Design of a Dynamic Pressure-Relieving Cushion for Wheelchair-Dependent Elderly Based on KANO-ANP

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***Abstract*—Pressure injuries (PIs) are a life-threatening complication for wheelchair-dependent elderly, a risk exacerbated by the loss of sensory feedback. Traditional cushions, acting as passive supports, fail to address this critical perception gap. This study aims to develop an evidence-based design strategy for a dynamic cushion by integrating Sensory Compensation Theory with a quantitative decision-making framework. A hybrid KANO-ANP model was established. First, 24 initial indicators were extracted from 116 stakeholders (users, caregivers, clinicians). The KANO analysis then revealed a crucial finding: users classified core physiological functions like Shear Cancellation and Dynamic Altering as 'Indifferent' (I), demonstrating a significant gap between their perception and clinical reality. A coefficient-based rule was used to filter out low-impact features while retaining these clinically vital "latent needs." Subsequently, a 7-member expert panel, including WOCN nurses, used the Analytic Network Process (ANP) to evaluate the interdependencies and assign priorities to the refined indicators. The ANP model forcefully corrected the user's perceptual bias. The expert evaluation assigned the highest weights to Shear Cancellation and Dynamic Altering , confirming their non-negotiable importance. Furthermore, Sensory Compensation emerged as the second most important dimension , with indicators like Vibration Alert (S1) ranking high, validating the need for sensory empowerment.Based on these findings, a novel three-pronged design strategy is proposed: a Dual-Layer Decoupled structure to neutralize physical forces, a Multimodal Warning system to compensate for lost sensation, and an Active Airflow system for microclimate control. This study provides a scientific paradigm for transforming assistive devices from passive supports into active, sensory-enabled health management systems that bridge the gap between clinical necessity and user awareness.**

Keywords—Pressure Injury Prevention;Wheelchair Cushion;KANO Model, Analytic Network Process (ANP); Sensory Compensation, Active Aging;

I. Introduction

As the world' s population grows older at a high speed, more and more wheelchair users have increased, thus causing sitting for too long time leading to a stress damage such as stress ulcers has become one of the leading causes of mortality and disability . Among patients with spinal cord injuries and elderly people with disabilities, the lifetime incidence of pressure sores could be around 85 percent. It' s long process, it can also be deadly and the rate of getting the disease again and again is also very high which has made the health care system face a huge economic cost; In America, each year more than $11 billion dollars is spent on treating Stress Ulcer, This is causing major problems in peoples' life[1].

Factors that interact with the physiological environment. Sitting nodules of the sitting position bear 60% of the body weight. Once the local pressure is more than 32 mm Hg (close to the capillary closure threshold), microcirculation is damaged and causes tissue ischaemia and hypoxia [2].In addition, shear force is another key pathological factor: in a semi-reclined position or when the body slides downward, the bones move forward while the skin is held in place by friction, causing the deep soft tissue to twist and tear blood vessels, resulting in deep tissue injury (DTI). Such injuries often involve deep muscle necrosis even before the skin surface shows any damage, a phenomenon known as the "subcutaneous iceberg" [3]. Current care models, due to insufficient staffing and lack of specialized knowledge, struggle to detect hidden DTI in a timely manner, increasing the risk of skin breakdown[4]. Therefore, there is an urgent need for the development of smart devices capable of actively managing pressure and shear force and providing real-time intervention in order to address this public health crisis.

In the field of rehabilitation engineering, two main types of products have been developed to address the challenges of pressure ulcer prevention and management: static cushions and dynamic cushions. Static cushions are typically made of high-density memory foam, gel, or static air pads. Material deformation to increase the contact area and decrease the vertical pressure. But this kind of passive pressure reduction approach is restricted by the very physics at hand, thus following maximum compression degree of material, degrees of pressure reduction give big dips. Besides, it does not have any effect at all for cushions to reduce shearing forces so that this increases the chances of someone getting a deep tissue injury[5]. Long-term use might also cause the material to disintegrate and fall apart, as well as a lack of breathability, further increasing the possibility of cumulative injury[6].

