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Research article

Age-appropriate design of domestic intelligent medical products: An example of smart blood glucose detector for the elderly with AHP-QFD Joint KE

Xiaojie Li [a,b,*], Hong Li [b,c]

[a] School of Intelligent Manufacturing and Electrical Engineering, Guangzhou Institute of Science and Technology, Guangzhou, 510540, China
[b] Faculty of Innovation and Design, City University of Macau, Macau, 999078, China
[c] School of Creativity and Design, Guangzhou Huashang College, Guangzhou, 511300, China

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ABSTRACT

Background: In response to the rise of intelligent products and the increasing prevalence of urban "empty nesters," we have developed a product specifically tailored for elderly diabetic patients. This product fulfils functional requirements and addresses stylistic preferences, contributing to the age-friendly evolution of home intelligent medical devices, particularly in intelligent blood glucose monitoring.

Methods: Our approach commenced with a comprehensive user experience analysis to ascertain the needs of elderly users regarding home blood glucose meters. This involved constructing a hierarchy of user demands, followed by analysing and prioritising these needs. Utilizing Quality Function Deployment (QFD), we aligned user requirements with design specifications, identifying specific product functionalities and service design elements. Further, we employed Kansei Engineering (KE) to select sample designs that resonate with the concept of sensual imagery, leading to the derivation of specific modelling intentions. Combining these design elements, we proposed product design strategies and conducted practical case studies. The effectiveness of these designs was then assessed through fuzzy evaluation methods, allowing for user feedback.

Results: Employing the Analytic Hierarchy Process for goal analysis, along with Quality Function Deployment theory and Kansei Engineering, we developed a home intelligent blood glucose meter catered to the elderly. This device not only meets its users' physiological and psychological needs but also provides an operationally convenient, health-conscious, and aesthetically pleasing experience.

Conclusions: This methodology enhances the age-appropriate design of home-based smart glucose monitors for the elderly, offering innovative insights and optimization strategies for designing elderly-centric smart medical products.

1. Introduction

The advancement of science and technology has facilitated the transition of various smart devices from laboratories to consumer

* Corresponding author. School of Intelligent Manufacturing and Electrical Engineering, Guangzhou Institute of Science and Technology, Guangzhou 510540, China.

E-mail address: 19358593039@163.com (X. Li).

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markets. This transition is particularly notable in products designed for the elderly, which have evolved significantly in function and form. In the context of an ageing population, intelligent healthcare products for the elderly are experiencing a surge in development opportunities. Diabetes, a globally prevalent health issue, is especially pertinent in this regard. According to the World Health Organization, approximately 155 million people worldwide are affected by diabetes, a number projected to nearly double to 300 million by 2025 [1,2]. As we progress into the 21st century, improved living standards have been accompanied by decreased physical activity, contributing to increased in diabetes prevalence, especially among the elderly. The Chinese Medical Association Diabetes Branch predicts that over 18% of individuals over 60 years old are diabetic. Concurrently, China's ageing population grows by an estimated 7 million annually. Given diabetes' incurability and increased prevalence with age, an ageing population could contribute to an influx of 300,000 to 400,000 new elderly diabetic patients each year [3].

Home blood glucose monitors, as convenient electronic devices, have become indispensable for elderly diabetic patients to manage their condition from the comfort of their homes. This study underscores the importance of designing and developing intelligent home medical products that are tailored to the needs of elderly users. Using the Web of Science database, a keyword search for "medical and health products for older adults" yielded 563 relevant entries. Vosviewer software was employed for the visual analysis and literature data interpretation, focusing on health products for the elderly. The keyword co-occurrence analysis focused on chronic diseases and healthcare (Fig. 1). Consequently, the design of a home blood glucose meter that caters to the physiological and psychological needs of elderly diabetics is not only necessary but crucial for their health management [4,5].

2. Literature review

2.1. Aging-friendly design of smart health products

The emergence of new generation information technologies, including big data, the Internet of Things (IoT), and artificial intelligence (AI), has catalyzed a paradigm shift towards intelligent upgrades across various product domains. This shift is evident in smart homes, digital healthcare, and online shopping, accelerating the digitalization and integration of intelligence into urban living [6]. However, this technological advancement presents a dichotomy, especially for the elderly demographic. While intended to streamline and enhance daily life, smart products may inadvertently introduce new challenges and barriers for older users [7]. This contrast underscores a critical consideration in the design and development of intelligent products: the need to align technological

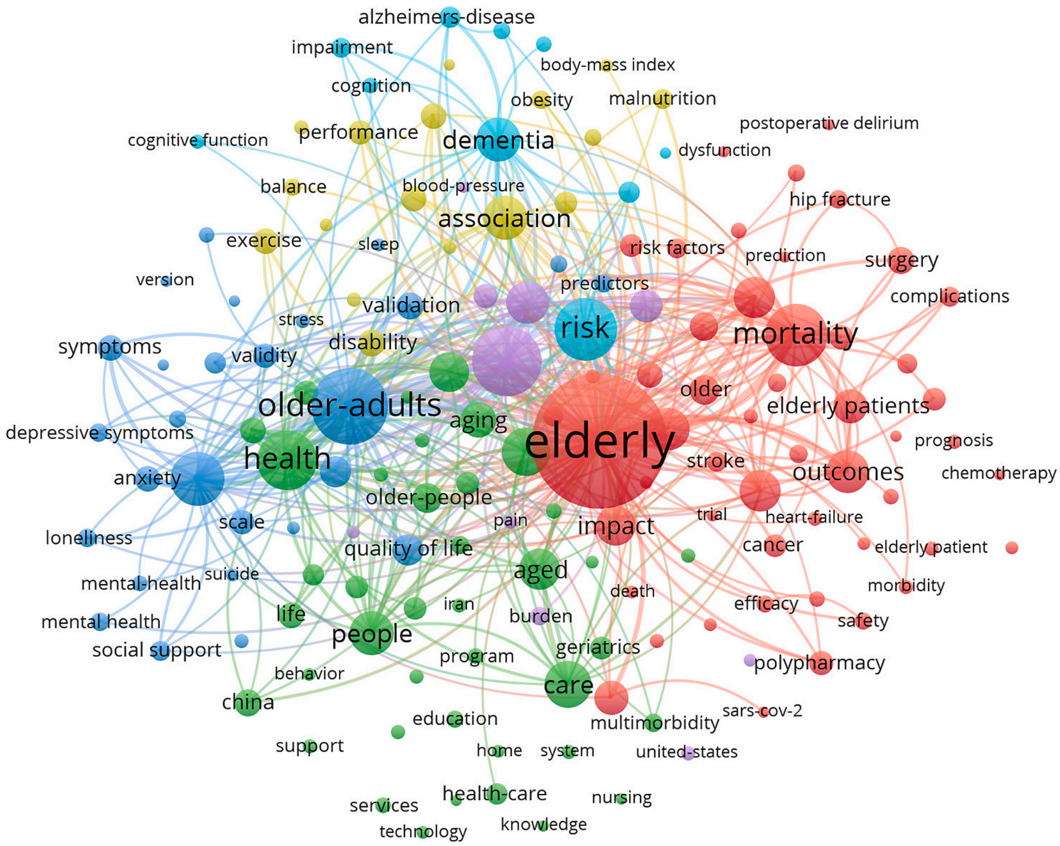

Fig. 1. Visual analysis of literature data on health products for older people.

advancements with user-centric design principles, particularly for populations that might not be as tech-savvy or physically agile as younger users. Exploring this technological-user gap is essential in ensuring that the benefits of smart technologies are accessible and advantageous to all age groups, especially the elderly.

The current focus on ageing-friendly design is twofold: addressing the decline in physiological functions among the elderly and innovating through technology integration. Predominant design theories include inclusive design and user experience design to make products accessible to a broader audience. Sumit Majumder and colleagues have highlighted the role of smart homes in this context. They propose that these homes, equipped with environmental and wearable medical sensors, actuators, and advanced communication technologies, can facilitate continuous remote monitoring of the health and well-being of older adults [8].

