designed for older adults, the study necessitated a minimum of 100 participants.

Statistical analysis

The enrolled older participants were classified into two groups based on a threshold of 3: those with mean item scores above 3 constituted the Positive Usability Group, while those with mean item scores of 3 or below defined the Negative or Neutral Usability Group. Detailed variable types and value assignment methods were provided in Additional Table S6. Continuous data was tested for normal distribution using the one-sample Kolmogorov–Smirnov test and expressed as medians with interquartile range (IQR) or mean ± standard deviation (SD) as appropriate. For the between-group comparison, student-*t* test was employed for continuous variables with normal distribution, while Mann–Whitney U test was utilized for non-normally distributed continuous data to avoid the influence of non-normal distribution and small sample size issues [45]. Categorical variables were expressed as frequencies and proportions (%), with comparison conducted using chi-square or Fisher's exact test.

Variables with a two-tailed $p < 0.10$ in the univariate analysis were considered to be entered into the bootstrapped forward stepwise logistic regression model. The odds ratio (OR) and their 95% confidence interval (CI) were used to assess the independent contribution of each variable. Model performance was evaluated by multiple measures including Nagelkerke R^2 to determine the proportion of variance accounted for, accuracy derived from the confusion matrix to reflect prediction correctness, and the Hosmer–Lemeshow test to evaluate the model calibration. Additionally, the Receiver Operating Characteristic (ROC) curve was illustrated and the Area Under the Curve (AUC) was computed to evaluate the model discriminatory ability. Statistical analysis was conducted using SPSS software version 26.0 (IBM Corp, Armonk, NY) with statistical significance set at two-sided $p < 0.05$.

Results

Phase 1: development of the SMART system

Functions of the SMART system

The overall functional components and system architecture of the SMART system were illustrated in Fig. 4 and Additional Figure S1.

The SMART system serves two main types of end users: care receivers (including older adults and their family members or daily caregivers) and professional care providers from both the healthcare (e.g., doctors and nurses responsible for medical assistance) and social care sectors (e.g., domestic workers to assist with daily living

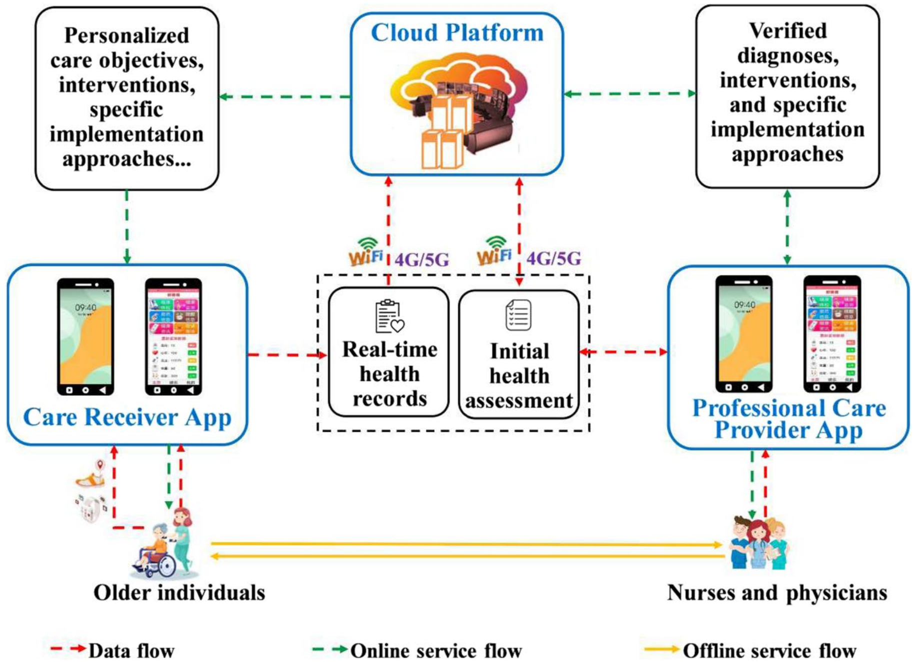

Fig. 5 The functional components and overall workflow of the SMART model

activities and provide basic support services). Therefore, we developed the Care Receiver App and Professional Care Provider App for the two types of end users, as well as the Cloud Platform (see Fig. 5).