Dynamic cushions, such as alternating air cushions, use electric pumps to alternately inflate and deflate air cells, enabling active pressure regulation at a physical level. However, they generally lack real-time sensing and feedback based on the user's physiological state. This results in an "information blind spot" for elderly users with impaired sensory function, making it impossible to replace the damaged nervous system' s warning signals for pain or abnormal pressure. As a result, nursing interventions often lag behind the onset of pathological damage[7]. Furthermore, existing designs often emphasize engineering and technical features while neglecting cognitive load and emotional needs of elderly users. Complicated operation and overtly medicalized appearance can cause anxiety and low

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user compliance, leading to underutilization of the equipment[8].

According to the problems mentioned above, the theory of "sensory compensation" in neurorehabilitation provides a theoretical basis for new design. It stresses that brain plasticity can strengthen the undamaged senses to rebuild the sense of the world such as blind people have a stronger sense of touch and hearing so as to get environmental awareness. This mechanism can be applied to smart cushion design to provide active mechanical feedback to make up for the loss of proprioception, and to replace the loss of the sense of pain with multimodal alerts (such as armrest vibration, visual cloud map, etc). This way solves out of the traditional single mode mode physical support restriction, realize actively intervene the physiological sensation interactive experience.

The closed-loop "human-machine collaborative defense system" Design idea already exists in the relevant theory and practice of neurorehabilitation and intelligent assistive technologies. Closed-loop neural prosthetic system obtain real- time monitoring and modulation of the user status by using the feedback. When compared to an open loop system, it performs better in task 1289performance and the users experience is also improved and it promotes collaboration between 1289human and device[9]. These systems use heterogeneous sensory signals such as vibration and light effect to promote cross-channel information transmission to alert users or caregivers to effectively interrupt the development of pathological processes. And, in terms of the design of closed-loop system, emphasis on multi - sensor fusion and physiological signal processing, improve the perception and response to users' physiological state, thus provide a technical foundation for early intervention of microcirculatory disorders related to pressure ulcers[10].

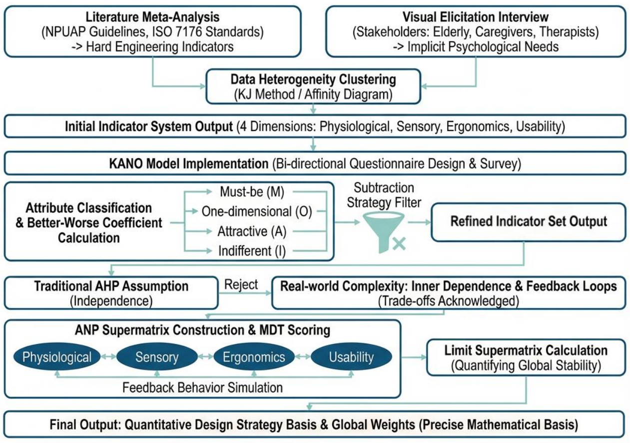

Fig. 1. Technical roadmap of hybrid research based on KANO-ANP model

II. METHODOLOGY

The Our overall research technology roadmap is shown in Figure 1.As for the research methods of design, the requirements for age-friendly medical assistive devices contain biomechanical parameters as well as subjective sensory experiences that are hard to be covered completely by qualitative or quantitative methods separately. The KANO model can help identify and classify user needs in terms of satisfaction and importance, while the Analytic Network Process (ANP) is capable of handling multi-factor, interrelated decision-making problems, precisely quantifying the weights of user requirements[11]. By combining these two approaches into a hybrid model, methodological triangulation and data source triangulation can be introduced, enhancing the scientific rigor and user adaptability of the design strategy — especially suitable for complex interaction analysis within the "human-machine- environment" system[12]. This "divergence-convergence-decision-making" logical loop aligns with the systematic process of modern intelligent assistive device design, promoting greater precision and personalization in design.

