Research on the Design Elements of Air Pressure Massage Cushion for Expanding the Elderly-Friendly Functions of Furniture

Changlong Yu, Wei Liu,* Yinan Fei, Jiaqi Chen, and Ziyan Hu

The use of aging aids can be used in conjunction with existing furniture to expand the aging function of the furniture, so that the furniture better meets the needs of the elderly. Pneumatic massage is a kind of massage technology that realises the massage function by inflating and deflating the airbag. Compared with mechanical massage, it has the advantages of simple structure, soft force, safety and reliability, and it is especially suitable for the application of old age recreation products. In order to accurately match the needs of the elderly for pneumatic massage products and develop suitable pneumatic massage cushion products, this paper constructs a research framework of user needs-user behaviour-design elements based on the joint AHP-AEIOU-QFD model, which clarifies the user needs and core design elements of the ageing pneumatic massage cushion and provides an important basis for product development. Firstly, the AHP method was used to construct the user requirements model, which clarified that safety and core functions are the core primary needs of the elderly, and structural rationality and pneumatic massage function are the core secondary needs of the elderly. Further, the QFD method converts the user requirements into technical parameters and analyses them and clarifies the modular airbag and support structure design as the core design elements of the age-friendly pneumatic massage cushion products. Finally, the JACK simulation platform is used to conduct comparative experiments on the design parts of the products, and the simulation data verifies the feasibility of the optimised products. The results of this paper have an important role in guiding the design and development of ageing massage cushion products.

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Keywords: Furniture; Massage products; AHP; QFD; Ageing friendly

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INTRODUCTION

The world is facing serious public health challenges as health problems become increasingly prominent in modern society. As of 2024, China's elderly population aged 60 years and above has reached 310 million, accounting for 22 percent of the total population (Xie *et al* 2024). Among them, they are commonly accompanied by underlying diseases such as high blood pressure and high blood cholesterol, as well as movement dysfunctions such as limited joint mobility and reduced muscle strength, leading to many inconveniences in daily life.

Furniture, as a durable product, is usually not replaced frequently after purchase. With the increase in the aging population, elderly people generally have difficulty getting up when using sofas, beds, and other products. Against this backdrop, there is a significant increase in demand for expanding the aging-friendly features of furniture. Pneumatic massage technology, with the advantages of flexible pressure, safety and portability, is becoming an emerging solution to relieve the back pain of elderly users and enhance the aging function of furniture.

In the past 10 years, the demand for massage equipment has grown steadily. The rapidly growing massage equipment industry has prompted more segmented vertical tracks, such as small products characterised by portability, ease of operation, and precision, and large equipment characterised by comfort and high end. The current market is divided into large and small massage appliances. Large massage appliances are mainly multifunctional massage chairs, massage mattresses, and other products that massage the whole body; small massage appliances include eye massagers, neck massagers, foot massagers and other massage products for specific body parts (Wang 2023), as shown in Fig. 1.

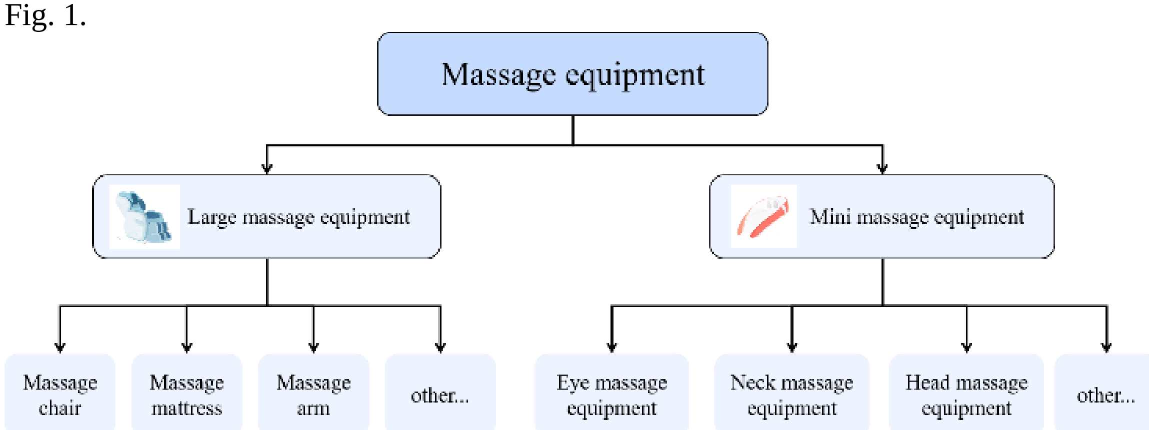


Fig. 1. Classification of massage appliances

The global market size of the massage apparatus industry is $15.7 billion in 2020, up 4.67% year-on-year, with a compound annual growth rate of 8.17% (Business Research Insights 2025). According to Research Nester report, the U.S. massage chair market size reached about USD 1.04 billion in 2018, the global massage chair market size was USD 3.37 billion in 2023, and is expected to reach USD 6.91 billion by 2032, at a CAGR of about 8.3% during the forecast period (Grand View Research 2025), as shown in Fig. 2. The above figures indicate that the massage equipment market has a huge potential for growth in the future.

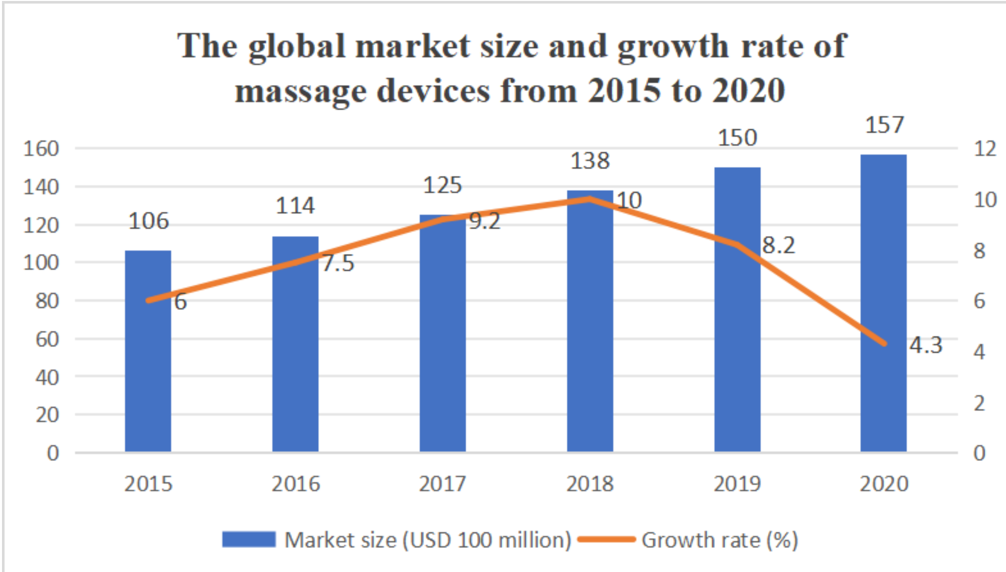


Fig. 2. Global massage devices market size and growth rate from 2015 to 2020

Therefore, the current expansion of furniture aging function of the massage cushion products can be divided into the following three categories:

1) Integrated air pressure massage cushion

Integrating massage functions as core modules into large furniture such as sofas and mattresses has become a key innovation. For instance, the U.S. brand Human Touch launched the ZeroG 5.0 intelligent massage sofa, which utilizes built-in air-pressure waves and roller systems to replicate professional masseur techniques (Kittrick and Jones 2021). This design aligns with the **"ergonomics-first" principle** proposed by Imamura, which emphasizes optimal pressure distribution to reduce muscle fatigue risks (Imamura *et al*. 2017). Similarly, Chinese brand CHEERS has developed electric massage sofas featuring zonal control technology, allowing independent adjustment of lumbar massage intensity. This validates the **"functional decoupling" theory** for modular smart furniture, as proposed by Bolognesi *et al*. (2020).

2) Modular Pneumatic Massage Cushion

The traditional furniture function is enhanced by removable massage cushions. For example, the Chair Cyclist massage cushion from the Japanese brand Inada is combined with an office chair through a magnetic interface to achieve lumbar spine massage in a seated position. The design echoes the concept of “non-invasive health intervention”, and its vibration frequency (10 to 50 Hz) has been shown to alleviate pyriformis syndrome (Carragee *et al* 2008).

3) Pneumatic nursing pads

Special patients use products developed for medical rehabilitation and other scenarios. For example, German brand Bock Me di Design's rehabilitation and massage mattress with integrated pressure sensing and heat therapy has been shown to reduce the incidence of pressure sores in bedridden patients by up to 37% in clinical data (Hatanaka *et al*. 2008). This is shown in Table 1.

Table 1. Massage Cushion Embedded Furniture Types

Product Category	Product Pictures	Massage Area	Embedded Furniture Location
Integrated air pressure massage cushion		Neck, shoulders, waist, back, hips, legs	Beds, sofas
Modular Pneumatic Massage Cushion		lower back	Chairs, sofas
Pneumatic nursing pads		special part	Beds, sofas

Analysis of Existing Product Pain Points

Research has identified a significant structural contradiction in the current massage cushion market. Existing integrated and modular products offer basic functions such as relieving muscle fatigue and improving blood circulation (Pang *et al*. 2019), yet they primarily target general users and lack scientifically calibrated intensity settings for special populations. However, while special user groups (elderly, disabled individuals, post-operative rehabilitation patients, *etc*.) can access targeted care through customized products, they face practical challenges including prohibitively high costs (averaging 5 to 8 times the price of standard products), large space requirements (standard dimensions reaching 2 m × 1.5 m), and poor household adaptability (Bazzano *et al*. 2017). This study focuses on developing an integrated smart massage product that combines the comfort of conventional massage cushions with the therapeutic effects of professional medical mattresses. The successful development of this product will provide innovative concepts and technical support for the embedded furniture industry specializing in massage cushions, driving continuous progress and advancement in the sector.