The Care Receiver App enables care receivers to record and upload health data of older adults to the Cloud Platform through the Comprehensive Assessment Module (see Fig. 6A and Additional Files 2–12). This module employs the Continuity Assessment Record and Evaluation (CARE) tool to provide a continuous and comprehensive evaluation of medical, functional, cognitive, and social support factors [46]. The CARE tool is structured into distinct sections with assessment statuses (to assess, in progress, and completed), allowing care receivers to complete assessments at their own pace and save progress as needed. Moreover, the Daily Monitoring Module allows care receivers to upload daily health data of older adults, including temperature, heart rate, blood pressure, blood glucose, electrocardiogram, weight, diet, exercise, sleep, bowel movements, and urination, via wearable devices or manual input. The SMART system integrates YouYiTang wearable device, which is equipped with a blood glucose sensor, an accelerometer, and a temperature sensor to monitor blood glucose levels, sleep, and exercise of older adults in real time. The collected data is wirelessly transmitted via Bluetooth to the Cloud Platform for comprehensive analysis through the Daily Monitoring Module to enable personalized interventions. Historical data is displayed graphically over different periods (day, week, month, year), with any abnormalities of the latest monitoring data highlighted in varying colors on the main interface. A Medication Management Module enables care receivers to manually upload or scan prescribed medications and access medication history. Besides data records, the Care Receiver App featured a Reminder Information Module to display care problems, personalized interventions, implementation approaches, and medication reminders, with the execution status indicated by a red dot. Additionally, a Health Information Module can provide health-related knowledge on health, wellness, exercise, and diet. To increase the ease of use of the Care Receiver App, a read-out mode is available for the Comprehensive Assessment Module and Reminder Information Module.

In the Professional Care Provider App, qualified geriatric nurses, owing to their specialized training and experience in addressing the unique needs of older adults, are appointed as the principal care providers to ensure the quality and appropriateness of care. To streamline the process, input from other medical professionals is not included. Geriatric nurses can assess older adults' overall status through the Comprehensive Assessment Module, Daily Monitoring Module, and Medication Management Module, and perform regular professional assessments via the Comprehensive Assessment Module. Following this, the designated geriatric nurses are empowered to review and modify the care plans generated automatically by the Cloud Platform within the SMART system.

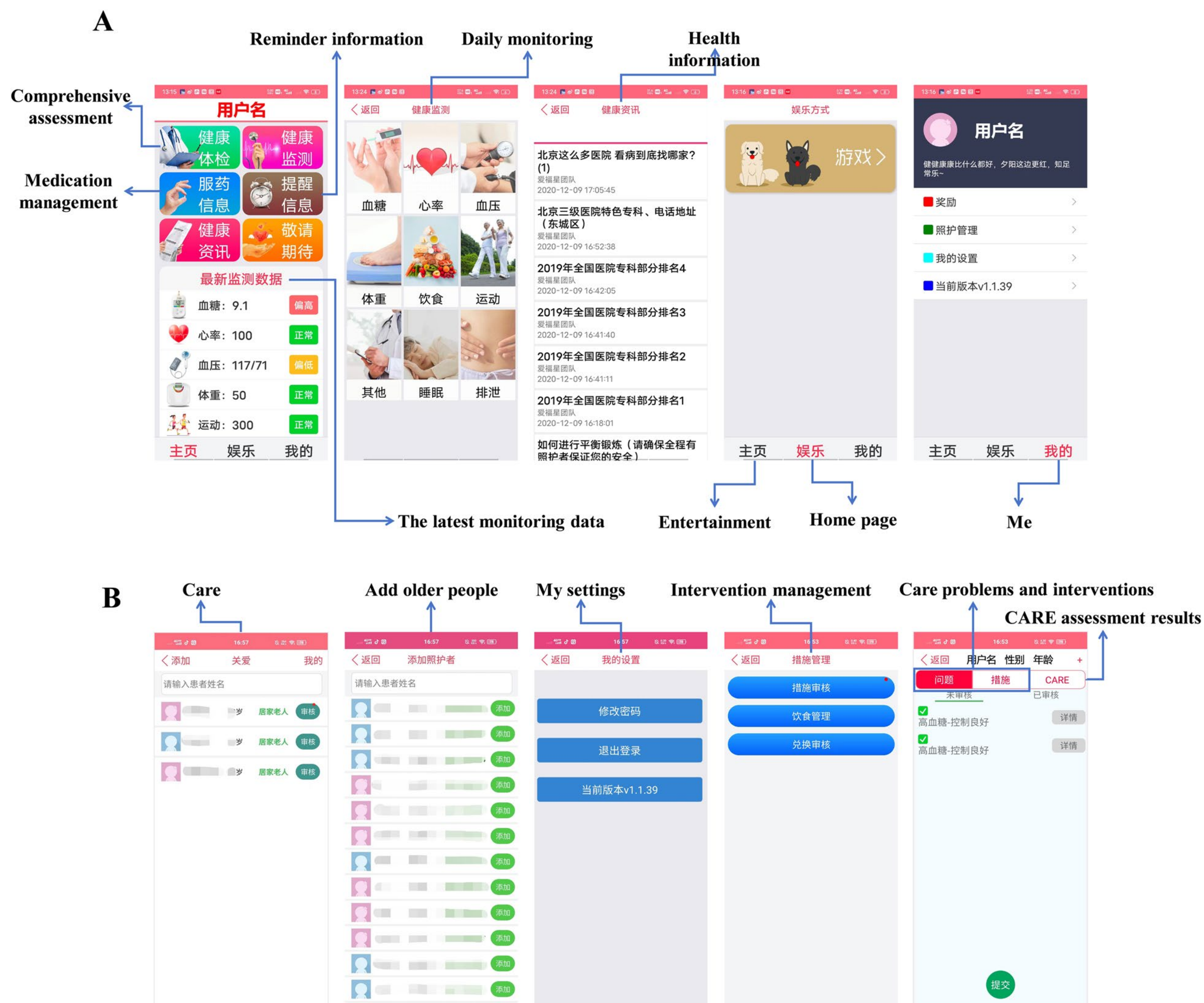

Fig. 6 The main functional modules of the Care Receiver App and Professional Care Provider App. App, application