Similarly, Wen. TN and others have emphasized the importance of considering the social needs of elderly individuals living alone in smart product design. They argue that prolonged loneliness in the elderly is associated with increased risks of illness and premature death, suggesting that intelligent products could potentially offer companionship services to mitigate these risks [9]. Furthermore, Shou Fang Liu and the team have contributed to this discussion by classifying common smartphone operation gestures. They propose a novel one-finger operation method instead of the conventional multi-finger approach. This suggestion is based on the premise that such adaptations can better accommodate the needs of the elderly, thereby providing valuable references and design principles for smartphone products catering to an ageing population [10].

Zhang Weiwei has introduced a concept in smart product design for the elderly that melds technological advancements with design ethics, particularly pertinent in the digital era [11]. This idea resonates with Dou Jinhua and Qin Jingyan's perspective, which posits that aging-friendly design is fundamentally human-centred. It emphasizes understanding and incorporating the psychological, physiological, and behavioural characteristics and preferences of the elderly into the design process. This approach ensures that products and services are attuned to the unique needs of this demographic [12].

Yang Minggang and colleagues expand on this by noting the specific challenges smart products present for the elderly, particularly regarding memory and sensory requirements. They highlight that memory decline in the elderly may hinder the recall of functional operations, and there is an increased demand for designs accommodating older users' vision and tactile abilities. Consequently, the design of smart homes for the elderly should consider multi-sensory and multifaceted interaction modes and adhere to user-friendliness, safety, and practicality. Moreover, these designs should integrate emotionally engaging and pleasurable elements, catering to the comprehensive needs of the elderly [13].

2.2. User experience and overview

The term 'user experience' encompasses the psycho-emotional responses elicited in users when interacting with products, both physical and non-physical. This concept extends to all facets of the product, including its inherent features, associated services, and the nature of user-product interaction [14–16]. User experience is inherently subjective and emotional, varying significantly among individuals interacting with products in diverse environments. This variability results in a range of physical and mental sensations experienced by different users [17,18]. Given the subjective nature of user experience, product design must balance personalization and general applicability. This approach aims to accommodate a broad user sample's shared characteristics while providing a tailored experience that allows each target user to derive enjoyment and satisfaction from the product. Such a design philosophy acknowledges individual users' unique needs and preferences, striving to ensure that each interaction with the product is pleasurable and meaningful [19].

Professor Donald Norman, a distinguished psychologist, introduced a pivotal concept in the realm of user experience, viewed through the lens of psychology and human needs [20]. He categorizes user experience into three levels: instinct, behaviour, and reflection. Norman emphasizes a 'human-centred' approach in product design, advocating for a focus on user needs and psychology [21,22]. This approach underscores the importance of fundamental product aspects such as functionality, usability, and safety while advocating for a comprehensive consideration in product design that encompasses functionality, ease of use, originality, artistic value, and engagement. Applying Norman's user experience design principles to the design of home glucose meters for the elderly necessitates focusing on this demographic's psychological and physical needs. It is particularly important to consider the experiences of elderly individuals living alone. The design should facilitate a positive user experience, ensuring that these individuals can effortlessly use medical products in their daily lives at home. This approach meets their medical needs and contributes to their overall well-being by addressing the broader aspects of user experience as outlined by Norman.

2.3. AHP-QFD

AHP hierarchical analysis is a decision-making method based on a multi-criteria context widely used in various fields [23]. The hierarchical analysis first identifies the factors that influence decision-making and then arranges these factors into different levels of hierarchy to reduce the complexity of the decision problem [24–28]. Three principles can be used to summarize the AHP procedure, namely decomposition, comparative judgment, and synthesis of priorities [29]. QFD quality engineering unfolding theory is a user needs-oriented quality management tool pioneered by Akao Corporation. It is a systematic approach to translating customer requirements into corresponding engineering features that allow the optimization of product design methods [30]. Ajit Kumar Singh combined AHP with QFD and then used the TOPSIS method to improve the quality of product design and services to meet the user's needs to a greater extent [31]. f. K. Varolgunes proposed to use QFD for finding customer satisfaction and combined with AHP to select the best design solution to improve the design quality of buildings [32]. O. A. Shvetsova proposed an integrated analysis approach combining QFD and AHP methods with data envelopment analysis DEA, which was validated by a case study of a new design concept

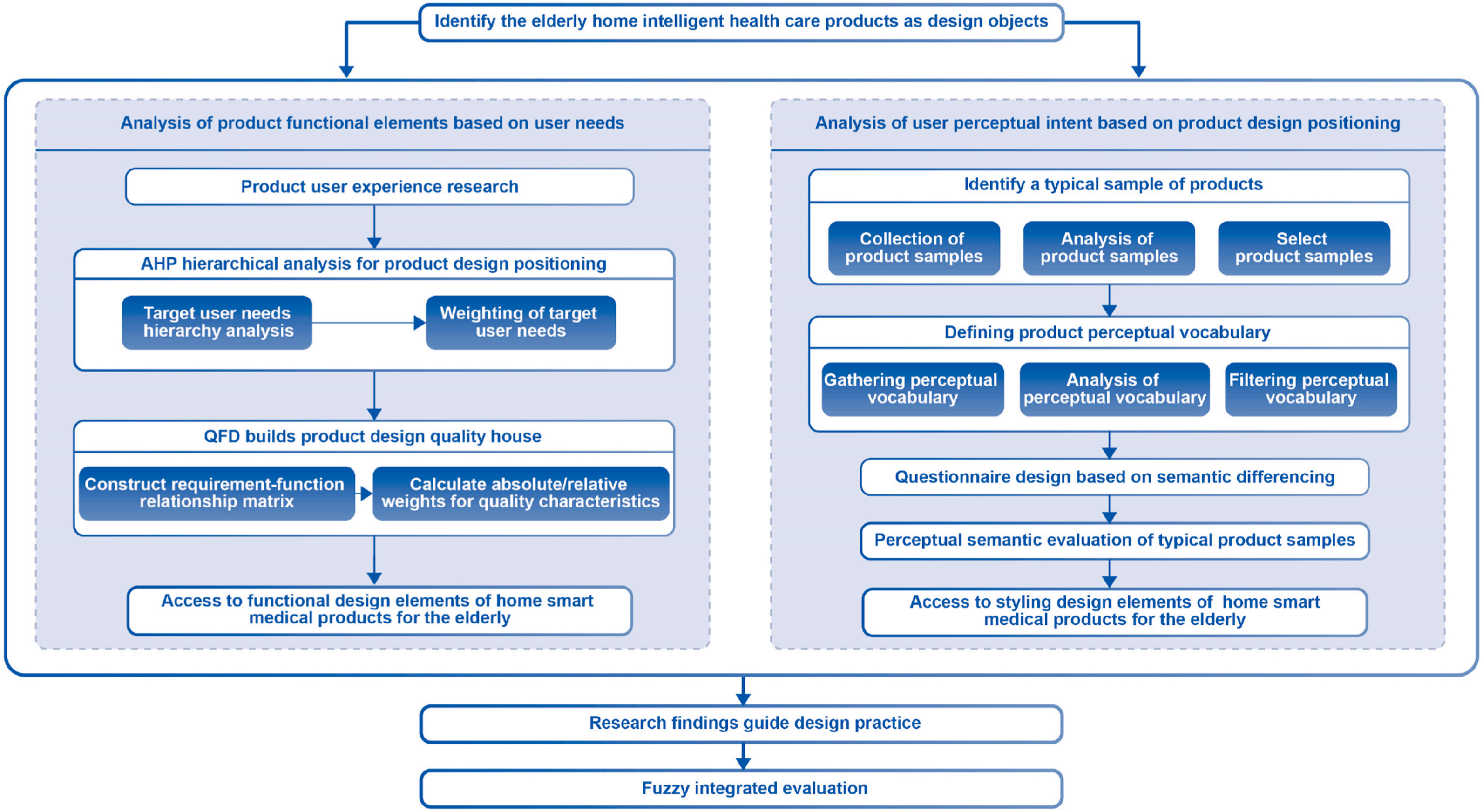

Fig. 2. Flowchart of the research framework of aging-appropriate innovative design of home intelligent medical products for the elderly.

of an evaporator in an automotive air conditioning system to improve the effectiveness of the method again in product decision making [33].