EXPERIMENTAL

AEIOU Framework: Principles and Implementation Steps

The AEIOU framework is a systematic methodology proposed by Robinson in 1991, comprising five key dimensions: Activities (A), Environments (E), Interactions (I), Objects (O), and Users (U). It guides researchers to observe, document, and analyze information based on these categories, as shown in Table 1. In this study, the AEIOU method was applied through offline experimental observations to uncover user needs and product requirements (Lee *et al*. 2022).

Table 2. A E I O U Observation Chart

A E I O U Observation Chart
(1) Activities: This section describes goal-oriented behaviors, such as what the user does, the methods they use, and the specific actions they take to achieve their objectives
(2) Environments: The settings where "activities" occur, including personal spaces and shared spaces.
(3) Interactions: "Activities" inevitably involve communication and interaction, which includes both person-to-person and person-to-object interactions.
(4) Objects: This section can be understood as components of the "environment."
(5) Users: Here, "users" refer to the individuals being observed.

Analytic Hierarchy Process (AHP): Principles and Implementation Steps

The AHP method, or Analytic Hierarchy Process, was proposed in the early 1970s by Thomas L. Saaty, a Professor of Operations Research at the University of Pittsburgh. Its primary aim is to structure and systematize complex decision-making problems by decomposing the problem, establishing a hierarchical framework, conducting comparative judgments, and performing comprehensive calculations. This process assists decision-makers in making more scientific and rational choices (Macharis *et al.* 2004). The implementation steps for this study are illustrated in Fig. 3.

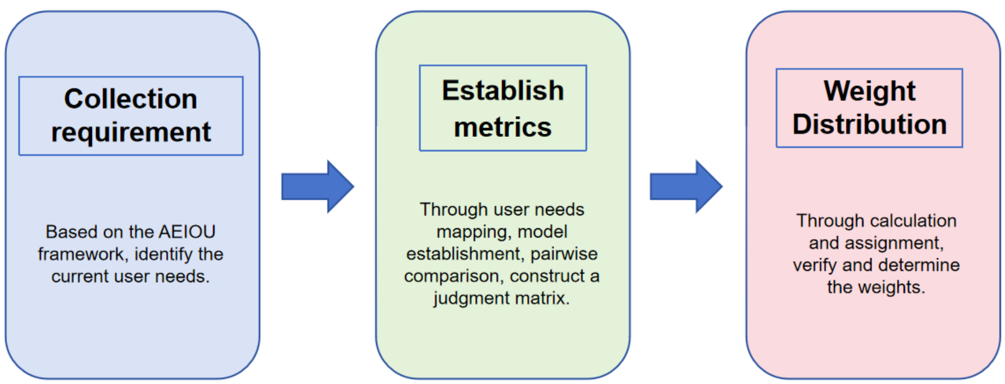


Fig. 3. AHP method flowchart

Quality Function Deployment (QFD): Theoretical Framework

QFD (Quality Function Deployment) is a multi-level deductive analysis method that translates customer or market requirements into design specifications, component characteristics, process requirements, and production requirements. Initially proposed by Japanese scholars Yoji Akao and Shigeru Mizuno around 1960, its core principle is to ensure that product characteristics reflecting customer needs are accurately conveyed throughout the subsequent stages of product development. By systematically unfolding and transforming customer requirements, the final product quality can effectively meet customer expectations (Cristiano *et al.* 2001). The implementation framework for this study is illustrated in Fig. 4.

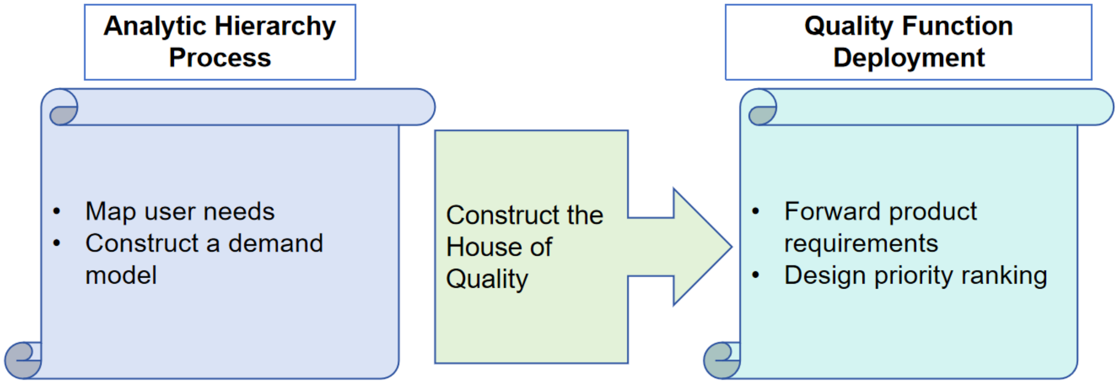


Fig 4. QFD Method Flowchart

Jack Simulation (Jack): Theoretical Framework

Jack simulation software was originally developed by the Center for Human Modelling and Simulation at the University of Pennsylvania for human modelling, ergonomic analysis and task optimisation in virtual environments (Ma *et al*. 2008). The software is based on accurate biomechanical models and supports the creation of digital human bodies of different genders, body types and ethnic characteristics (e.g., Asian, European and American human body databases), and automatically generates statistically compliant human body models from parameters such as height and weight. Its core functions include reachability analysis, field of view simulation, posture prediction, fatigue assessment, and dynamic task simulation.

RESEARCH FRAMEWORK

The innovation of this research method is to propose a combination of AHP+QFD to optimise the design of massage cushion products. Firstly, the AEIOU method is used to observe the target user's demand, and the big data is used to mine the specific demand, then the AHP+QFD is used to derive the specific design demand, and the design demand is weighted and sorted to derive the optimal data; finally, the JACK software is used to verify the design, which provides a new way of thinking about the research method of the pneumatic massage cushion products. As shown in Fig. 5.

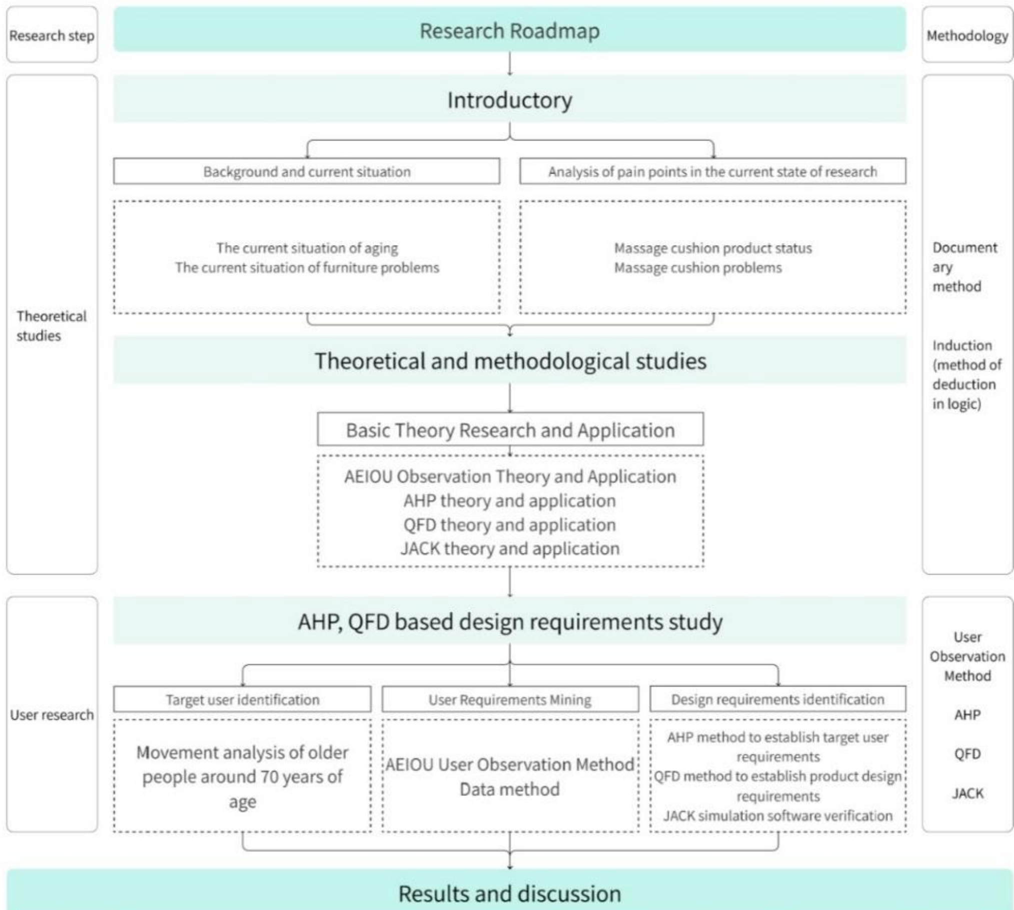


Fig. 5. Technology roadmap

RESULTS AND DISCUSSION

User Needs Mining Based on the AEIOU Framework

The AEIOU observation method has demonstrated cross-domain effectiveness through multiple empirical studies. In architecture, Mcintyre and Harrison (2017) conducted observations in elderly residential environments, yielding profound insights into how built environment quality impacts senior residents' activities and wellbeing. Five distinctive spatial qualities were identified: spatial legibility, spatial connectivity, spatial traversability, spatial diversity, and spatial aesthetics. The framework was also applied by Lee to analyze interaction drivers in handheld augmented reality technology (Lee *et al*. 2012). A retail case study revealed that documenting customer pain points at self-checkout stations and optimizing interface prompts reduced error rates (Ivanauskienė *et al*. 2012) . In smart homes, Li *et al*. (2022) addressed elderly users' communication barriers with voice assistants by implementing multilingual support, resulting in improved task completion rates. These cases collectively validate the practical value of the AEIOU method in systematically deconstructing user scenarios.