Specifically, in the Reminder Information Module, they can access the care problems along with the associated diagnostic rules (e.g., abnormal conditions in older adults), as well as the corresponding long-term and short-term care objectives, personalized interventions, detailed implementation strategies, and intervention triggering algorithms. Any inaccurate or inappropriate content can be amended, with the modified information requiring further verification by the Cloud Platform before being disseminated to various care providers (see Additional File 8). Other professional care providers are also granted access to a list of older adults. However, their access was limited to viewing the comprehensive assessment reports, daily monitoring data, current medication, and the reviewed care problems of older people, as well as care interventions and implementation approaches that have undergone meticulous review and approval for their implementation (see Fig. 6B and Additional Files 2-8). The rationale behind the care problems, customized interventions, and implementation approaches is also accessible, thereby fostering transparency and interpretability in the decision-making process.

The Cloud Platform, functioning as the brain of the SMART system, designed primarily for data analysis. Utilizing the preset knowledge base and diagnostic rules, it can diagnose care problems according to the assessment results, daily monitoring data, and medication of older people, and further automatically match personalized interventions and implementation approaches through amalgamating older people's characteristics (e.g., demographics, lifestyle, preferences). Umeng Analytics and Kafka User Behavior Tracking were integrated to capture the behaviors and preferences of older adults, generating detailed logs that facilitate personalized interventions