2.4. KE

The study of users' emotional needs is also significant in the product design. Many scholars have adopted the approach of perceptual engineering [34] to explore users' emotional factors in depth. KE is to map between users' abstract emotional factors and the elements of product design and use users' emotional expectations of the product to design products that meet users' emotional needs [35]. Hartono [36] used perceptual engineering to study lounge and concourse services in international airports to specify customers' emotional needs. Zabotto et al. [37] developed a perceptual engineering system based on a rough set of probability statistics to capture users' opinions on product design. Tong [38] implemented a product development design process using perceptual engineering and grey correlation analysis to establish the relationship between customer needs and product elements relationship between them.

2.5. Research hypothesis

An extensive review of existing literature reveals several critical research gaps in the field of blood glucose monitoring for diabetic patients, particularly concerning elderly users. Firstly, while various blood glucose monitoring products have been developed, there is a conspicuous absence of studies focused on age-appropriate design and exploring theoretical frameworks tailored to the elderly. This gap indicates a need for more targeted research in this area.

Secondly, the current market offers a range of blood glucose monitoring products and services, including home blood glucose testers, continuous blood glucose monitoring devices, and blood glucose management apps. However, there is a noticeable deficiency in research aimed at improving the design of these existing products, especially in terms of integrating intelligent technologies for optimization.

Thirdly, the combined method of Analytic Hierarchy Process (AHP), Quality Function Deployment (QFD), and Kansei Engineering (KE) has not yet been applied to the specific context of glucose monitoring and management for elderly diabetic patients. The absence of this application in existing research underscores a significant opportunity for innovation and improvement in this field.

Examining the current international research landscape reveals that foreign studies on new technologies and design concepts are more advanced, emphasising practical applications. In contrast, domestic research remains exploratory, and current findings do not fully address the aging-friendly design of smart products. Particularly, there is a notable gap in research on the integration and innovation of new technologies, as well as a lack of focus on the real-world needs of the elderly in various scenarios for smart health products. To address these deficiencies, this study leverages user experience theory to deeply explore the psychological, physiological, and behavioural characteristics of the elderly. Employing the Analytic Hierarchy Process (AHP), it constructs a hierarchical model of user needs with the elderly as the primary focus, analyzing and determining the significance of these needs. Once user needs are established, they are transformed into design elements using the Quality Function Deployment (QFD) method. This approach encompasses structural and interactive services, forming a systematic product design function and service model. However, the AHP-QFD methodology needs to adequately consider user emotions, which are crucial in influencing user experience. Thus, this study proposes integrating the Kansei Engineering (KE) method to construct an emotional intention model of product design, focusing on the emotional preferences of users. By effectively combining the functional service model with the emotional intention model, this research enhances the design principles and decision-making processes for intelligent products tailored to the elderly. The integrated AHP-QFD-KE design method represents a user-centred approach, considering the physical, psychological, emotional, and experiential factors influencing the elderly's interaction with products and service systems. This comprehensive methodology aims to expand and improve the knowledge system and theoretical methods in the field of aging-adapted design.

Given these identified gaps, the research proposed in this study holds substantial significance and value. It aims to address these shortcomings by developing a more effective, age-appropriate, and technologically advanced approach to the design of home smart medical products for the elderly. The research framework for this innovative design approach is illustrated in Fig. 2 of the study.

3. Methods

The purpose of this research work is to address the issue of glucose detection as well as intelligent management in elderly diabetic patients. We proposed three research questions to identify User Requirements(URs) and Design Requirements(DRs) in home innovative glucose management products for the elderly regarding user experience. Identify URs and DRs in designing home glucose meters for the elderly to monitor and enhance the glucose self-management of elderly diabetic patients. Capture and analyze Emotional Requirements(ERs) of elderly users to enhance the emotional experience of product use for elderly diabetic patients to understand how to develop effective design strategies based on theoretical results. The synthesis anticipates that the integrated AHP-QFD-KE approach will show advantages in addressing the three research questions we propose. This study complies with ethical standards and is approved by the Guangzhou Institute of Science and Technology. It obtains written informed consent from participants. The recruitment period for this study started in June 2022 and ended in August 2022.

The three research questions we proposed on the design of a product for glucose self-management in the elderly with the following research steps are shown in Fig. 3.

Step 1. Identifying the needs of elderly users: Market research and expert involvement formed the basis for defining user needs and expectations and identifying user requirements for home smart glucose monitoring products for diabetes glucose self-management in the elderly.

Step 2. Definition of product design elements: Work with expert groups to define product characteristics (PChs). In collaboration with the group of experts, the definition of the characteristics of the product (PChs) and the service's (SChs) characteristics is performed.

Step 3. Application of AHP: Based on the output of a particular customer survey, user requirements were prioritized using AHP hierarchical analysis. Prioritization was performed, and the importance of each user's requirements was determined by conducting two-pair comparisons. A 9-level Likert scale was used for pairwise comparisons. Level 9 represents the matrix's most important degree, while level 1 represents the miniature matrix's most important degree of the matrix. The most important degree of the matrix. Once the pairwise comparisons are performed, the consistency of the results is immediately checked. Finally, the relative weights of the user requirements will be denoted as the feature vector W.

Step 4. Application of AHP-QFD: This phase allows engineers to assess the relative importance of each user requirement to the product design elements and to define the quality functional design elements of the Product.

Step 5. Application of KE: By establishing a perceptual vocabulary of home blood glucose testers for the elderly, we analyzed the perceptual intention of elderly diabetic users for existing blood glucose management products and used qualitative and quantitative methods to analyze and obtain the elements of product design for older adult's blood glucose self-management based on perceptual intention.

Step 6. Propose product design strategies: The product functional design elements derived from AHP-QFD and KE's product styling design elements were synthesized and analyzed to derive a product design strategy for blood glucose self-management products that meet the user experience of elderly diabetic patients.

Step 7. Design Case Studies: Based on the theoretical design model, the design practice of blood glucose testing products for elderly diabetic patients is carried out. The user satisfaction with the proposed theoretical design model is finally verified by fuzzy analysis.

4. Research process: age-appropriate design of intelligent blood glucose testing products for the elderly

4.1. Step1. User experience and overview

The target user group of the product is mainly those older adults aged 55 and above who have diabetes and are on home maintenance, whose children work outside the home and are neglected by them and who may have already retired. Our data collection process consisted of two phases. The first phase identified URs and DRs of home smart health products in the self-management of diabetes in older adults.In this phase, we conducted a user interview. For the user interviews, 24 respondents from different backgrounds were selected to participate in our study, including six older adults with diabetes over 55 years of age, four family members of the patients, four medical caregivers, two physicians, two industrial designers, three design university faculty members, three design doctoral students, and two technicians. In the second phase, a second user interview was conducted, as well as a questionnaire survey, with 80 questionnaires placed and 68 valid questionnaires returned.

4.1.1. The physical needs of the older adults

The most direct physical response of the older adult population due to their increasing age is the deterioration of the functions of various organs [39,40]. As a result, many complications arising from organ degeneration, such as diabetes, heart disease, rheumatism, etc., will gradually appear in the body of older adults. Memory will also slowly decline, learning ability is not as good as before, and presbyopia hearing loss is most of the problems older adults face. On the other hand, with the rapid development of society, some older adults have difficulty keeping up with the development of the times in terms of their way of thinking and living habits [41,42]. Unreasonable design can seriously affect the usability and user experience of a product.