Using the AEIOU method, observations were conducted in the process of elderly individuals moving from the living room to the bedroom to lie down and rest, and then getting up. The images are sourced from real users, and the specific disclaimer for this observation is provided in Table 3. The movement process of the individuals in the images is detailed in Tables 4 , while the AEIOU method observations are presented in Table 5.

Table 3. Disclaimer

Personal Information	The study does not involve personal privacy or sensitive information of the users
Anonymization	The observational data is anonymized, making it impossible to identify specific individuals.
Non-Intervention	The observation process does not interfere with the subjects' behavior and does not record their personal information
No Potential Risks	The observation does not pose any risks or discomfort to the subjects

Table 4. User Status Flowchart

User Status	Picture
The process of lying down	
The process of getting up	

Table 5. The Application of the AEIOU Method

A	Moving from the living room to the bedroom	Transitioning from standing to lying on the bed	Getting up
E	Living room, bedroom, bed	Bedroom, bed	Bedroom, bed, living room
I	Preparing to lie down and rest	Moving from standing to lying on the bed: Supporting the upper body with arms, tensing the torso to lie down, moving arms away, and lying flat.	Getting up from lying down: Tensing the torso to rise, supporting the upper body with arms, moving arms away, and standing straight
O	Bed, other bedroom items	Bed, other bedroom items	Bed, other bedroom items
U	User	User	User
Questions	Q1: Does the bedroom environment reduce sleepiness? Q2: Can the user relax more before resting?	Q1: Does the user face mobility difficulties due to physical limitations? Q2: Does the difficulty in moving increase the risk of injury? Q3: Does the difficulty in lying down affect sleep	Q1: Does the user face mobility difficulties due to physical limitations? Q2: Does the difficulty in moving increase the risk of injury? Q3: Does poor sleep quality make the process

		quality?	of lying down and getting up particularly frustrating?
Impacts	The bedroom environment and sleep-promoting products influence the user's state.	Elderly users struggle to independently and comfortably complete the lying-down process. The lying-down process may cause physical injury. The lying-down process may affect sleep quality.	Elderly users struggle to independently and comfortably complete the getting-up process. The getting-up process may cause physical injury.
Opportunities	Relaxation aids.	Mattress design, Assist in turning over, relaxation aids.	Mattress design, Assist in turning over .

In this phase, the current study used mobile phone photographic recording to observe the behaviour of three 70+ year olds in the process of getting up - lying down. Behavioural analysis was conducted using one of the 80-year-old elderly users as an example, as shown in Table 4. This process can better observe the dynamic trunk state of the elderly users from lying down to rising up. Through user observation, it was found that: the elderly users were affected by the degeneration of the lumbar and abdominal muscle groups, and showed a typical compensatory behavioural pattern when rising up, i.e., the trunk formed an angle of about 45° from the bed in the cervical spine rigidity state, and the upper limbs performed supportive force with an elbow angle of about 90°, with the overall action exerting greater pressure on the arm department. And lying down process, the same for the arm support, and then the stiff upper body to get up. Therefore, in the process of designing the product structure of the air pressure massage cushion, the body characteristics of the elderly users should be fully considered, and in the design process, it is necessary to increase the support structure of specific body parts, and set up a widened and reinforced support structure to improve stability. At the same time, the design of two-stage tilt-assisted airbag structure, the initial stage of slow rise, activate the core muscles to prepare for the subsequent tilt-assisted rise.

Research on Big Data Collection

The data collection mechanism aims to achieve automated acquisition of target web page data resources, and its technical path includes: HTTP request construction, HTML structure parsing, response content decoding, structured data extraction, and persistent storage operation, which provides a standardised dataset for subsequent data analysis and visualization (Ren *et al*. 2006). In this data collection section, the main network crawler technology, through the 'Octopus Collector' crawler software, which can be used for data mining, data monitoring and other functions, the use of the software on Taobao, Tmall platform for the acquisition of relevant data. The specific process is shown in Fig. 6 below.

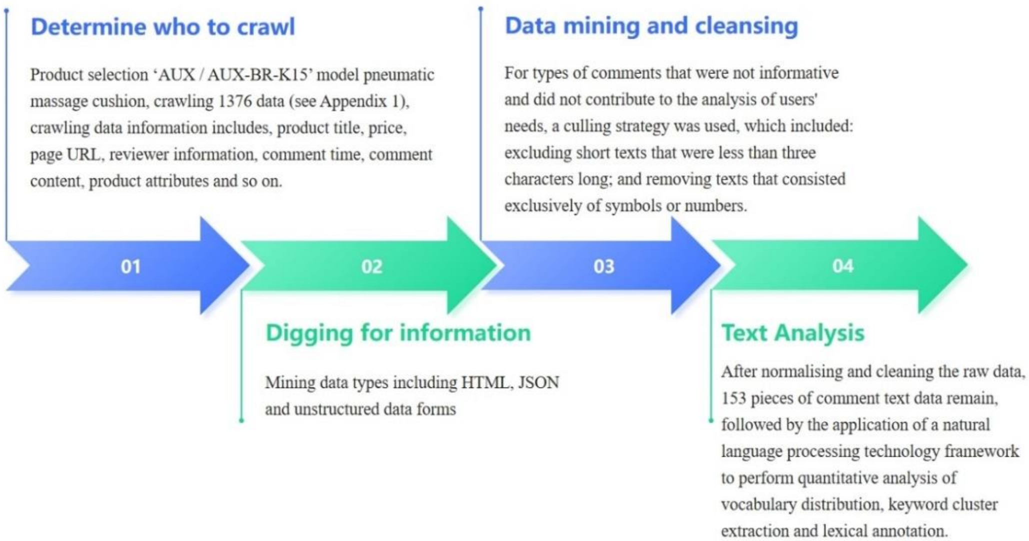


Fig. 6. Big data mining flowchart

This time, 1376 data of user comments were collected, and the *jieba* software tool was used to process their data. The final statistical results based on word frequency are shown in Table 6. The word frequency of 'massage' is the highest, indicating that most of the comments are for the main function of massage, followed by 'legs', 'back' and 'waist'. The high frequency of 'waist' indicates that this body part is often discussed by users during the massage process. The high-frequency words such as 'feeling', 'comfortable', 'effect', 'pain' and so on indicate that most of the elderly users' current subjective feelings about the product. The high-frequency words such as 'feeling', 'comfortable', 'effect', 'pain' and so on indicate the subjective feelings of most elderly users. High-frequency words such as 'function', 'vibration', 'design', 'experience', etc. also reflect consumers' The high-frequency words such as 'function', 'vibration', 'design' and 'experience' also reflect the consumers' concerns about the pneumatic massage cushion, which can provide a basis for the subsequent establishment of the function model. For details, see appendix 1.

Table 6. The Application of the AEIOU Method

Keywords	Word Frequency	Keywords	Word Frequency
Massage	97	**Feeling**	13
purchase	26	**Vibration**	13
strength	23	**Comfortable**	11
speak	15	**Effect**	11
Leg	15	**good**	11
Waist	14	**Waist and back**	10
Function	13	**Design**	10

According to the observation method and data mining to obtain user demand information, text analysis of the data, in which 'massage', 'function' collated into functional demand, 'pain' collated into safety demand, 'feeling', 'waist', 'legs' collated into comfort demand and human-computer interaction demand, 'design' collated into human-computer interaction demand. demand, 'feeling', 'waist' and 'legs' are sorted into comfort demand and human-computer interaction demand, and 'design' is sorted into appearance demand. into appearance needs. To sum up, through the existing aeiou method and data mining, the evaluation criteria of five demand dimensions were finally established: the demand dimensions were classified as the criterion layer (B1-B5), and 21 specific indicator layers (C1-C21) were obtained by summarizing the demands of elderly users.