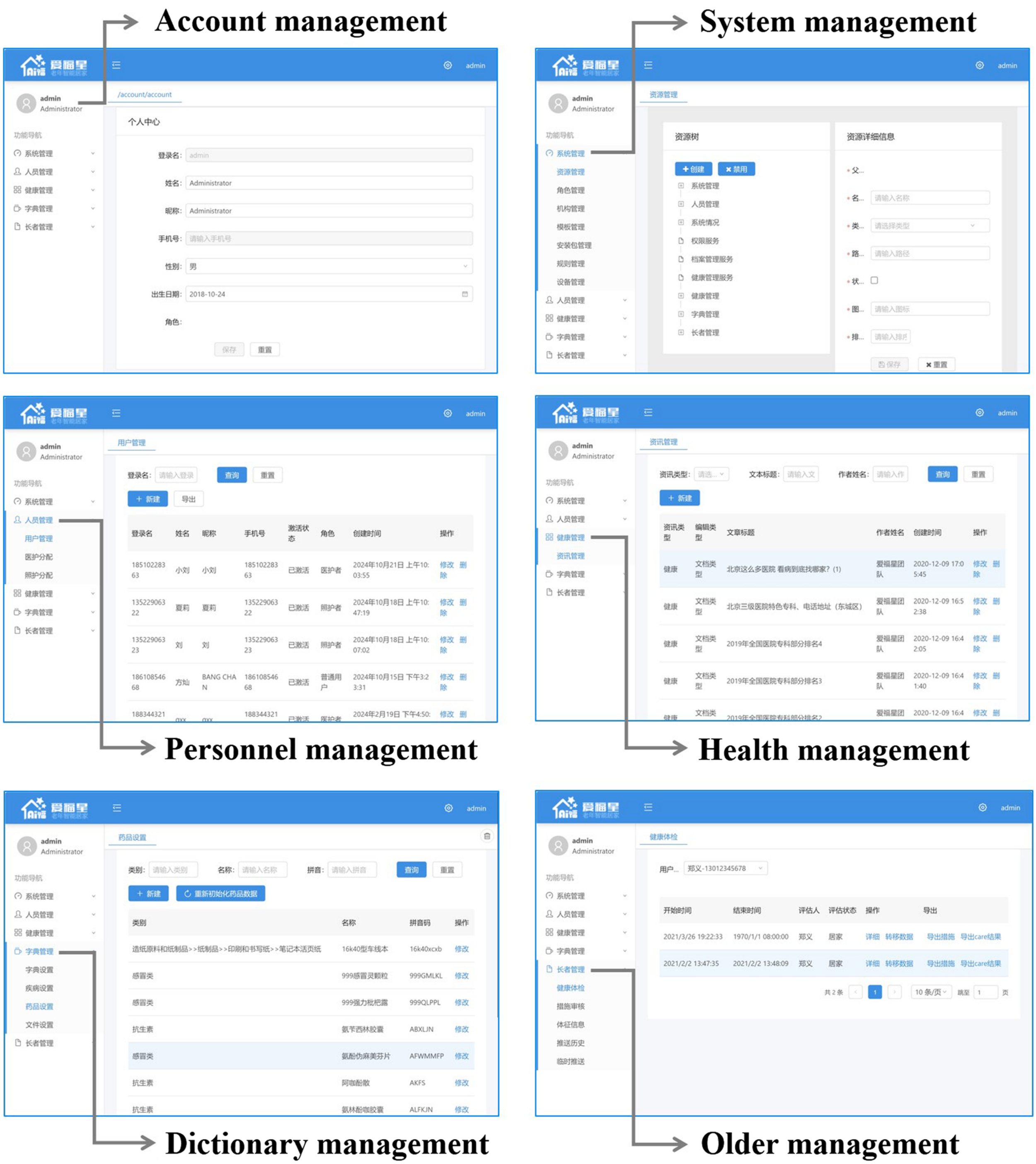

Fig. 7 The main functional modules of the Cloud Platform

and system refinements through an ongoing feedback loop. Additionally, in response to the continuously evolving knowledge in geriatric care, the Cloud Platform also featured a knowledge maintenance function that allows for the dynamic update and modification of knowledge items and trigger rules, ensuring alignment with the latest advancements in medical and healthcare fields. Meanwhile, it could monitor the usage of the system (see Fig. 7).

UIs of the SMART system

The UIs and logical relationships of the Care Receiver App and Professional Care Provider App were illustrated

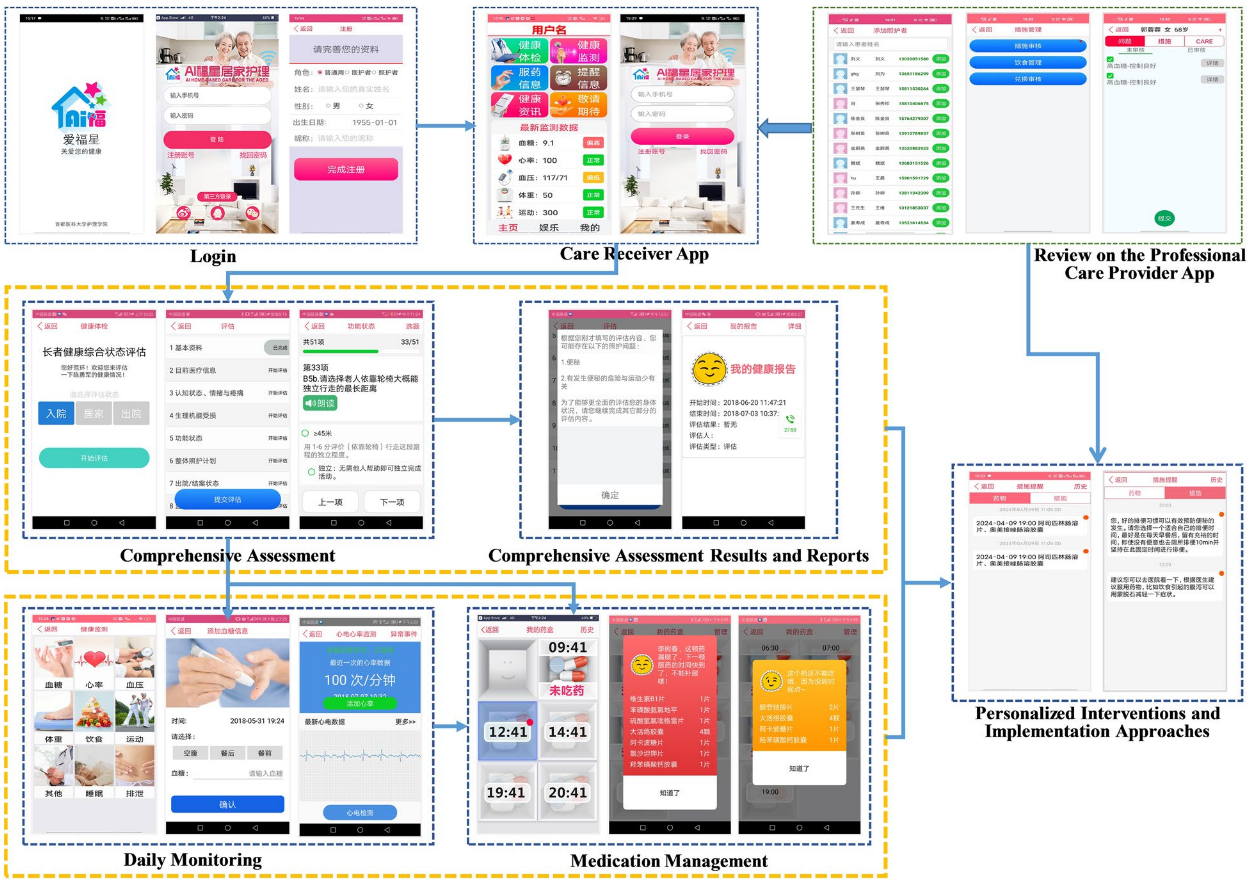

Fig. 8 The interfaces and logical relationships of the Care Receiver App and Professional Care Provider App. App, application

in Fig. 8 and Additional Figure S2. The Care Receiver App was designed to incorporate various modules, color blocks, icons, and large fonts to facilitate easy access to specific modules and minimize complex navigation. To reduce cognitive load of older people and increase their perceived usability of the Care Receiver App, we limited text messages and used figures and videos for clearer and more visual information presentation.