According to a meta-analysis of literature based on the latest NPUAP clinical guidelines for pressure ulcers and the ISO 7176 wheelchair standards, the pool of user needs can be divided into two main categories: objective engineering criteria and implicit psychological needs. In terms of engineering indicators, key requirements include shear force coefficient breathability, pressure distribution management,cushion adjustment and fit, stability assurance, selection of durable materials, and safety performance in compliance with relevant standards. Additionally, mobility and ease of control,as well as pressure and posture monitoring feedback systems,are important technical indices. Psychological needs were deeply explored through "visual symbol induction interviews" ,encompassing users' desire to be respected and not treated as patients, their longing for comfort and a sense of safety, autonomy and a sense of control, psychological support, as well as the need to reduce cognitive burden and for personalized customization[13]. With the KJ method (Affinity Diagram), clusters analysis of the above heterogeneous data was carried out to build up an initial index system including four parts: physiological care, sensory compensation, ergonomics and usability. So it ensures that the index system has the framework of the authoritative medical guidelines as well as the substance of real users' perception, and achieves a "no omission" construction of the needs pool.

The key after divergence lies in "convergence." Not all needs that are mentioned are worth implementing in the product; excessive piling on of features not only increases costs but also creates a cognitive burden for older adults. At this time, the KANO model [14] is introduced for the second layer of screening. Design both positive and negative questionnaires to calculate the satisfaction coefficient of each indicator as well as the indifferent attributes – functions that users simply don't care about and would be a waste to build such as some overly entertainment-focused design. In this study, it is carried out with a stringent "subtraction" , unreservedly dropping those items falling in "I" , and keeping only the items that must be (M), those that are single (O) and attractive (A) for the following. This process is about making the focus of design go from broad and all inclusive to selective and refined[15].

ANP, the Analytic Network Process was put forth in 1996 by Saaty, and this is a multi-criteria decision making technique which expands the AHP - Analytic Hierarchy Process as well as is made use of in respect of complex systems and it has the dependencies and feedback relationships amongst the criteria and indicators[16]. Unlike AHP which assumes all the indicators are independent, ANP permits the development of a network structure among criteria and indicators. Form a supermatrix including dependence and feedbackloop so as to simulate the complexinteractions within the system[17].

When it comes to anti-pressure ulcer cushions, “dynamic alternating pressure relief” and “silent operation” can be mutually constrained due to air pump power considerations, and “material breathability” directly influences the effectiveness of “microclimate management”, and such issues influence each other, and feedback loops are formed, and traditional AHP can hardly effectively catch such influence requirements. By using the ANP method, these indicators can be regarded as a fully connected network. A supermatrix is built up to show the weights and dependencies between the indicators and an MDT are asked to do pairwise comparisons.The global stable weights of each indicator are then obtained through mathematical calculation of the limit supermatrix[18].

Theoretically, this method is similar to the feedback mechanism of neural reflex arcs in the human body, making the model highly isomorphic to physiological systems in terms of logical structure. This helps to more accurately reflect the trade-offs among physiological and experiential dimensions. Ultimately, ANP not only reveals "which indicators are more important," but also clearly shows "who influences whom," providing a precise, systematic, and controllable mathematical foundation for the design strategy of anti-pressure ulcer cushions, and supporting multidimensional balanced decision-making and optimized design.

To ensure that the indicator system covers the full chain of "pathology-psychology-behavior," this study first conducted semi-structured interviews based on visual induction. Purposeful sampling was used to recruit a total of 15 stakeholders to participate in the first phase of the study. The sample consisted of:

- wheelchair-dependent older adults (n = 5): Aged 65–85 years, Braden pressure ulcer risk score ≤ 14 (medium to high risk);
- primary caregivers (n = 5): including family members and nursing home staff, with an average daily care duration of more than 8 hours;
- clinical rehabilitation physicians (n = 5): holding at least an intermediate professional title.