Construction of a Hierarchical Needs Model

The Analytical Hierarchy Process (AHP) has wide applicability in the field of structured decision making. In supply chain management, Falsini *et al.* (2012) scholars develop a multilevel supplier evaluation model in conjunction with fuzzy AHP, proposing a mathematical approach that combines AHP, DEA, and linear programming to support multi-criteria evaluation of third-party logistics service providers. The proposed model aims to overcome the limitations of the AHP approach by combining expert instructions with objective judgements derived from historical data analysis. In healthcare, Gao *et al.* (2022) applied AHP to build priority factors in a model of regional vulnerability indicators for infectious diseases, including population density and infection rates, to build consensus among stakeholders. For environmental assessment, In terms of environmental assessment, Uyan (2013) combined analytic hierarchy Process (AHP) with geographic information system (GIS) techniques to evaluate the economic and environmental criteria for the site selection of the Konya electric field in Turkey, identifying three optimal areas with a combined score more than the traditional method. In urban planning, Gao and Wan (2017) employed an AHP-TOPSIS hybrid approach to optimize Wuhan metro line planning, weighting parameters such as population density and construction costs, which reduced budget overrun risks by 25%.

In this study, an AHP hierarchical model was constructed based on user needs for massage cushion products. The top layer (goal layer) represents the hierarchical framework of user requirements, while the middle layer is divided into criterion and sub-criterion layers. The criterion layer includes five overarching user needs: core functional requirements, human-machine interaction needs, comfort requirements, safety requirements, and aesthetic design needs. The sub-criterion layer further breaks down these needs into 21 specific sub-requirements. The complete hierarchical structure is illustrated in Fig. 7.

Expert Questionnaire Design and Consistency Validation

The construction of the judgment matrix serves as the informational foundation for the AHP model. Each element A_{ij} in the judgment matrix is assumed to satisfy $A_{ij}>0$, where A_{ij} represents the importance of indicator A_i relative to A_j. If the comparison is reversed, the result is $1/A_{ij}$ (where $i,j=1,2,\ldots,n$), with n being the order of the judgment matrix. Using an online questionnaire as the research method, the *"user needs for massage cushion products"* were selected as the evaluation object. 10 experts in the field of massage were invited to participate, and a scale quantification approach was applied to conduct a questionnaire survey on the judgment matrices for each hierarchical indicator (scoring criteria: Table 7).

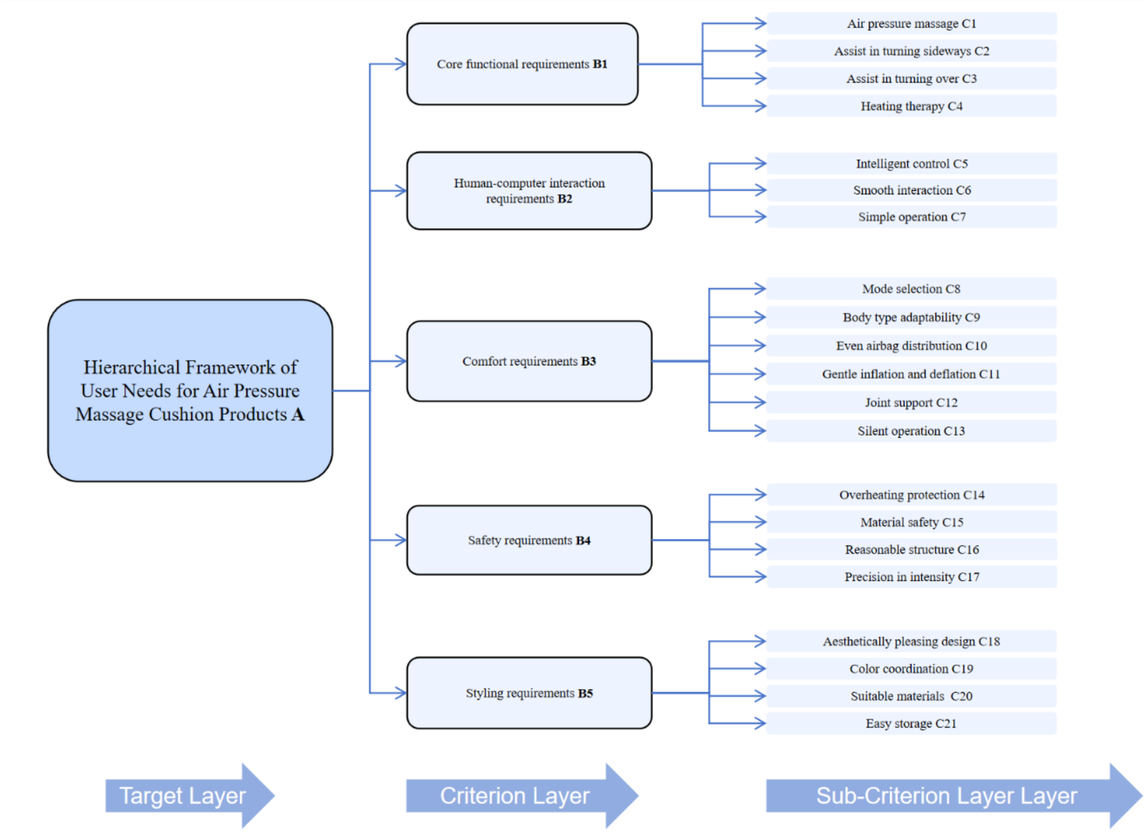


Fig. 7. Creating a user requirements model diagram

Table 7. Judgment Matrix Scales

Scale	Level of Importance
1	*i, j* elements are equally important
3	*i* is slightly more important than *j*
5	*i* is significantly more important than *j*
7	*i* is strongly more important than *j*
9	*i* is definitely more important than *j*
2, 4, 6, 8	Intermediate values
Inverse of scale	If the ratio of the importance of element *i* to element *j* is a_{ij}, then the ratio of the importance of element *j* to element *i* is $1/a_{ij}$

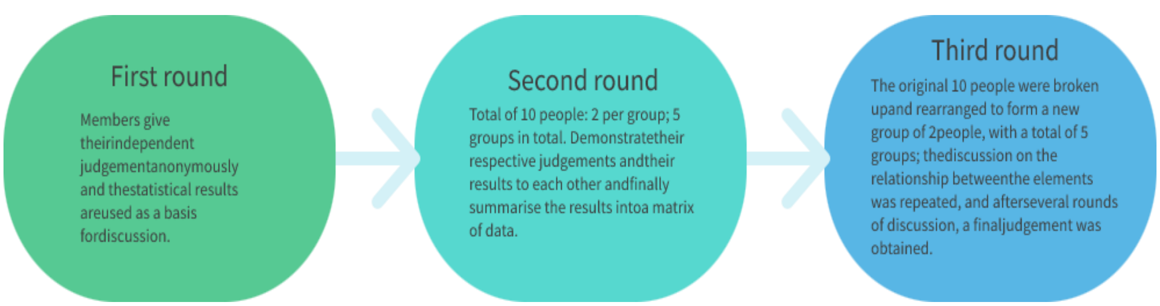


Fig. 8. Flowchart of the Delphi method

Hierarchical Ranking and Its Consistency Test

According to the evaluation scale in Table 3, a judgment matrix is constructed, and this subject is assigned to 10 experts, and two-by-two comparisons are made at each level. The calculation steps are as follows.

1. Calculate the product of the elements of each row of the judgment matrix *A*, calculated as in equation (1).

$$M_i = \prod_{j=1}^{n} a_{ij}, i=1, 2, \ldots n \quad (1)$$

2. Calculate the *n* root of M_i, calculated as in equation (2).

$$\overline{\omega_i} = \sqrt[n]{M_i} \quad (2)$$

3. Normalized to $\overline{\omega \mathrm{i}}$ for ωi and $\omega \mathrm{i}$ is the maximum eigenvalue, calculated as in equation (3).

$$\omega_i = \frac{\omega_i}{\sum_{j=1}^{n} \omega_i} \quad (3)$$

4. To calculate the maximum eigenvalue see Eq. 4,

$$\lambda_{max} = \sum \frac{(A\omega)i}{N\omega i} \quad (4)$$

where λ_{max} is the maximum eigenvalue; *A* is the matrix *A* multiplied by the phase; *i* is the relative weight; *N* is the order of the matrix.

5. The consistency index is shown in Eq. 5, and the consistency ratio is shown in Eq. 6,

$$CI = \frac{\lambda_{max} \quad -N}{N-1} \quad (5)$$

$$CR = \frac{CI}{RI} \quad (6)$$

where *CI* is the consistency index; *RI* is the random consistency index; *CR* is the consistency ratio. The weights of each index are shown in Tables 9 through 14.

The closer λ_{max} is to *N*, the more consistent the *CI* is, and the smaller the judgment error derived, and when the matrix judgment $CR < 0.1$, the judgment matrix is considered to have satisfactory consistency. The consistency test results are shown in Table 8.