Surveys show that 77% of people develop presbyopia at 50 [43], so for these changes in the body of older adults, the physiological needs are mainly in terms of ease of operation, simplicity, safety and hygiene.

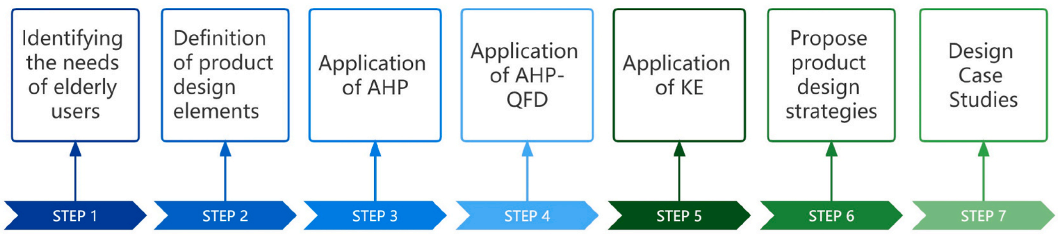

Fig. 3. Research steps.

4.1.2. Psychological needs of the older adults

On the one hand, older adults living alone often feel strongly lonely due to lacking family members, and others do not easily understand them. On the other hand, they often have low self-esteem due to changes in their bodies and feel that they are getting worse [44]. Medical products often give people a cold and indifferent feeling, which makes older adults feel more intimidated when using them.

Based on the above research and analysis, the needs of the target users were collated. A hierarchy of user needs analysis was established [45,46], with the first layer being the total needs of the target users and the second layer functional needs, ease of use, safety and appearance (see Fig. 4).

4.2. Step 2. Definition of product design elements

Through the collation of 68 valid questionnaires, research information from on-site interviews and focus groups involving 14 relevant users and 10 experts, and inviting 3 industry experts to summarize and conclude the product design elements (see Table 1).

4.3. Step 3. Application of AHP

After constructing the user needs hierarchy, the AHP hierarchical analysis method is applied to construct the user needs judgment matrix, which can hierarchize the multi-objective complex problems and further determine the weight of user needs through the decision evaluation consistency test to achieve the purpose of reducing decision bias [47]. Specific calculation steps.

4.3.1. Construct a judgment matrix

Six relevant experts are invited to rate the target demand elements, four of which have valid scores, and the weighted average of the

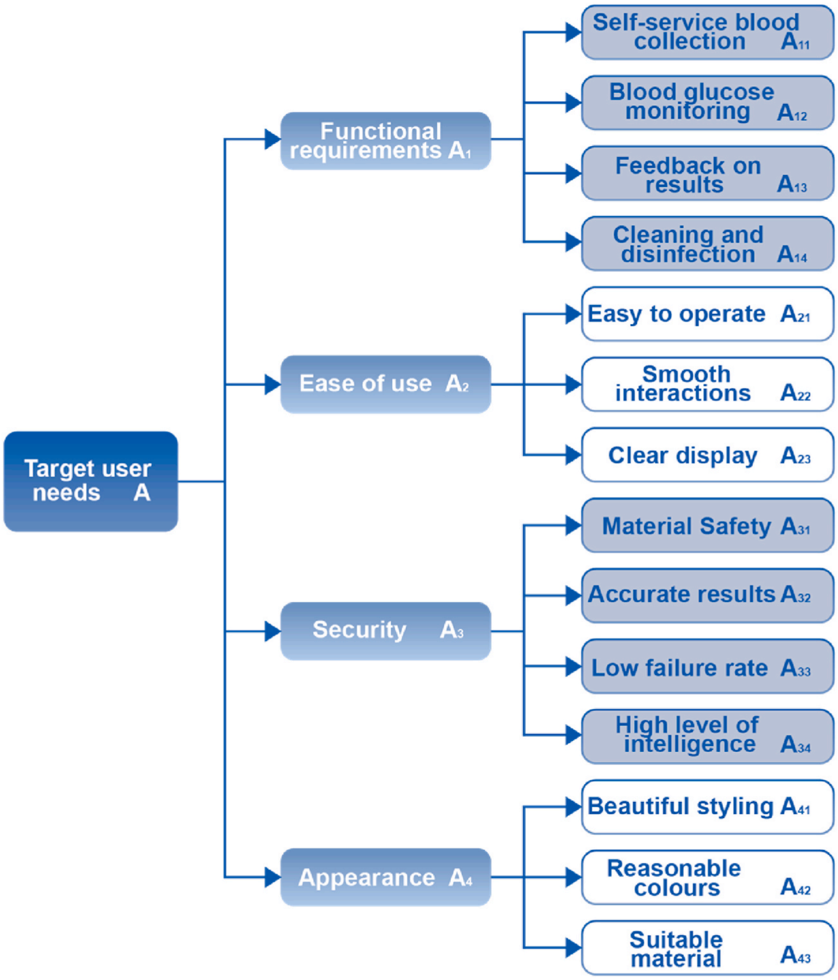

Fig. 4. Target user needs hierarchy analysis model.

Table 1
List of product design elements of intelligent glucose meter for elderly home use.

Classification	Notation	Design Requirement	Description
Technology & Functionality	DR1	Easy to operate	Reduce the operation steps. Patients can do the blood collection and testing by themselves.
	DR2	Smart Results Feedback	Integration of intelligent-based sensors, actuators and control functions, the results are automatically uploaded to the cloud after detection and big data analysis and feedback, real-time accurate monitoring of the user's blood glucose health.
	DR3	Safe and reliable materials	The materials selected for the products conform to the industry standards for related products, and the selection of consumables must conform to the industry standards for medical consumables-type supplies.
	DR4	Styling and aesthetics	The materials chosen for the products are in line with the relevant product industry standards, and the choice of consumables must be in line with the industry standards for medical consumables.
Interaction and Service	DR5	Multiple information channel feedback	Intelligent information feedback using multimodal channels of sound, light and electricity.
	DR6	Interface Aging	The design of the interaction interface should align with the elements of age-appropriate design, simple and smooth interface interaction, simple learning, and good interaction vision.
	DR7	Consumables Distribution Service	The product service provider should provide convenient delivery services for blood collection needles, test strips and other consumables for blood glucose meters.
	DR8	Telehealth Consultation Service	A provider of blood glucose meter products and services, offering long-term blood glucose monitoring, big data analysis and forecasting, and remote health care consulting services.

raw data is calculated as the user demand weights based on the rating values [48]. A pairwise comparison judgement matrix is constructed in Equation (1).

$$A = (aij)n \times n, aij > 0, aji = \frac{1}{aij} \tag{1}$$

where: *aij* is the importance of each element of a level relative to the previous level, the weighting relationship obtained by comparing two, Ai: Aj = aij (i, j = 1, 2 …, n)

4.3.2. Hierarchical single ranking and consistency test

Calculate the maximum characteristic root λ_{max} of the judgment matrix A. The normalized eigenvector corresponding to this eigenvalue is marked as w. The elements of w are the weights of the relative importance of the same level factor corresponding to a factor in the previous level factor [49,50]. This process is called single hierarchical ordering. The ability to confirm the single hierarchical ranking is also subject to a consistency test. In the specific calculation process, Equation (2) is applied to calculate the CI to represent the consistency indicator of the judgement matrix, and apply Equation (3) to calculate the CR for the consistency ratio test.

$$CI = \frac{\lambda \max - n}{n - 1} \tag{2}$$

$$CR = \frac{CI}{RI} \tag{3}$$

where: λ_{max} - maximum characteristic root. CI - consistency indicator. RI - random consistency indicator. CR - consistency ratio. n - number of indicators.

Generally, the consistency test is passed when the consistency ratio is $CR < 0.1$. If it does not pass, the judgment matrix needs to be reconstructed.

Following the steps of the hierarchical analysis, firstly, the requirement weights of each required element in the second level are calculated relative to the target layer in the first level and tested for consistency (see Table 2). At this point, all the judgment matrices satisfy the consistency test (see Tables 3–6).