Prototypes of the SMART system

The software engineers developed, tested, and refined the alpha version of the SMART system. They subsequently conducted independent tests on each module using simulated data 10–20 times to ensure that basic functionalities were operational. After resolving any technical issues in the alpha version, the beta version was launched. The research team conducted over 100 rounds of testing on the beta version until a consensus was reached. Following a three-month testing period, the fully functional beta version demonstrated stability and was primed for usability testing.

Phase 2: usability testing of the care receiver App within the SMART system

Characteristics of the older participants

A total of 110 eligible older adults were included in the usability testing. Table 1 summarized their characteristics. The median age was 67.00 (64.00, 71.00) years with 67.27% being male. Of the participants, 52.73% had limited experience in using mobile phones, while the rest (47.27%) exhibited moderate experience. Furthermore, most older people spent less than 3 h per day on their mobile phones, with only 10.00% using their mobile phones for more than 3 h per day.

Health-ITUES scores of the older participants

As presented in Table 2, the mean total score for older participants was 65.80, with an average item score of 3.29 ± 0.32, indicating acceptable usability of the Care Receiver App. The mean item scores concerning the impact, perceived usefulness, and user control all exceeded 3.00, with the perceived usefulness dimension scoring the highest, followed by the impact dimension,

Table 1 Basic characteristics of the included older individuals

Variables	Older adults ($n=110$)	Variables	Older adults ($n=110$)
Age	67.00	**Monthly income (￥)**	
	(64.00,71.00)	**≤ 1000**	16 (14.55%)
Male	74 (67.27%)	**1001 ~ 3000**	41 (37.27%)
Education		**3001 ~ 5000**	42 (38.18%)
Primary school and below	28 (25.45%)	**> 5000**	11 (10.00%)
Junior high school	51 (46.36%)	**Daily mobile phone use time**	
Senior high school and above	31 (28.18%)	**< 1 h**	52 (47.27%)
History of chronic diseases		**1 ~ 3 h**	47 (42.73%)
Hypertension	75 (68.18%)	**> 3 h**	11 (10.00%)
Diabetes mellitus	35 (31.82%)	**Mobile phone use experience**	
Hyperlipidemia	31 (28.18%)	**Less experience**	58 (52.73%)
Stroke	42 (38.18%)	**Moderate experience**	52 (47.27%)
Coronary heart diseases	12 (10.91%)	**Abundant experience**	0 (0.00%)

Table 2 Scores of the Health-ITUES version designed for older adults

Items of the Health-ITUES version designed for older adults	Mean scores
All domains (Cronbach's α = 0.874)	3.29 ± 0.32
Impact	3.41 ± 0.43
1. I think the Care Receiver App can be a positive addition to obtaining home-based care services	3.70 ± 0.55
2. I think the Care Receiver App can improve my quality of life	3.31 ± 0.57
3. The Care Receiver App is an important tool for me to access home-based care services	3.23 ± 0.60
Perceived usefulness	3.42 ± 0.41
4. Using the Care Receiver App makes it easier for me to apply for home-based care services	3.33 ± 0.62
5. Using the Care Receiver App enables me to apply for home-based care services more quickly	3.37 ± 0.59
6. Using the Care Receiver App makes it more likely to obtain the home-based care services that I need	3.55 ± 0.54
7. Using the Care Receiver App is useful for me to apply for home-based care services	3.55 ± 0.57
8. I think the Care Receiver App presents a more equitable process for applying home-based care services	3.35 ± 0.57
9. I am satisfied with the Care Receiver App for applying home-based care services	3.34 ± 0.65
10. The Care Receiver App allows me to obtain home-based care services promptly	3.52 ± 0.63
11. Using the Care Receiver App promotes the application of home-based care services	3.68 ± 0.52
12. I can obtain home-based care services that I need whenever I use the Care Receiver App	3.07 ± 0.69
Perceived ease of use	2.95 ± 0.54
13. I am comfortable with my ability to use the Care Receiver App	3.05 ± 0.79
14. Learning to use the Care Receiver App is easy for me	3.14 ± 0.95
15. I can easily become skillful at using the Care Receiver App	2.60 ± 0.90
16. I find the Care Receiver App easy to use	2.84 ± 0.78
17. I can always remember how to log on to and use the Care Receiver App	3.11 ± 0.68
User control	3.34 ± 0.43
18. The Care Receiver App gives messages that tell me how to fix problems	3.29 ± 0.61
19. Whenever I make a mistake using the Care Receiver App, I recover easily and quickly	3.01 ± 0.76
20. The information (such as online help, on-screen messages, and other documentation) provided by the Care Receiver App is clear	3.73 ± 0.45

and the usability dimension having the lowest score. In contrast, the mean item score for the perceived ease of use was slightly below 3.00, at 2.95 ± 0.54, which may be attributed to the relatively low scores for items 15 (2.60 ± 0.90) and 16 (2.84 ± 0.78). Meanwhile, responses from older adults regarding items 1, 7, and 9 revealed