Table 8. Consistency Test RI Chart

Matrix Order	1	2	3	4	5	6	7	8	9	10	11	12
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49	1.52	1.54

Table 9. Judgment Matrix of Criterion Layer Factors' Impact on the Objective Layer

A	B1	B2	B3	B4	B5	CR
B1	1	3	5	7	9	0.0089
B2	1/3	1	3	5	7	
B3	1/5	1/3	1	3	5	
B4	1/7	1/5	1/3	1	3	
B5	1/9	1/7	1/5	1/3	1	

Table 10. Judgment Matrix of Sub-criterion Layer Factors' Impact on the Criterion Layer-B1

B1	C1	C2	C3	C4	CR
C1	1	3	5	7	0.0339
C2	1/3	1	3	5	
C3	1/5	1/3	1	4	
C4	1/7	1/5	1/3	1	

Table 11. Judgment Matrix of Sub-criterion Layer Factors' Impact on the Criterion Layer-B2

B2	C5	C6	C7	CR
C5	1	1/3	1/5	0.0176
C6	3	1	1/3	
C7	5	3	1	

Table 12. Judgment Matrix of Sub-criterion Layer Factors' Impact on the Criterion Layer-B3

B3	C8	C9	C10	C11	C12	C13	CR
C8	1	3	5	7	9	9	0.0432
C9	1/3	1	3	5	7	7	
C10	1/5	1/3	1	3	5	5	
C11	1/7	1/5	1/3	1	3	3	
C12	1/9	1/7	1/5	1/3	1	1	
C13	1/9	1/7	1/5	1/3	1	1	

Table 13. Judgment Matrix of Sub-criterion Layer Factors' Impact on the Criterion Layer-B4

B4	C14	C15	C16	C17	CR
C14	1	1/3	1/5	1/7	0.0385
C15	3	1	1/3	1/5	
C16	5	3	1	1/3	
C17	7	5	3	1	

Table 14. Judgment Matrix of Sub-criterion Layer Factors' Impact on the Criterion Layer-B5

B5	C18	C19	C20	C21	CR
C18	1	3	5	7	0.0412
C19	1/3	1	3	5	
C20	1/5	1/3	1	3	
C21	1/7	1/5	1/3	1	

Prioritization of Key Needs Elements

Based on the comprehensive weights of user needs for massage cushion products, the sub-criterion layer was ranked as shown in Table 15. Through AHP hierarchical analysis, the product needs were weighted across three levels: the goal layer, the criterion layer, and the sub-criterion layer. Among the first-level indicators, Safety requirements had the greatest impact on consumers' choice of massage cushion products, with the highest weight of 0.5339, followed by Core functional requirements with a weight of 0.2854, and Styling requirements having the lowest weight of 0.0364. From the first-level indicators, it can be inferred that the design of massage cushions for the elderly should follow a progressive framework of safety as the foundation, precise functionality, and user-friendly experience. Among the second-level indicators, Reasonable structure had the highest weight of 0.2440, followed by Air pressure massage and Precision in intensity with weights of 0.1593 and 0.1600. In summary, structural rationality, material safety, and massage functionality had the greatest influence on consumers' choices within their respective evaluation indicators. Additionally, elderly users place greater emphasis on the safety and practicality of the product, while attributes such as color coordination, gentle inflation/deflation, precision in massage intensity, and mode selection had lower weights, indicating weaker consumer preference for these additional features.

Table 15. AHP Method Weight Ranking Table

Sub-Criteria Level	Global Weight	Ranking
Reasonable structure (C16)	0.2440	1
Air pressure massage (C1)	0.1600	2
Precision in intensity (C17)	0.1593	3
Material safety (C15)	0.0904	4
Assist in turning sideways (C2)	0.0812	5
Simple operation (C7)	0.0457	6
Silent operation (C13)	0.0428	7
Overheating protection (C14)	0.0405	8
Joint support (C12)	0.0346	9
Assist in turning over (C3)	0.0329	10
Gentle inflation and deflation (C11)	0.0276	11
Body type adaptability (C9)	0.0212	12
Aesthetically pleasing design (C18)	0.0203	13
Smooth interaction (C6)	0.0174	14
Even airbag distribution (C10)	0.0147	15
Heating therapy (C4)	0.0113	16
Intelligent control (C5)	0.0100	17
Color coordination (C19)	0.0096	18
Mode selection (C8)	0.0087	19
Suitable materials (C20)	0.0045	20
Easy storage (C21)	0.0020	21

User Needs-Technical Characteristics Transformation Matrix

To achieve the directional transformation of user needs into technical parameters, it is necessary to systematically construct the product engineering characteristics system. Based on the QFD theoretical framework, this chapter applies structured processing to the obtained user needs dataset for massage cushions: first, cluster analysis is used to semantically deconstruct the 21 design elements, eliminating redundant expressions and establishing a needs correlation matrix; then, to ensure rigor and professionalism during the quality function deployment phase, a Delphi method is employed to form an expert team, consisting of 3 professionals, 5 master’s students in industrial design and industrial design engineering, and a total of 8 members (Crisp *et al*. 1997). The technical solution set for the core functional modules is derived, as shown in Table 16.

Table 16. Core Design Elements Mapping Table

Design Elements		Design Requirements
Airbag massage design	Mapping	Multi-chamber airbag layout design D1
Assist users in turning sideways		Lifting structure design of airbag D2
Assist users in turning over		Wave-like air pressure mode design D3
Heating design with overheating protection		Zoned temperature control module D4
Voice control and smooth product system operation		Intelligent voice design D5
Simple product system operation		Interactive interface design D6
Massage mode adjustment		Massage mode adjustment D7
Suitable for elderly user groups		Modular design of airbag D8
Even airbag distribution with gentle inflation and deflation		Exterior design of airbag D9
Airbag support for key body areas to reduce pressure		Support structure design of airbag D10
Silent operation		Silent air pump D11
Safe and easy-to-clean materials for massage pads		Material safety D12
Avoid sharp edges and unreasonable structures		Rounded corner design D13
Rounded design, low-saturation color scheme, and quick folding		Styling design D14

Extraction of Product Design Elements

In the House of Quality model, the ceiling layer represents the technical characteristics layer, whose primary function is to translate product functional requirements into quantifiable engineering metrics. The QFD methodology has demonstrated remarkable effectiveness in cross-domain applications through its systematic requirements transformation mechanism (Ertay *et al*. 2005). In manufacturing, Pinquart (2002) employed QFD matrices to map automotive safety and comfort requirements to engineering characteristics such as material strength, resulting in a significant reduction in brake system failure rates and substantial improvement in customer satisfaction for a specific manufacturer. In medical care service, Lee *et al*. (2015) used the coupling of fuzzy logic and QFD to enable medical practitioners to understand customer needs and incorporate them, and this method will carry out continuous improvement in the process of medical service delivery. In educational technology, Bier and Cornesky (2001) applied QFD to transform e-learning interactivity requirements into modular content design, better aligning with learner needs to ensure graduates' skills directly match job market demands. By incorporating both student and faculty perspectives during QFD development, essential competencies were embedded in curricula, addressing the mismatch between societal expectations and higher education outcomes. In sustainable energy, Bevilacqua *et al*. (2008) innovatively developed an iterative QFD matrix process encompassing the entire supply chain from product lifecycle inception, while considering manufacturing equipment and components. This approach meets the requirements of diverse stakeholders including suppliers, manufacturers, and end-users. Validation studies confirmed the method's effectiveness.

These cases collectively demonstrate that QFD's structured requirements-characteristics mapping possesses universal value for enhancing product/service quality and user satisfaction across industries.

1) Place the user needs and their weights in the left column of the House of Quality table.
2) Fill the design requirements into the ceiling section of the House of Quality.
3) Establish a relationship matrix between user needs and technical elements, determining the strength of their correlations through discussions with an expert panel. Use symbols to denote the relationships:

- **●** (strong correlation, score = 5),
- **○** (moderate correlation, score = 3),
- **△** (weak correlation, score = 1).
- Leave blank for unrelated pairs.

4) Organize and fill these relationships into the "room" matrix of the House of Quality.
5) Finally, calculate the weights of the technical elements in the "basement" using the formula shown in Eq. 7.

$$W_j = \sum_{i=1}^{n} d_i \times r_{ij} \left(i, j = 1, 2, \ldots, n\right) \tag{7}$$

where *wj* represents the weight value of the *j-th* design element, *wi* represents the weight value of the *i-th* user need, and *rij* represents the value of the correlation symbol between the *i-th* user need and the *j-th* design element. The larger the *rij* value, the greater the calculated weight, indicating that this design element is more important.

The resulting House of Quality for the air pressure massage cushion product is shown in Figs. 9 and 10.

USER NEEDS	NEEDS WEIGHT	DESIGN ELEMENTS						
		D1	D2	D3	D4	D5	D6	D7
C1	0.16	Θ		Θ		O		O
C2	0.0812	O	Θ	O		▲		O
C3	0.0329	O	▲	Θ		▲		O
C4	0.0113				Θ	O	▲	O
C5	0.01					Θ	▲	O
C6	0.0174					Θ	Θ	O
C7	0.0457		▲		▲	Θ	Θ	Θ
C8	0.0087	▲	▲	▲	▲	O	▲	Θ
C9	0.0212						▲	▲
C10	0.0147	▲	▲	▲	▲			O
C11	0.0276	▲		Θ		▲		▲
C12	0.0346		Θ					
C13	0.0428							
C14	0.0405				Θ	Θ		
C15	0.0904	▲						
C16	0.244	Θ	Θ					
C17	0.1593							▲
C18	0.0203					▲	▲	
C19	0.0096							
C20	0.0045							
C21	0.002	▲						
DESIGN ELEMENTS WEIGHT		2.5057	1.9010	1.3695	0.3281	1.2700	0.3870	1.4626

Fig. 9. QFD Scoring Chart D1-D7

USER NEEDS	NEEDS WEIGHT	DESIGN ELEMENTS						
		D8	D9	D10	D11	D12	D13	D14
C1	0.16	Θ	O	O				
C2	0.0812	Θ	O	Θ				
C3	0.0329	Θ	O	Θ				
C4	0.0113	Θ				▲		
C5	0.01	Θ			▲			
C6	0.0174	Θ		▲				
C7	0.0457	Θ		▲				
C8	0.0087	Θ						
C9	0.0212	Θ	Θ	Θ				O
C10	0.0147	Θ	Θ	Θ		▲		O
C11	0.0276	Θ	Θ	Θ	▲			
C12	0.0346	Θ	O	Θ			O	O
C13	0.0428		▲		Θ			
C14	0.0405							
C15	0.0904	Θ	Θ			Θ		O
C16	0.244	Θ	Θ	Θ				O
C17	0.1593	Θ	Θ	Θ				▲
C18	0.0203	▲	O				Θ	Θ
C19	0.0096	O	O	▲				Θ
C20	0.0045		▲			Θ	Θ	Θ
C21	0.002		Θ	▲			Θ	Θ
DESIGN ELEMENTS WEIGHT		4.8441	3.8591	3.6322	0.2516	0.5005	0.2378	1.556

Fig. 10. QFD Scoring Chart D8-D14

Prioritization of Engineering Characteristics

Based on the results of the House of Quality for the air pressure massage cushion product from Fig. 11, the design elements are ranked according to their weight values (retaining four decimal places).