Finally, the total hierarchical ranking is carried out again. The weight values of the demand elements under the total demand of the user are multiplied by the weight values of other sub-demand elements, respectively to calculate the comprehensive weight value of each sub-demand element in the whole target demand system (see Table 7).

Table 2
Judgement matrix and weights for each demand element (A1 to A4) under total user demand A.

A	A1	A2	A3	A4	Weighting *w*
A1	1	1/3	1/5	1/3	0.0736
A2	3	1	1/3	3	0.2476
A3	5	3	1	5	0.5495
A4	3	1/3	1/5	1	0.1293

It was calculated that $\lambda_{max} = 4.1981$, CI = 0.660, RI = 0.90 and CR = 0.0734 < 0.1, which satisfied the consistency test.

Table 3
Judgement matrix and weights for each requirement element (A11 to A14) under functional requirement A1.

A1	A11	A12	A13	A14	Weighting *w*1
A11	1	3	5	7	0.5650
A12	1/3	1	3	5	0.2622
A13	1/5	1/3	1	3	0.1175
A14	1/7	1/5	1/3	1	0.0553

It was calculated that $\lambda_{max} = 4.1170$, CI = 0.0390, RI = 0.90 and CR = 0.0433 < 0.1, which satisfied the consistency test.

Table 4
Judgement matrix and weights for each demand element (A21 to A23) under Ease of Use A2.

A2	A21	A22	A23	Weighting w3
A21	1	1/3	1/5	0.1095
A22	3	1	1/3	0.3090
A23	5	3	1	0.5815

It was calculated that $\lambda_{max} = 3.0385$, CI = 0.0193, RI = 0.58, CR = 0.0332 < 0.1, which satisfied the consistency test.

Table 5
Judgement matrix and weights for each demand element (A31 to A34) under security A3.

A3	A31	A32	A33	A34	Weighting w4
A31	1	1/3	5	3	0.2876
A32	3	1	5	3	0.5084
A33	1/5	1/5	1	1/3	0.0645
A34	1/3	1/3	3	1	0.1431

It was calculated that $\lambda_{max} = 4.1981$, CI = 0.0660, RI = 0.90 and CR = 0.0734 < 0.1, which satisfied the consistency test.

Table 6
Judgement matrix and weights for each demand element (A41 to A43) under appearance A4.

A4	A41	A42	A43	Weighting w5
A41	1	5	3	0.6370
A42	1/5	1	1/3	0.1047
A43	1/3	3	1	0.2583

It was calculated that $\lambda_{max} = 3.0385$, CI = 0.0193, RI = 0.58, CR = 0.0332 < 0.1, which satisfied the consistency test.

4.4. Step 4. Application of AHP-QFD

The House of Quality (HOQ) is built based on the design features proposed in step 2 [51–53], combined with the user requirements elements, to meet the needs of elderly diabetic users for innovative home blood glucose testing products.

Table 7
Combined weights of sub-demand elements relative to total user demand.

	A1 0.0736	A2 0.2476	A3 0.5495	A4 0.1293	Target weights	Sort by
A11	0.5650	–	–	–	0.0416	7
A12	0.2622	–	–	–	0.0193	11
A13	0.1175	–	–	–	0.0086	13
A14	0.0553	–	–	–	0.0041	14
A21	–	0.1095	–	–	0.0271	10
A22	–	0.3090	–	–	0.0765	6
A23	–	0.5815	–	–	0.1440	3
A31	–	–	0.2876	–	0.1580	2
A32	–	–	0.5084	–	0.2794	1
A33	–	–	0.0645	–	0.0354	8
A34	–	–	0.1431	–	0.0786	5
A41	–	–	–	0.6370	0.0824	4
A42	–	–	–	0.1047	0.0135	12
A43	–	–	–	0.2583	0.0334	9

$$Wj = \sum_{i=1}^{n} wipij \tag{4}$$

$$Wk = \frac{Wj}{\sum_{i=1}^{m} Wj} \tag{5}$$

Where: *Wj*-Absolute weighting of quality characteristics. *Wk*-Relative weights of quality characteristics. *wi*-User demand weighting. *pi j*-Correlation coefficient. *n*-Total user demand. *m*-Total number of quality characteristics.

In addition, the importance degree was converted by the independent matching point method [54], and use Equations (4) and (5) to convert the importance degree of user needs into the importance degree of quality characteristics, which constituted the basement of the design quality house. The scoring and calculation results were filled into the corresponding quality house locations to establish the quality elements and customer demand quality house of the ageing-appropriate design of smart blood glucose meters for the elderly, and the results are shown in Table 8.

From the results unfolded by the functions in the quality characteristics, the design factors of the home smart blood glucose testing products for the elderly accounted for 56.4% in the technical function part. Among the design factors, according to the results of the absolute weight of quality characteristics, intelligent result feedback, easy operation, multi-information channel feedback, and age-appropriate interface are the main design points to guide the product design examples and meet the users' functional demands for the elderly's home smart blood glucose testing products.

4.5. Step 5. Application of KE

4.5.1. Establishing the perceptual vocabulary of home blood glucose testers for older adults

Firstly, through questionnaires and face-to-face interviews with target users, we obtained many perceptual vocabulary about older adult users' intentions for older adults home blood glucose testers and established a vocabulary of intention [55,56]. The perceptual vocabulary database was filtered based on the product opportunities obtained after the AHP user demand analysis, plus the existing product modelling analysis as the judgment condition and combined with the expert opinions. Finally, six groups of perceptual vocabulary pairs were obtained: easy to operate - challenging to use, safe - dangerous, professional - useless, technological - archaic, simple - complex, and exquisite - rough.

4.5.2. Questionnaire design based on the semantic differential method

The 10 product samples were coded, and the 6 sets of perceptual word pairs were finally selected and ordered to build a 7-level semantic differential scale, with a total of 10 perceptual scales, to create a semantic differential questionnaire for home glucose meters for the older adults (see Fig. 5).

4.5.3. Product typical sample perceptual semantic evaluation

Seventy people were selected for the perceptual questionnaire research, including 20 people aged 50–65 years old in the first age group, 20 people aged 65–80 years old in the older adults group, 10 people aged 30–50 years old in the children of the older adults, 15 people in the medical profession and 5 people working as medical product designers. 70 questionnaires were distributed, and 70 valid questionnaires were collected.

Table 8
The quality house of aging-appropriate design of intelligent blood glucose meter for the elderly.

User requirements	Product quality characteristics								Quality Needs Importance
	Technology & Functionality				Interaction and Service				
	DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	
A11	5	3	5	0	3	0	3	1	4.16
A12	5	5	5	0	3	0	3	1	1.93
A13	1	5	0	0	5	3	0	3	0.86
A14	3	1	5	0	1	0	3	0	0.41
A21	5	3	0	0	3	3	1	1	2.71
A22	3	3	0	0	3	5	1	1	7.65
A23	0	0	0	3	3	5	0	0	14.4
A31	0	0	5	0	0	0	3	0	15.8
A32	3	5	1	0	3	1	0	0	27.94
A33	1	0	3	3	3	0	0	0	3.54
A34	5	5	0	0	5	3	0	0	7.86
A41	0	0	0	5	0	5	0	0	8.24
A42	0	0	0	5	0	5	0	0	1.35
A43	0	0	5	3	0	0	0	0	3.34
Quality Characteristic Absolute Weighting	195.7	236.92	166.76	111.79	231	220.43	77.26	19.03	
Relative weights of quality characteristics%	15.5	18.8	13.2	8.9	18.3	17.5	6.4	1.5	

Fig. 5. Sample questionnaire design for a semantic differential method questionnaire on home glucose meters for the older adults.