Table 3 Comparisons of characteristics for older individuals in the Positive Usability Group and Negative or Neutral Usability Group

Variables	Positive Usability Group ($n=75$)	Negative or Neutral Usability Group ($n=35$)	Z/χ^2	*p-value*
Age	66.00 (63.00, 70.00)	68.00 (65.00, 72.00)	−2.03	**0.043**
Male	49 (65.33%)	25 (71.43%)	0.40	0.526
Education			−8.58	**< 0.001**
Primary school and below	17 (22.67%)	11 (31.43%)		
Junior high school	37 (49.33%)	14 (40.00%)		
Senior high school and above	21 (28.00%)	10 (28.57%)		
History of chronic diseases				
Hypertension	49 (65.33%)	26 (74.29%)	0.88	0.348
Diabetes mellitus	23 (30.67%)	12 (34.29%)	0.14	0.704
Hyperlipidemia	21 (28.00%)	10 (28.57%)	0.004	0.951
Stroke	33 (44.00%)	9 (25.71%)	3.38	0.066
Coronary heart diseases	8 (10.67%)	4 (11.43%)	0.01	0.905
Monthly income (￥)			0.27	0.965
≤ 1000	11 (14.67%)	5 (14.29%)		
1001 ~ 3000	29 (38.67%)	12 (34.29%)		
3001 ~ 5000	28 (37.33%)	14 (40.00%)		
> 5000	7 (9.33%)	4 (11.43%)		
Daily mobile phone use time			−0.64	0.521
< 1 h	36 (48.00%)	16 (45.71%)		
1 ~ 3 h	33 (44.00%)	14 (40.00%)		
> 3 h	6 (8.00%)	5 (14.29%)		
Mobile phone use experience			7.00	**0.008**
Less experience	29 (38.67%)	23 (65.71%)		
Moderate experience	46 (61.33%)	12 (34.29%)		

Bold indicates that the differences between groups are statistically significant ($p < 0.05$)

that 72.73% (80/110), 57.27% (63/110), and 40.00% (44/110) perceived the Care Receiver App as positive, useful, and satisfactory, respectively.

Between-group comparisons and logistic regression results

Table 3 presents the comparison results between the Positive Usability Group (mean item score: 3.37 ± 0.24) and the Negative or Neutral Usability Group (mean item score: 2.79 ± 0.18). Older individuals in the Positive Usability Group tended to be younger, have a higher level of education, and possess more extensive experience with smartphone usage (all $p < 0.05$).

Following bootstrapped forward stepwise Logistic regression (see Table 4), age and mobile phone use experience emerged as significant factors associated with poor perceived usability of the Care Receiver App ($p < 0.05$), while education was no longer statistically significant ($p = 0.812$). Individuals who are younger and have more experience using mobile phones perceive the Care Receiver App as more useful, with ORs of 1.08 (95%CI: 1.01, 1.17) and 0.31 (95%CI: 0.13, 0.73), respectively.

Table 4 Logistic regression results of the perceived usability of the Care Receiver App

Variables	β	SE	Wald χ^2	*p-value*	OR (95%CI)
Intercept	−4.44	2.55	3.03	0.082	0.012
Age	0.08	0.04	4.58	0.032	1.08 (1.01, 1.17)
Mobile phone use experience	−1.18	0.44	7.13	0.008	0.31 (0.13, 0.73)

SE standard error, *OR* odds ratio, *CI* confidence interval

The Nagelkerke R^2 value of 14.32% demonstrated the model can explain 14.32% of the variance in older people's usability perception of the Care Receiver App. The True Positive Rate of 68.75% and True Negative Rate of 74.47% implied acceptable ability in identifying positive and negative cases, yet with room for enhancement considering the False Positive Rate of 25.53% and False Negative Rate of 31.25%. The Hosmer–Lemeshow test suggested a satisfactory model fit ($\chi^2 = 7.73$, $p = 0.460$). As illustrated in Figure S3, the AUC was 0.702 (95%CI: 0.590–0.813), indicating moderate discriminatory ability.