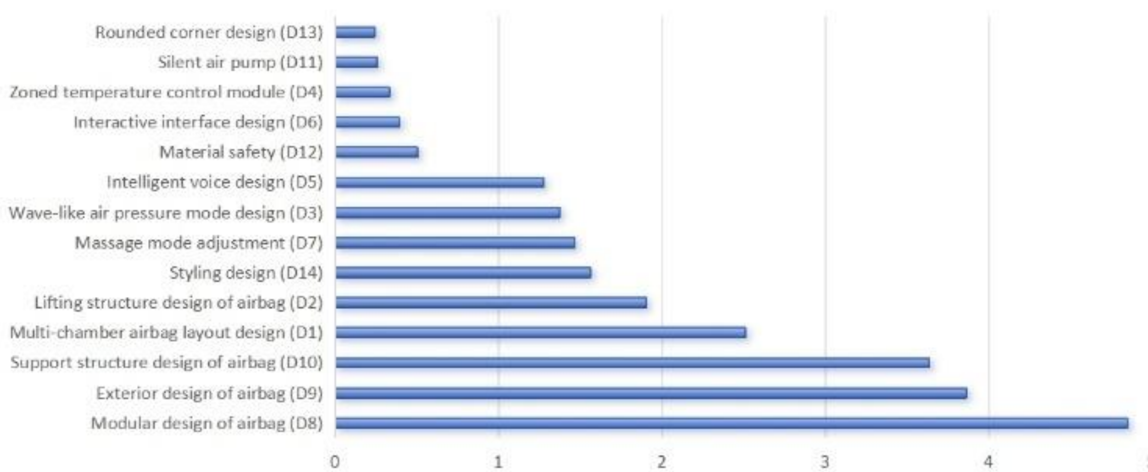


Fig. 11. Core Design Elements Weight Ranking

The Modular airbag design (4.8441) is the absolute core, followed by Exterior design of airbag (3.8591), Support structure design of airbag (3.6322), and Multi-chamber airbag layout design (2.5057), which together form the first tier. Lifting structure design of airbag (1.901) focuses more on upgrading and optimizing product functionality and also ranks high among the design elements. The importance of other elements (*e.g.*, intelligent design, silent air pumps, *etc.*) is significantly lower.

Therefore, in the design of the product, modularization and airbag support and airbag lifting structures should be given priority.

Jack-based Product Human-machine Relationship Validation

Jack simulation software is used and was based on the Chinese standard male and female base models in the built-in digital human model library of Jack software. The software generated the height and weight distribution spectrum covering the P50-P95 percentile through parametric modelling techniques. The product simulation model was then restored one-to-one according to the angle and size of the real product, as shown in Fig. 12.

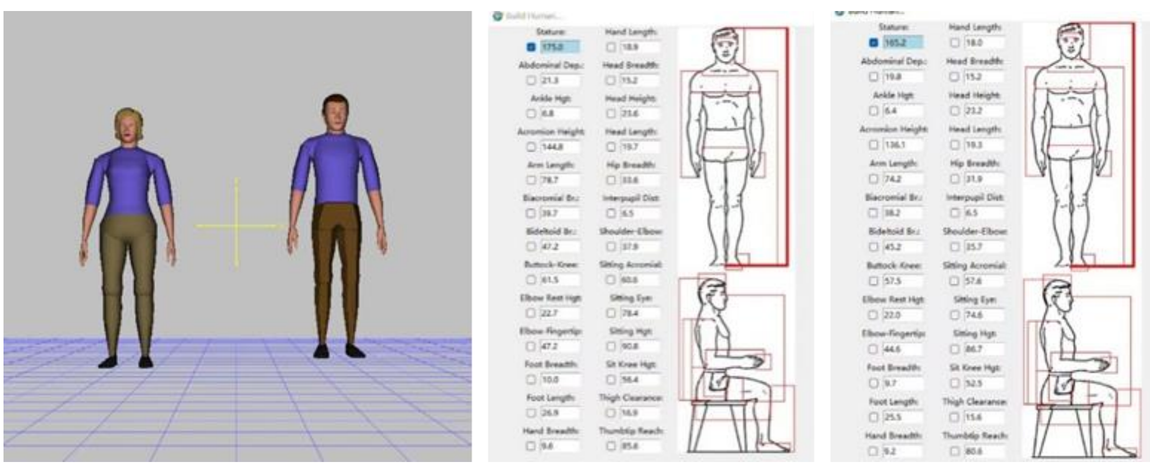
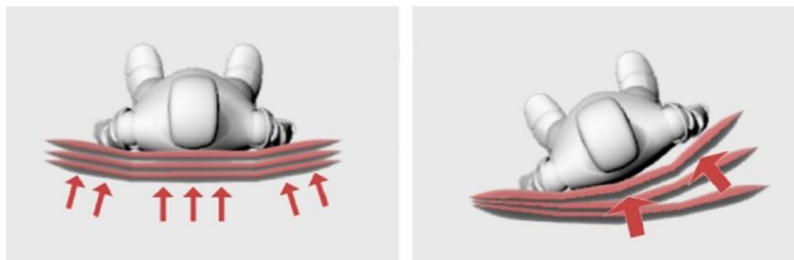


Fig. 12. Jack Digital Man Build

The study was conducted by comparing the biomechanical properties of a pneumatic massage cushion product before and after optimisation. The researchers used a standardised mannequin of 175 cm (male) height to simulate assisted rising and turning movements at three tilt angles of 20°, 40° and 60°. The focus of the study was to explore the effect of airbag lift angle on the body burden of elderly users during assisted standing up and turning. In the construction of the product model, the typical product model (dual airbag) and the optimised product model (triple airbag) in the market are compared, as shown in Table 17.

Table 17. Comparison Before and After Modelling

Comparative Analysis	Product Schematic Diagram
Traditional product structure (double airbags)	
Optimize the product structure (three airbags)	

The model files were used for the study. Using modelling software, the model file was converted to JT format and imported into Jack software for simulation analysis as shown in Fig. 13.

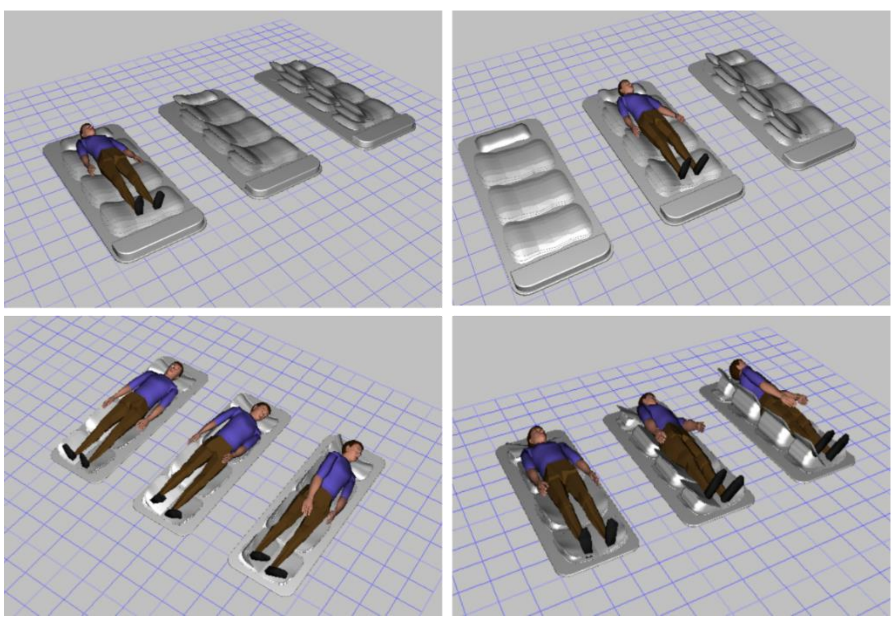


Fig. 13. Jack Model Import

Man-machine Ergonomics Analysis and Validation

Three biomechanical analysis methods were adopted in this simulation: 1) Joint comfort analysis, which evaluated the biomechanical load under complex postures based on digital human modeling technology. Liu Sheming *et al.* confirmed that the correlation between joint torque and posture comfort could be quantified (Liu *et al* 2013) and Yin Qingsong's team further verified the mapping relationship between joint angles and lower limb torque in driving scenarios (Yin *et al* 2016); 2) Force analysis of the lower back: Calculation of the pressure and shear force of the lumbar vertebrae through a virtual model. Liu Guanghui's research shows that this method has significant predictive value for preventing occupational lumbar injuries (Liu *et al* 2022); 3) Static force prediction and analysis: Tao *et al.* calculated the joint torque ratio based on the biomechanical model and constructed the sitting posture comfort evaluation system (Tao *et al* 2016). Gu *et al.* (2020) improved the application of this model in the prevention of musculoskeletal injuries.