4.5.4. Data analysis and design guidance

The data from 70 questionnaires were statistically analyzed by summing the scores of perceptual terms for each sample and calculating the mean. The data were analyzed using SPSS statistical software for Mac (IBM Corp. 2014, version 24.0. Armonk, NY, USA). Based on the software analysis results, a principal component analysis was conducted on the perceptual factors that affect users' perceptions. The relevant principal components were extracted as the main perceptual influencing factors of the product design. The samples with the highest scores in the relevant components were further analyzed to obtain the product design elements with principal component perceptual influencing factors. Finally, the feasibility of the method is verified through design practice.

4.5.4.1. Qualitative and quantitative analysis. The data from the 70 questionnaires were statistically analyzed by summing the scores of the perceptual vocabulary for each sample and calculating the mean (see Table 9).

The KMO was determined by comparing the simple and partial correlation coefficients between the variables. The research data showed that the KMO value was 0.659, with a significance of 0.000 (Table 10).

The mean values of the obtained perceptual vocabulary were imported into the statistical SPSS analysis software. The data were downscaled by factor analysis and principal component analysis of the SPSS software to obtain the common factor variance of the typical sample perceptual vocabulary data (see Table 11), the total variance explained (see Table 12), the gravel plot (see Fig. 6), and the component matrix (see Table 13), rotated component matrix (see Table 14), Factor scores and composite factor scores table (see Table 15).

The common factor variance plot indicates the interpretation of the original information of the variable by the extracted common factor and the degree it achieves [57–59]; the closer the extracted value Is to 1, the more accurate the factor analysis of that variable is. As seen from Table 11, with extracted values ranging from 0.793 to 0.957, most of the information in the variables of the glucose meter for older adults can be extracted by the common factor; therefore, the factor analysis results are valid. The number of principal components was determined by the interpreted total variance plot and the fragmentation plot. Table 12 shows that there are 2 components with eigenvalues >1, and the cumulative proportion is 87.353%, so these two components were extracted as principal components. Fig. 6 shows that the slope changes obviously; the first and second eigenvalues are more significant than 1 and significantly higher than the other points. The third eigenvalue point is at the inflexion point. From the third point onwards, the eigenvalues tend to level off, thus determining that component 1 and component 2 are the principal components.

Table 14 shows the results of the rotation of the factor loading matrices according to the "maximum variance method" set out earlier [60–62]. In the unrotated loadings matrix shown in Table 13, the factor variables have high loadings on many variables. As can be seen from Table 14 of the rotated factor loadings matrix, principal component 1 has higher loadings on easy-to-use gold and safety, and the first two in principal component 2 are technology and sophistication, respectively. Through the data analysis of the results of the perceptual semantic evaluation of a typical sample of home blood glucose meters for older adults, the main perceptual words that influence the design of home blood glucose meters for older adults can finally be derived: easy-to-operate, safe, technological and

Table 9
Summed mean of perceptual vocabulary scores for the sample.

Sample	Easy to use	Safe	Professional	Technology	Simple	Sleek
Sample1	−0.32	−1.21	−2.47	−2.83	−0.62	−1.89
Sample2	0.24	−1.46	−0.56	−2.61	0.46	−1.43
Sample3	−2.12	−1.63	−2.04	−2.34	−1.79	−2.56
Sample4	1.87	−0.84	0.34	1.14	0.87	2.23
Sample5	1.49	−0.53	2.14	−0.87	1.17	2.27
Sample6	2.74	−1.19	2.47	1.52	2.62	2.21
Sample7	−1.58	−1.96	−0.73	−1.71	−2.14	1.49
Sample8	−2.32	−2.12	0.17	−1.08	−2.62	−1.17
Sample9	−2.51	−2.14	−2.18	1.16	−2.72	−2.21
Sample10	−1.87	−2.05	−2.08	−0.45	−1.67	−1.25

Table 10
KMO and Bartlett's test.

KMO Number of sample suitability measurements	0.659	
Bartlett Sphericity Test	Approximate cardinality	49.038
	Freedom	15
	Significance	0.000

Table 11
Common factor variance.

	Initial	Extraction
Easy to use	1.000	0.957
Safe	1.000	0.887
Professional	1.000	0.793
Technology	1.000	0.894
Simple	1.000	0.910
Sleek	1.000	0.800

Table 12
Total variance explained.

Ingredie nts	Initial Eigenvalue			Extraction of sum of squares of loads			Sum of squared rotating loads		
	Total	Percenta ge variance	Cumula tive %	Total	Percenta ge variance	Cumulati ve %	Total	Percenta ge variance	Cumulat ive %
1	4.206	70.106	70.106	4.206	70.106	70.106	3.644	60.735	60.735
2	1.035	17.248	87.353	1.035	17.248	87.353	1.597	26.618	87.353
3	0.419	6.980	94.333						
4	0.213	3.544	97.877						
5	0.120	1.997	99.874						
6	0.008	0.126	100.000						

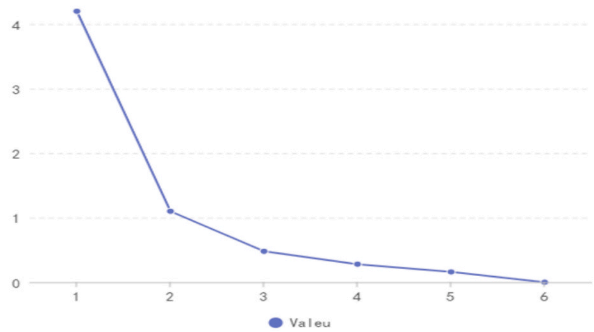

Fig. 6. Gravel map.

Table 13
Component matrix.

	Ingredients	
	1	2
Easy to use	0.967	−0.150
Safe	0.833	−0.440
Professional	0.875	0.168
Technology	0.448	0.833
Simple	0.929	−0.217
Sleek	0.866	0.223

Extraction method: Principal component analysis 2 components were extracted.

Table 14
Rotated component matrix.

	Ingredients	
	1	2
Easy to use	0.940	0.271
Safe	0.941	−0.048
Professional	0.723	0.521
Technology	0.055	0.944
Simple	0.934	0.194
Sleek	0.692	0.567

Extraction method: Principal component analysis. Rotation method: Kaiser normalized maximum variance method. Rotation has converged after 3 iterations.

Table 15
Factor scores and composite factor scores table.

FAC1_1	FAC1_2	F
0.30141	−1.62148	−0.25
0.50905	−1.13461	0.01
−0.47558	−1.10633	−0.58
0.86953	0.90069	0.77
1.48335	0.01058	0.90
1.13058	1.43805	1.07
−0.47719	0.11743	−0.26
−0.91700	0.28881	−0.48
−1.51404	0.92112	−0.67
−0.91012	0.18575	−0.50

sophisticated.

4.5.4.2. Analysis of design requirements. The above quantitative analysis shows that easy-to-operate, safe, technological and sophisticated have the most significant influence on the styling design. By comparing the images of sample 6, sample 5 and sample 4, it can be seen that the overall shape of these products is a simple geometric form; the display is divided mainly by a rounded rectangle, with the area divided being approximately 1/2–3/4 of the operating panel; the buttons are mostly 2–3 control buttons. The display is divided mainly by a rounded rectangle, with the area divided being about 1/2–3/4 of the operating panel; the keys are primarily in the form of 2–3 control keys, with the on/off key in the middle of the up/down flip key; the detection port is mainly located at the lower end of the detector. Therefore, designers can start from the above elements when designing an easy-to-operate, safe, technological and exquisite home blood glucose meter for older adults.

4.6. Step 6. Propose product design strategies

Combining the product function design conclusion presented in step 4 and the product shape design conclusion obtained in step 6, a product design strategy for home smart blood glucose detection for the elderly is proposed as follows.

4.6.1. Integrated design of operation

The conventional blood glucose meter blood collection, testing equipment and consumables memory, which are separated separately, are optimized and integrated by modular design and integrated design to simplify the product operation process and make it easier for users to use and learn.