Discussion

Inspired by the principle of neural reflex, the current study developed the SMART system, a knowledge-based CDSS, to facilitate integrated home-based geriatric care. Equipped with evidence-based interventions and a set of algorithms, the SMART system was designed to assist in diagnosing care problems and customizing integrated care plans across eleven predefined domains based on older people's comprehensive assessment results, daily monitoring data, and current medication status. Following a meticulous review by geriatric nurses, the care plans were sent to appropriate care providers based on their roles in implementing the interventions. This approach aimed to provide unified, coordinated, and continuous care to address older people's multifaceted needs. Specifically, interventions necessitating action from older adults, such as medication reminders, were delivered to themselves, while interventions like assisting older people with turning over were distributed to their daily caregivers. Professional interventions, including indwelling gastric tube care, were allocated to qualified nurses, and cleaning services were sent to domestic workers. Although primarily intended for home-dwelling older people, the SMART system is also accessible to older individuals in various institutions, except those undergoing acute hospital treatments. The usability testing revealed positive usability perceptions of the Care Receiver App among older individuals. To the best of our knowledge, this is the first exploration to develop an integrated home-based geriatric care model facilitated by the principle of neural reflex and knowledge-based CDSS, offering both a methodological paradigm for future research and a promising option for integrated home-based geriatric care at home.

A key strength of this study lies in applying the principle of neural reflexes to design our SMART system, addressing the lack of effective collaboration among various care providers [47–49]. In human physiology, a neural reflex involves the coordinated actions of sensory receptors, sensory neurons, integration centers, motor neurons, and effector organs, enabling rapid and automatic responses to stimuli that maintain homeostasis and protect against potential harm. For example, when blood sugar drops, the body initiates a series of reflexive responses, such as releasing glucose from the liver and stimulating appetite, to ensure sufficient energy supply. Similarly, the SMART system mirrors this coordinated response by transmitting data collected by Sensors and Scales to the Cloud Platform via WiFi or 5G for comprehensive analysis to generate customized integrated care plans. These plans are then communicated to appropriate care providers within the Total Care System, supporting coordinated care. An example is that if the SMART system detects a sudden fall, it could promptly alert family members or main caregivers for immediate assistance, nurses for timely assessment and professional suggestions, and medical institutions for further treatment if necessary. This coordinated effort allows all parties to work together effectively, with the expectation of mitigating fall-related injuries through real-time detection of abnormal situations and prompt activation of integrated interventions.

The transparency and interpretability of the SMART system represent another potential strength [26]. As a knowledge-based CDSS, the SMART system relies on the pre-embedded knowledge base and rules for decision-making. After collecting data on older people, the SMART system could diagnose the existing or potential care problems based on their abnormal conditions, and further customize interventions and implementation approaches by considering their preferences, lifestyle, and other characteristics. The Professional Care Provider App allows care providers to access the care problems, interventions, implementation approaches, and their underlying evidence. This feature could enhance decision-making accuracy and transparency, promote alignment with clinical guidelines, and facilitate personalized and appropriate care for older adults.

Overall, the Care Receiver App within the SMART system was perceived as useful among older people. Several possible reasons could account for this. Firstly, following the IM framework and nursing process, the SMART knowledge base incorporates evidence-based interventions tailored to older people's multifaceted care needs [50]. Secondly, instead of predefined interventions, the SMART system could customize interventions and implementation approaches with real-time feedback [51, 52]. Furthermore, rooted in the principle of neural reflex, the SMART system could provide continuous, coordinated, and integrated interventions. Individuals who were younger and had more mobile phone experience found the Care Receiver App more useful, likely due to their familiarity with technology, higher confidence in using digital tools, and ease in integrating new systems into their daily routines [53]. While the model performance remains moderate in explanatory power, case identification, and discriminatory ability, likely due to the limited sample size, this exerts minimal impact on our findings. The core objective of usability testing was to assess the perceived usability of the Care Receiver App among older adults and explore influencing factors, rather than to construct a prediction model.

Meanwhile, the perceived ease of use is another essential element in developing useful tools [54]. In our SMART system, we applied several strategies to enhance its ease of use, such as using large font sizes and distinct color blocks, incorporating a read-out mode to reduce visual fatigue, and introducing multimedia elements for better comprehension [55]. However, the perceived ease of use among older people remained low. There may be multiple reasons for this. First, the SMART system's multiple functions designed to satisfy older people's multifaceted care needs may overwhelm them during the learning process, potentially compromising its ease of use [56]. Second, lower digital literacy among older people [53] and the challenges faced by hospitalized older participants in familiarizing themselves with the Care Receiver App and completing the designated tasks within 24 h, along with treatment tasks, may further hinder perceived ease of use. Therefore, we will simplify the interfaces while maintaining functionality and implement strategies to improve digital literacy.