The specific core research achievements are as follows. (The specific table can be found in the Appendix, Table A2).

(1) Optimization of joint comfort

At high tilt angles of 40° and 60°, the optimization scheme significantly improves the biomechanical characteristics of the upper limbs, mainly including the reduction of shoulder joint load, the neutralization adjustment of the wrist, and the improvement of hip joint symmetry. This optimization effectively reduces the risk of carpal tunnel syndrome and improves the comfort of the thighs.

(2) Lumbar pressure optimization

The optimized product significantly reduced the compressive force of the L4/L5 segments of the lumbar vertebrae. At a 40° Angle, the compressive force decreased from 2220N to 1008N. At a 60° Angle, the compression force decreased from 3552N to 1051N. This optimization achieved a systematic transformation from high-risk actions to the safe range.

(3) Improvement in muscle strength distribution

Static strength prediction shows the optimization of load redistribution in the core muscle group, mainly including the safety threshold of increasing shoulder strength capacity from 50% to 100% and the load tolerance capacity of the trunk by 30 to 80%, significantly reducing the risk of compensatory injury.

This research establishes for the first time a quantitative relationship model between the tilt Angle of pneumatic massage products and the biomechanical load of elderly users. Through digital simulation technology, it reveals the substantial improvement of the human-machine relationship brought about by the optimized design of pneumatic massage pads, confirming that the structural innovation of pneumatic massage pad products can reduce the risk of lumbar injury for elderly users.

CONCLUSIONS

1. This study systematically integrates AHP and QFD methods to solve the design problems of pneumatic massage cushions for the elderly, providing an innovative framework for optimising product functions and user experience. The research results reveal the priorities of user needs and the key paths for transforming user needs into technical parameters of air pressure massage cushion products, which provide important insights for the design of massage products.
2. Through AHP analysis, safety needs were identified as the primary factor influencing elderly users' preference for pneumatic massage cushions, followed by core functional needs. This result is consistent with previous research findings that emphasise the risk of physical injury to the elderly from inappropriate product design. It is worth noting that older users will pay extra attention to product requirements in terms of reasonable

structure (AHP weight: 0.2440) and material safety (AHP weight: 0.0904), which reflects the high sensitivity of older users to the risk of falls and skin irritation.

3. The integration of QFD further clarifies the mechanisms for translating user requirements into engineering priorities. For example, the modular design of the airbag (QFD weight: 4.8441) becomes the most critical technical feature, which signifies that most of the current products are not well adapted to elderly users; the design of the airbag support structure (QFD weight: 3.6322) and the airbag lifting and lowering structure (QFD weight: 1.901) can indirectly address the need of the elderly users for adaptive support when they make lateral adjustments or change their posture. Needs. This finding innovatively proposes a different design direction for current airbags.
4. The product innovation proposes a modular detachable airbag and a three-bag tilt assist structure, taking into account the functions of general use and special scenarios.
5. Using Jack software to simulate and validate the optimized product, construct a biomechanical model of Chinese elderly people (P50-P95 percentile), and then construct a comparative product model to simulate 20°, 40°, and 60° tilt scenarios and analyse lumbar vertebrae pressure and joints, etc. The analysis concludes that the optimized three-segment airbag structure makes the pressure of the L4/L5 segment drop from 3552N to 1051N when tilted at 60°. 3552N to 1051N, and the optimised solution significantly improves the biomechanical characteristics of the upper limb, mainly including shoulder joint load reduction, wrist neutralisation adjustment, and hip joint symmetry enhancement.
6. The results of the research and practice show that the use of the methodological framework can effectively solve the scenario of furniture products using pneumatic massage cushion products to assist elderly users, compared with the existing furniture assistive products on the market, the innovative design solution significantly reduces the load on caregivers in the elderly assistive getting up scenario.

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APPENDIX

Table A1. Raw Data of Selected Users

No.	Reviewer	Comment time	Comment
1	哈**弗	2024/03/10 02:40:28	气囊按摩仪做工很好，全身放松按摩，家庭成员都可以用，按摩力度到位。
2	x**n	2024/03/10 02:40:28	特色功能：很好 外观材质：精美好看 档位调节：3 个　按摩效果：舒服
3	t**0	2024/05/02 02:40:28	给老妈买了这款按摩床垫，看着高端大气上档次。，老人特别喜欢。收到货到今天，按摩好几次了。颈部、腰部特别舒服。非常满意
4	谢**呵	2024/02/10 02:40:28	做工挺好，看起来很不错，希望爸爸妈妈喜欢，能让他们放松一下🐼。
5	老**2	2024/04/10 02:40:28	给家人买的用上很舒服，客服必须好评，非常细心，已经把链接发给同事，他也要买
6	袁**桦	2024/03/10 02:40:28	实物与描述的一样，质量相当好，卖家态度也好，有问必答，发货速度杠杠的，值得购买哦
7	巫**7	2023/12/10 02:40:28	对比了几款 这款比较舒适 解乏 。也挺助眠的
8	沁**6	2024/04/10 02:40:28	不愧于五百强称号！效果很好哦！完全出乎我的预料！昨天一拆开就迫不及待用了！
9	阿**0	2024/04/10 02:40:28	发货快 物流稳 包装严实 老板不错
10	找**儿	2023/12/10 02:40:28	此用户没有填写评价。
11	城**d	2024/04/10 02:40:28	客服许大宝 shadow 服务非常好，沟通有耐心，回复快，反映电源接触不好后马上补寄一根，能感觉到责任心，对客户的重视，点赞！
12	m**4	2024/02/10 02:40:28	躺着可以全身按摩，挺舒服的，值得购买
13	y**8	2024/04/10 02:40:29	满意，整体是拉伸挤压的感觉！
14	牛**8	2023/12/10 02:40:29	非常好，按摩特别舒服，大品牌值得信任
15	t**5	2023/12/10 02:40:29	按摩的很舒适，特别到位，力度也刚刚好
16	豆**8	2023/12/10 02:40:29	评价方未及时做出评价,系统默认好评!
17	t**7	2023/12/10 02:40:29	按摩效果：还不错，全身来一次比较放松。
18	t**0	2023/12/10 02:40:29	质量非常好，与卖家描述的完全一致！
19	s**3	2023/12/10 02:40:29	再給家人買多張
20	s**3	2023/12/10 02:40:29	感覺很好，達到我預期要求，已再下單
21	我**4	2024/05/06 02:41:03	奥克斯气动按摩床垫，确实是舒适睡眠的优质之选！　深度放松：每次躺在奥克斯气动按摩床垫上，都能感受到那种从内而外的深度放松。气动按摩功能仿佛有专业的理疗师在为我服务，舒缓了我紧绷的神经和肌肉。 智能控制：这款床垫配备了先进的智能控制系统，可以根据个人喜好和需求，

			调节按摩强度、速度和部位。这种个性化的服务让我感到非常贴心和满意。 优质材料：奥克斯气动按摩床垫采用高品质材料制作，表面柔软舒适，内部支撑力足够。长期使用也不易变形，保证了床垫的持久耐用。 总的来说，奥克斯气动按摩床垫给我带来舒适与健康的睡眠体验。
22	m**2	2023/12/10 02:41:03	评价方未及时做出评价,系统默认好评!
23	可**奶	2024/04/10 02:41:03	真的超级喜欢，非常支持，质量非常好，与卖家描述的完全一致，非常满意,真的很喜欢，完全超出期望值，发货速度非常快，包装非常仔细、严实，物流公司服务态度很好，运送速度很快，很满意的一次购物
24	t**3	2023/12/10 02:41:03	质量很过关，品质有保障，相当不错的选择，好多朋友看我用都想买，我都推荐了想买的别犹豫哇！，很高端，特别棒！
25	t**5	2024/02/10 02:41:03	不得不赞，质量真的好，包装物流也不错。真心喜欢，入手后不会让你后悔的！
26	t**8	2023/12/10 02:41:03	效果很好，使用方便，按摩效果可以，非常满意。
27	1**c	2024/01/10 02:44:50	按摩效果：我已收到货了，质量很好，非常满意，按摩半个小时挺舒服的。
28	t**4	2024/01/10 02:44:51	东西质量非常好，与卖家描述的完全一致，非常满意
29	z**6	2023/12/10 02:44:51	用了觉得很不错，按摩垫品质不错，用着方便。
30	酸**5	2023/12/10 02:44:51	发货速度很快，价格美丽，疲惫的时候按一下真舒服