4.6.2. Intelligent monitoring and tracking

Equipped with intelligent sensors, actuators and controllers, Bluetooth, WIFI and other interfaces, it provides real-time blood glucose testing, including non-invasive and blood testing, etc. The detected data are uploaded to the cloud in time and analyzed and tracked by big data. AI intelligent learning and analysis provide users with more accurate blood glucose control solutions and healthy living advice, including daily diet recommendations, exercise recommendations, knowledge of blood glucose, etc. It also provides users with more accurate blood glucose control plans and healthy living advice, including daily diet recommendations, exercise recommendations, blood glucose knowledge learning, etc.

4.6.3. Multimodal information feedback mechanism

The feedback of the intelligent blood glucose meter includes before, during and after testing, before testing and proposing the current blood glucose testing plan, reminding users to test at regular intervals; during testing is mainly for the feedback of operation, including power on, blood collection, testing, result feedback, etc. after testing includes the feedback of abnormal result and health recommendation etc. Full use of sound, light, electricity and other multimodal information feedback mechanisms, such as auditory (voice prompts), tactile (vibration prompts), etc., to promote the ageing-appropriate design of product use.

4.6.4. Interaction interface design for ageing

In the design of the interaction interface, an ageing-friendly design should be considered as much as possible, as perceptual decline weakens senior people's ability to recognize information around them. The interface should use enlarged fonts and high contrast colours as much as possible (avoid using cyan, green, etc.), and can also use light hints or light brightness to guide the selection of immediate information to strengthen the operation information of intelligent products effectively. Similarly, a multi-information feedback mechanism should be considered to assist elderly users in perceiving the operation information of intelligent products from multiple dimensions to enhance the efficiency of information acquisition and improve the accuracy of operation.

4.6.5. Safe and easy-to-operate shape design

Simple shape and operation keys, usually based on simple geometry, with appropriate rounded corners to make it safer and more reliable. Using fewer lines to divide functional parts will make the product more useable. The number of physical buttons should be limited to 4 to reduce the user's learning curve. The product's colour scheme should be more excellent, and the rational colour should be more in line with the colour scheme of medical products.

4.6.6. Design of additional services provided

The purchase of consumables should provide more convenient services, and the function of one-click purchase can be set up in the design part of the product APP, which is convenient for users to repurchase. In addition, for the significant data blood glucose analysis results, the product service provider can provide a more accurate and convenient telemedicine consultation service, which is one of the visions of the future product-service design. This will bring more significant benefits to diabetes home treatment patients, as well as help to balance social and medical resources as well.

4.7. Step 7. Design Case Studies: intelligent glucose meter design for the elderly home use

Following the product design strategy outlined in step 6, we initiated a design case study focused on the physical product to begin design validation. We established design principles and practical applications, defining the usage scenario as home-based. The specific design outcomes and effectiveness of this application are illustrated in Figs. 7–10. The blood glucose meter integrates blood collection and testing into a single process, simplifying operation and minimizing learning costs for elderly users. Its design is straightforward, safe, and eco-friendly, as depicted in Fig. 11. The device features a large LCD screen, enhancing readability with increased font size to accommodate the visual needs of elderly users. Additionally, the meter incorporates an Internet of Things (IoT) module for intelligent analysis and voice prompts based on test results. It also connects to mobile devices for remote monitoring and alerts. In abnormal results, the meter employs multimodal interactions – visual, auditory, and tactile – to provide comprehensive and timely notifications to elderly users and their caregivers. In terms of styling, the combination of simple geometry is used to simplify the form around the functional division [63]. In terms of CMF design, in order to better reflect the technological sense of the product, the primary colour of the product is classic white with rational blue accents; the material is plastic to reduce the overall weight of the product; the surface treatment process is frosted to improve the tactile experience, as well as the sense of refinement. In addition, we have completed the mobile interaction design aspect of our product. We designed an app called 'Smart Sugar Diary,' featuring an overall color scheme of blue and green. The font is sans-serif and larger, ensuring easy readability. The interface is simple and user-friendly, adhering to the principles of age-friendly design. Moreover, to cater to the social needs of elderly users, we have incorporated features for children's supervision and interaction, as well as online consultations with doctors. These additions aim to assist elderly diabetic patients in better managing their health, as illustrated in Fig. 12. Specific design practices are illustrated below.

5. Results and discussion

5.1. Results

In order to verify the feasibility of the above scheme, a survey was conducted to evaluate the user needs with high weighting coefficients in the third level of the target user needs and the extracted principal component factors of perceptual engineering. 80 questionnaires were administered, and the average of the questionnaire research data was used as the final evaluation result data to draw up a user evaluation feedback graph (see Fig. 13). 9 of the 12 evaluation values were above 8 points, meeting user expectations.

Through design example validation and fuzzy comprehensive evaluation, the results found that the home glucose meter for older adults improved the product's general use and user experience in terms of ease of use, safety and accurate determination of results.

5.2. Discussion

To tackle the challenges of designing smart products for an ageing society, we employed a systematic approach integrating the Analytic Hierarchy Process (AHP), Quality Function Deployment (QFD), and Kansei Engineering (KE). Our case study illustrates the efficacy of this AHP-QFD-KE approach in managing User Requirements (URs) and Design Requirements (DRs), along with their

Fig. 7. Glucose meter for older adults at home.

Fig. 8. Product details of the glucose meter for older adults at home.

Fig. 9. Older adults home blood glucose meter home scenario diagram - blood collection phase.

interdependencies. These insights are instrumental in developing further design strategies.

From the AHP-QFD decision model, eight key DRs emerged, focusing on functionality, technology, and services. Four of these – Smart Results Feedback (DR2), Easy to Operate (DR1), Multiple Information Channel Feedback (DR5), and Interface Aging (DR6) – were particularly prominent. Smart Results Feedback (DR2) emerged as the most critical, receiving the highest weight (0.188). This

Fig. 10. Older adults home glucose meter home scenario diagram - testing phase.

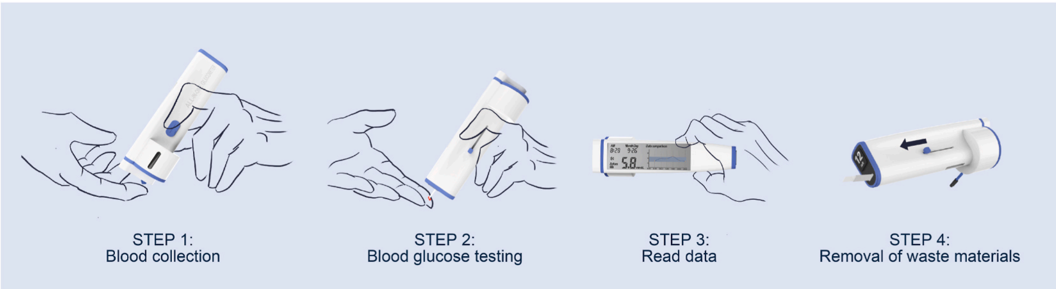

Fig. 11. Procedure for using home blood glucose monitors for older adults.

underscores the preference of elderly users for smart product feedback, advocating for a multimodal design approach. The importance of Multiple Information Channel Feedback further reinforces the need for intelligent multi-channel feedback. The emphasis on Ease of Use and Interface Aging aligns with strategies for integrating intelligence into healthcare products, considering both policymakers and designers. Other significant factors include Safe and Reliable (DR3), Styling and Aesthetics (DR4), and Consumables Distribution Service (DR7), weighted at 0.132, 0.089, and 0.064, respectively. Future design studies should consider the relative weights of these DRs and their inherent dependencies. Axiomatic design theory and game theory could provide multidimensional perspectives on the interplay between design elements, offering valuable references for formulating design strategies.

In conjunction with the Kansei Engineering (KE) approach, our study emphasizes enhancing the multi-sensory experience in product design from an affective design perspective. Quantitative analysis indicates that attributes such as ease of operation, safety, technology, and sophistication align closely with the emotional desires of the elderly for medical and healthcare products. Accordingly, designers are encouraged to prioritize these affective characteristics in the exterior design of these products. This approach ensures that the design not only meets functional needs but also resonates with the emotional expectations of elderly users.