This study is subject to several limitations. Firstly, older people were absent in the initial design of the SMART system. To remedy this, we conducted a needs assessment to guide system development, ensuring alignment with their needs and preferences. An iterative design process by periodically inviting older adults to test the system was also employed. The usability testing yielded satisfactory results, indicating that our strategies compensated for this limitation. Secondly, while separate portals for professional care providers from both the healthcare and social care sectors have been designed, the interfaces for those in the social care sector are still under development. Thirdly, the SMART system is merely compatible with Android-based smartphones, future iterations of the SMART system will ensure compatibility with both Android and iOS through WeChat mini-programs. Ongoing improvements of the SMART system and its implementation will focus on optimizing functions, simplifying processes, enhancing algorithms for better performance, upgrading the user interface to enhance friendliness and visual appeal, ensuring data security, gathering user feedback for targeted adjustments, and expanding compatibility with various devices and operating systems. Fourthly, due to the difficulties arising from the COVID-19 pandemic, we included hospitalized older individuals for usability testing, which may introduce potential selection bias since these adults are more likely to exhibit a stronger interest in App use and receive more support from healthcare professionals. To mitigate this bias, we specifically recruited older adults in geriatric wards who were about to be discharged to their homes. Fifthly, using self-reported ratings for usability testing could lead to neglecting certain usability issues within the SMART system. Considering the feedback of older adults when performing the assigned tasks can provide valuable insights to refine our SMART system in future studies. Finally, despite the acceptable perceived usability and potential usefulness, further investigation into the feasibility and effectiveness of implementing the SMART system to improve integrated home-based geriatric care is urgently needed, covering areas like participant retention, fidelity to the personalized interventions, user adherence and engagement, and effectiveness across various health dimensions.

Conclusion

Our study developed an integrated geriatric care model using a knowledge-based CDSS architecture inspired by the principle of neural reflex. The development process can provide methodological foundations for similar future initiatives, and the SMART system could serve as a viable reference for addressing the implementation challenges of the integrated geriatric care model. Furthermore, our study indicated acceptable usability perception of the SMART system among older population. To fully evaluate the feasibility and effectiveness of the SMART system in enhancing integrated home-based geriatric care, a rigorous large-scale randomized controlled trial is essential in the future.

Abbreviations

WHO	World Health Organization
IoT	Internet of Things
AI	Artificial intelligence
CDSS	Clinical Decision Support System
IM	Intervention Mapping
B/S	Browser/Server
C/S	Client/Server
API	Application programming interface
UI	User interface
ISO	International Standards Organization
Health-ITUES	Health Information Technology Usability Evaluation Scale
IQR	Interquartile range
SD	Standard deviation
CARE	Continuity Assessment Record and Evaluation

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12877-025-05829-5.

Additional File 1: Additional Method 1. The methods to identify older individuals for the iteratively testing of the alpha version of the SMART system. Table S1. The care problems that the SMART system was designed to diagnose and address. Table S2. Matrices of care problems and personalized interventions that the SMART system was designed to address: examples. Table S3. Functionality requirements of each component of the SMART system. Table S4. The international and national data standards used to develop the SMART system. Table S5. Characteristics of the included older individuals for the iteratively testing of the alpha version of the SMART system. Table S6. The types of candidate variables and value assignment methods in the usability testing. Figure S1. The overall functional modules of the SMART system. Figure S2. Examples of user interfaces of the Care

Receiver App. Figure S3. ROC curve of the Logistic Regression model. ROC, Receiver Operating Characteristic.

Additional File 2. Logo of the SMART system.png.

Additional File 3. Registration.mp4.

Additional File 4. Login and logout.mp4.

Additional File 5. Comprehensive Assessment Module.mp4.

Additional File 6. Daily Monitoring Module.mp4.

Additional File 7. Medication management module.mp4.

Additional File 8. Professional review and Information Reminder Module. mp4.

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Authors' contributions
Rongrong Guo: Formal Analysis, Data Curation, Writing—Original Draft. Huan Fan: Methodology, Investigation. Shuqin Xiao: Methodology, Investigation. Ziling Zheng: Formal Analysis, Data Curation. Fangyu Yang: Methodology, Data Curation. Yanyan Xiao: Data Curation. Xue Yang: Data Curation. Ying Wu: Conceptualization, Methodology, Writing—Review & Editing, Supervision. Rongrong Guo, Huan Fan, and Shuqin Xiao made equal contributions to this manuscript. The corresponding author of this article is Ying Wu. All authors reviewed the manuscript.

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Data availability
Any personnel affiliated with an academic institution can request access to relevant data from Professor Ying Wu (helenywu@vip.163.com) for research purposes. Applicants are required to submit a research proposal. Once approved, they will be granted access to the data.

Declarations

Ethics approval and consent to participate
The study was conducted in compliance with the ethical principles outlined in the Helsinki Declaration (https://www.wma.net/policies-post/wma-declaration-of-helsinki/). The study, encompassing the system development and usability testing, was approved by the Institutional Review Committee of the Capital Medical University (Approval No. 2015SY49). It was also registered in the Chinese Clinical Trial Registry (Registration number: ChiCTR-IOR-17010368) on 12/01/2017. All participants provided written informed consent on enrollment.

Consent to publication
Not Applicable.

Competing interests
The authors declare no competing interests.

Author details
[1]School of Nursing, Feng-Tai District, Capital Medical University, 10 You-an-Men Wai Xi-Tou-Tiao, Beijing 100069, China. [2]Peking University First Hospital, Beijing 100034, China. [3]Department of Nursing, Beijing Hospital, National Center of Gerontology, Institute of Geriatric Medicine，Chinese Academy of Medical Sciences, Beijing 100730, China.

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