Table A2. Analysis of Joint Comfort Levels

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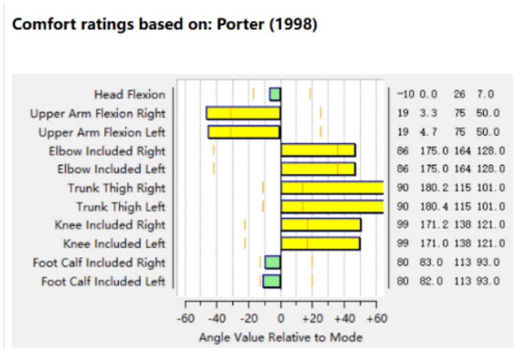
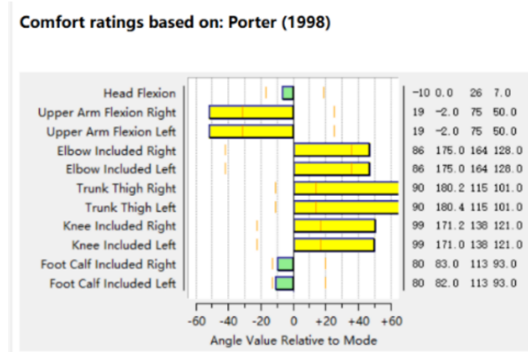
<tr><th>Angle</th><th>Pre-optimisation</th><th>Post-optimisation</th></tr>
<tr><td>20°</td><td>
</td><td>
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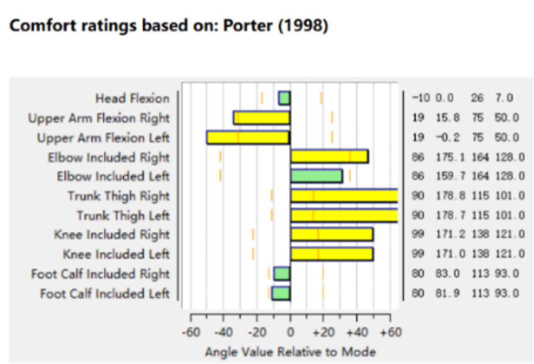
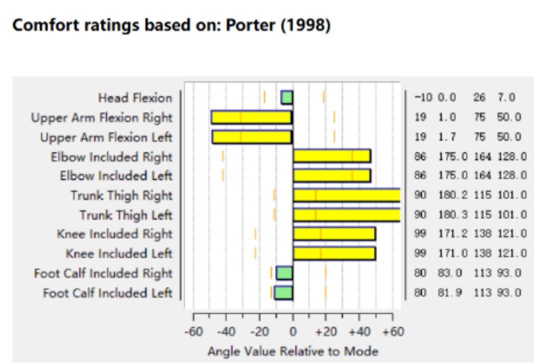
<tr><td>40°</td><td>
</td><td>
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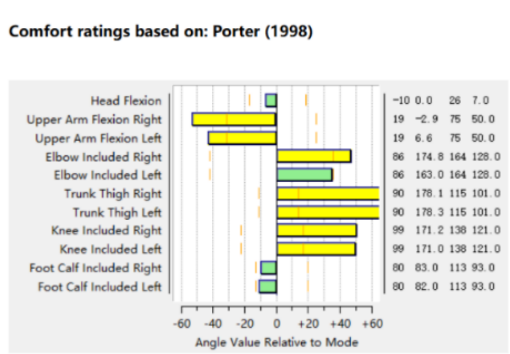
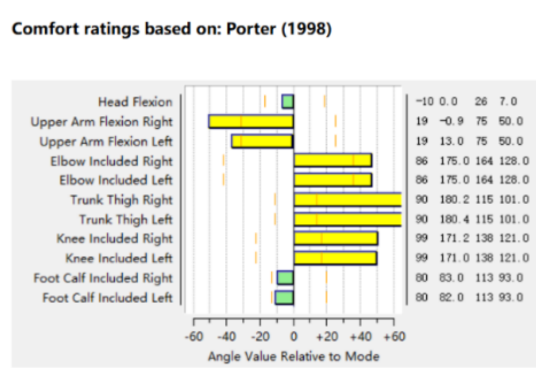
<tr><td>60°</td><td>
</td><td>
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Table A3. Mechanical Stress Analysis of the Lower Back

<table>
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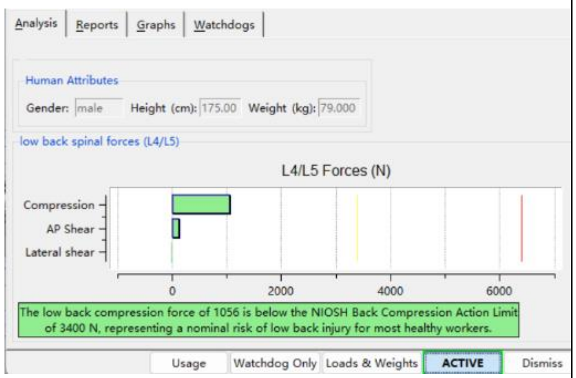
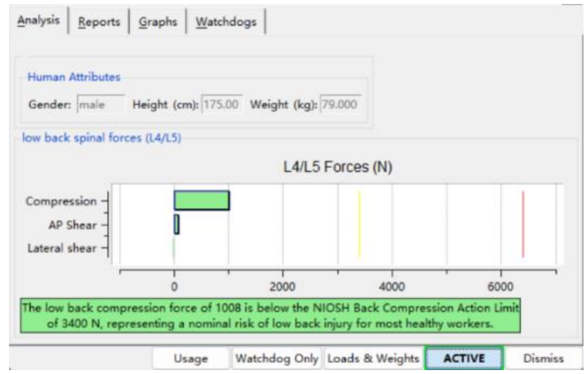
<tr><td>20°</td><td>
</td><td>
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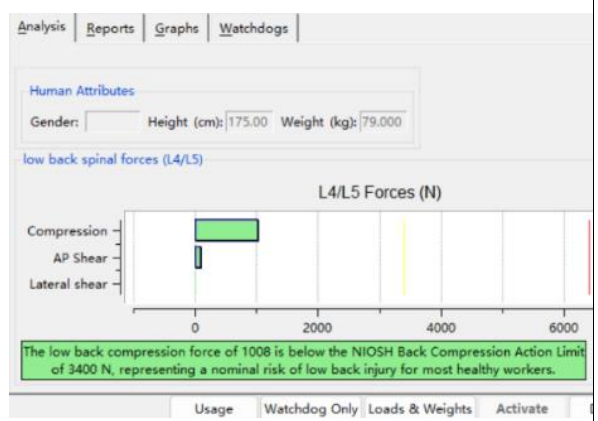
<tr><td>40°</td><td>
</td><td>
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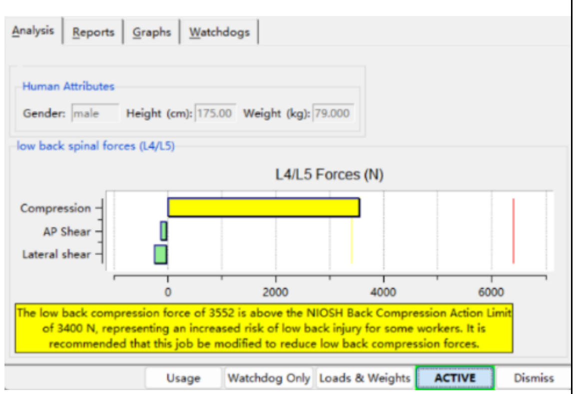
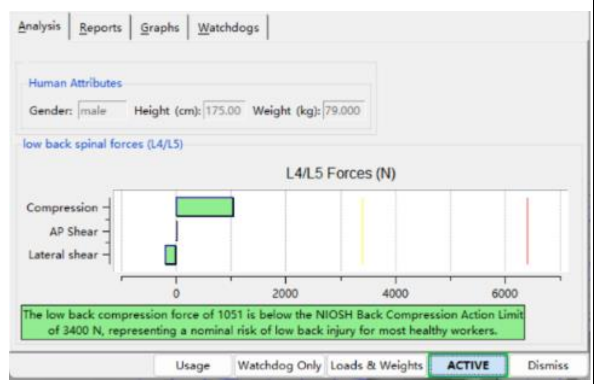
<tr><td>60°</td><td>
</td><td>
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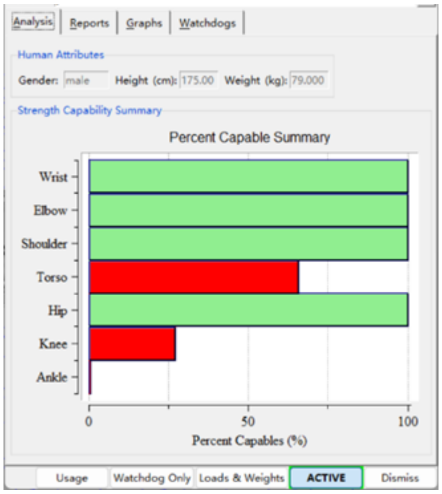
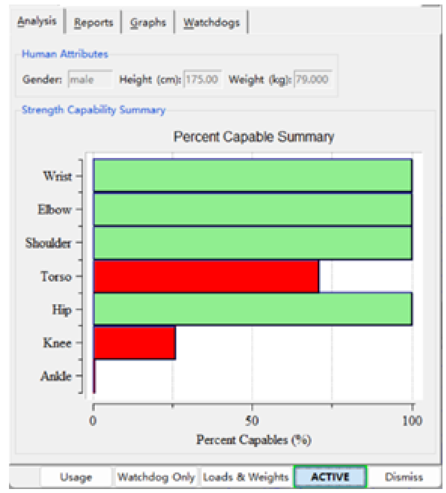
Table A4. Analysis of Workload Intensity

Angle	Pre-optimisation	Post-optimisation
20°		
40°		
60°