TWhile insightful, the perceptual semantic evaluation of typical samples in this study is limited by its subjective nature and the small sample size. To address these limitations, future research will consider a more comprehensive perceptual measurement approach that integrates physiological and psychological aspects. This will include in-depth investigations using EEG (electroencephalogram) analysis and eye-tracking experiments to understand user perception and experience better.

6. Conclusions

This study provides a home diabetes detector for older adult diabetic patients. Design based on hierarchical analysis methods and perceptual engineering designs support techniques that translate user needs and feelings into product design orientation. This paper investigated a product design approach based on hierarchy analysis combined with quality function deployment and Kansei Engineering theory using an example of a home blood glucose meter for older adults. The hierarchical analysis method is used to analyze the needs of older adults users, the semantic difference method is used to quantify the perceptual vocabulary of the older adults home blood glucose meter, and the factor analysis and principal component analysis of SPSS are used to transform multiple perceptual vocabularies into preferred perceptual vocabularies, extracting "easy to operate", "safe", "technology" and "safety". Safety", "Technology", and "Delicate" were extracted as the four main perceptual words affecting the older adults home blood glucose meter, and the product design innovation process was constructed and verified by design examples. This research employs the Analytic Hierarchy Process (AHP) in conjunction with Quality Function Deployment (QFD) and Kansei Engineering (KE). This innovative approach focuses on user-centred product system design, bridging user needs with design elements and user experience to develop a home health

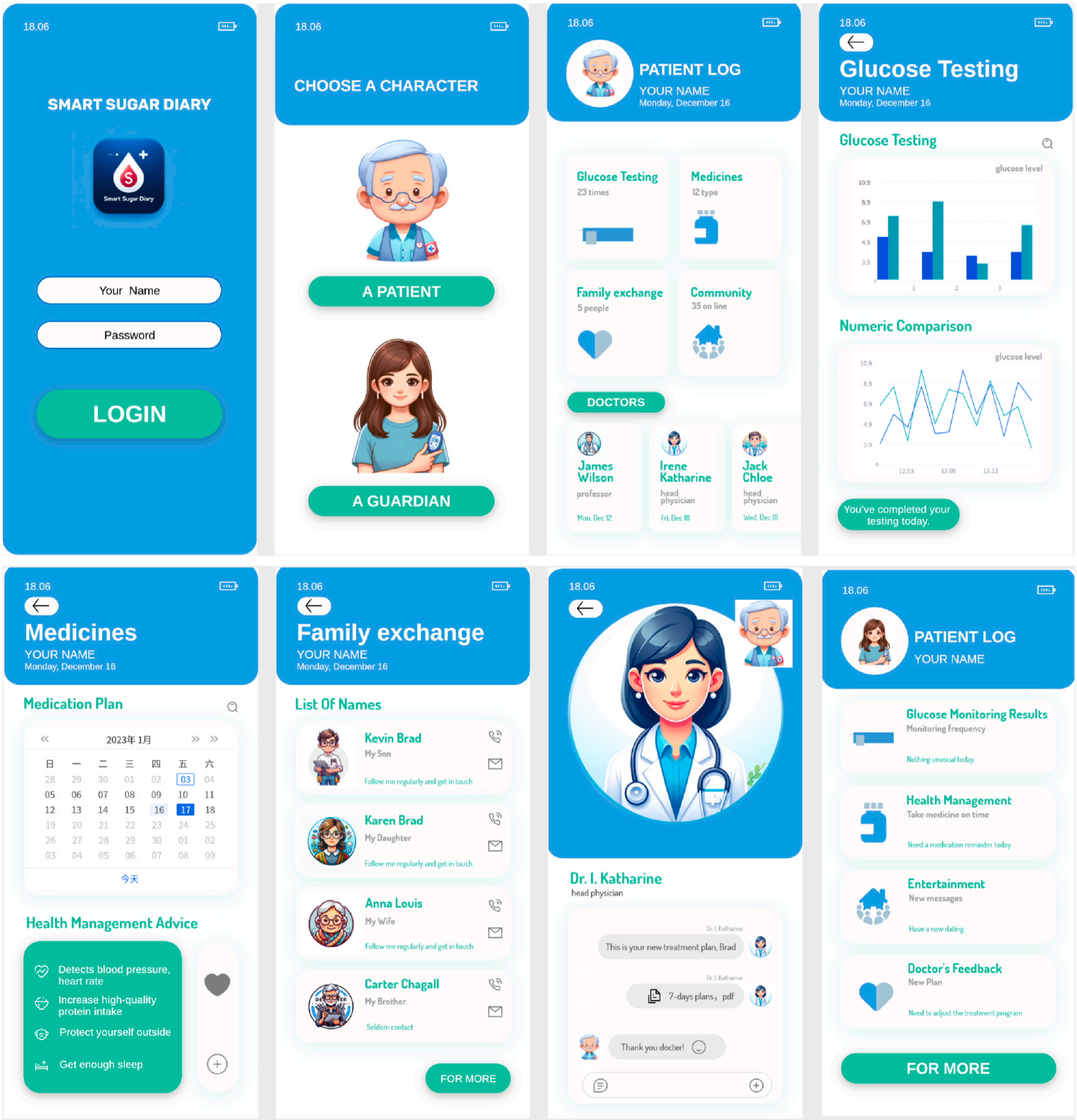

Fig. 12. APP Interactive interface design of home blood glucose monitors.

management product for the elderly. The product adheres to scientifically informed, intelligent, and aging-friendly design principles, addressing older adults' physiological and psychological needs. Specifically, the design integrates easy-to-use operations, intelligent result analysis, multimodal information feedback, and aesthetic preferences tailored to elderly users. This innovative approach offers new theoretical and practical perspectives for designing home self-testing blood glucose meters for the elderly.

Ethics Statement

This study complies with ethical standards and is approved by the Ethics Committee of the Guangzhou Institute of Science and Technology (approval number: 2022BL-035-01). It obtains written informed consent from participants.

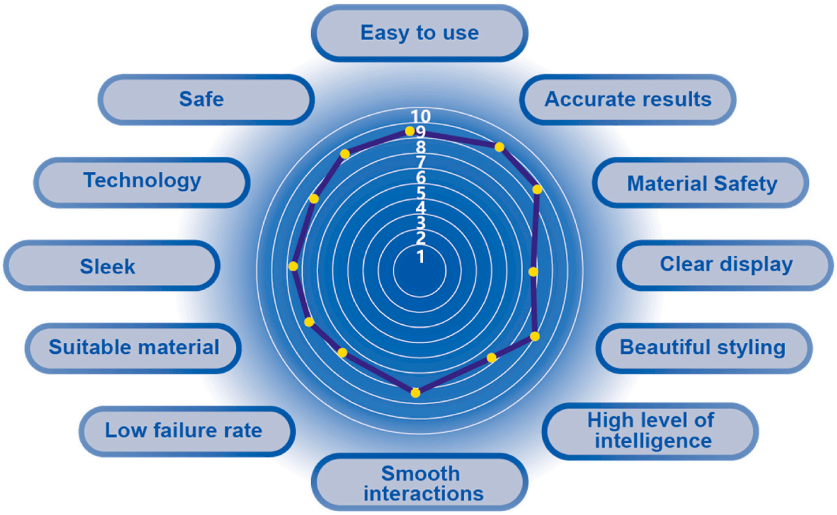

Fig. 13. User evaluation feedback Chart.

Data Availability Statement

The data used to support the findings of this study are included within this article or supplementary information file(s).

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CRediT authorship contribution statement

Xiaojie Li: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Hong Li:** Writing – original draft, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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X-J.L. designed the pilot and case study projects, conducted a user study, developed a framework, and drafted the manuscript. H.L. guided the study and assisted with editing. All authors have read and agreed to the published version of the manuscript.

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