Units The 45-hour-long interview audio recordings were transcribed into approximately more than 120,000 words of raw text, followed by two-level coding using the KJ method (Affinity Diagram). The research team kept the translation rule of transforming “user language to academic language” by turning vague and emotional demands into concrete design indicators. Take the example of an elderly person saying “it feels like sitting on a stove” to be mapped to the pathological term “microclimate heat and moisture management,” when a caregiver said “I can’t tell if the air mattress is broken, no sign of activity” it was translated to the interaction term “visualization of operational status” after deduplication and semantic consolidation, the initial comprehensive indicator system of this study consisting of four primary dimensions and twenty-four secondary indicators was obtained as shown in Table 1.

TABLE I. INITIAL DESIGN INDICATOR SYSTEM AND SOURCE MAPPING

Dimension	Code	Indicator Name	Source Mapping (Rationale)
C1 Physiological (Nursing Care)	P1	Dynamic Altering	Interview + ISO 7176-26
	P2	Shear Cancellation	Interview + NPUAP Guideline
	P3	Microclimate	Interview + Literature
	P4	Deep Immersion	Interview + Hydrostatic Theory
	P5	Ischial Off-loading	Anatomical Feature
	P6	Anti-bacterial	Interview
C2 Sensory Comp. (Sensory Compensation)	S1	Vibration Alert	Sensory Compensation Theory
	S2	Visual Mapping	Interview
	S3	Voice Feedback	Interview
	S4	Sedentary Reminder	Behavioral Psychology
	S5	Fault Alarm	Interview
	S6	Haptic Texture	Interview
C3 Ergonomics (Body Support)	E1	Pelvic Stability	Interview
	E2	Thigh Alignment	Anthropometry
	E3	Edge Support	Safety Standard
	E4	Low Profile	Wheelchair Compatibility Standard
	E5	Non-slip Base	Interview
	E6	Lightweight	Interview
C4 Usability (Ease of Use)	U1	Auto-Set	Interview
	U2	Long Battery	Scenario Analysis
	U3	Wireless	Interview
	U4	Silent Mode	Interview
	U5	Remote Monitor	Interview
	U6	Multimedia	Interview

As for the physiological care items in Table 1 (C1) such as “shear force mitigation” and “microclimate breathability”, due to the fact that these care items involve high-complex soft tissue biomechanics and pathogenesis, engineers can’t make clinical significance judgment only based on the experience of industrial design. Therefore, it is very important to import experts with clinical powers in WOCN(WSKD) domains.

In order to make sure the professionalism of the following ANP evaluation and KANO questionnaire Design, This study composed a group of high-quality multi-field experts. The panel consists of seven people who are selected based on the following conditions: (1) have a senior professional title or equivalent qualifications; (2) have more than ten years of practical experience in their respective fields.The experts' average years of professional experience is 14.5 (SD = 3.2). The specific composition is as follows:

- Wound, Ostomy, and Continence Nurses (WOCN), 2 members:

This is a core feature of our expert panel. WOCNs represent the highest level of expertise in pressure injury care and possess authoritative insight into the micro-pathological mechanisms of pressure injury formation (such as vascular occlusion thresholds). The inclusion of WOCN specialists aims to address the "engineering-over-medicine" bias present in previous design studies.

- Chief Physicians of Rehabilitation Medicine, 2 members:

From top-tier hospital rehabilitation centers, focused on spinal cord injury and geriatric rehabilitation, responsible for assessing the long-term effects of cushions on the musculoskeletal system (e.g., risk of scoliosis).

- Senior Medical Product Designers, 2 members:

Winners of Red Dot/iF Design Awards, responsible for evaluating the feasibility of the indicators from the perspectives of engineering, material selection, and human- machine interaction.

- Professor of Geriatric Psychology, 1 member:

Specializes in cognitive impairment in the elderly and environmental psychology, responsible for evaluating the cognitive load of the interactive interface and the suitability of sensory compensation strategies.

This expert panel was involved throughout the entire research process: calibrating medical terminology during the indicator extraction phase and, as key decision-makers, constructing the judgment matrix in the ANP stage. This kind of cross-integration basically secures an active coordinating between "medical scientific requirements" and "design humanism" for this research result.

Traditional Likert scale tend to measure the users' explicit satisfaction, thus making it very easy for the feature creep of medical assistive devices. To precisely determine which are must-haves and which are attractions, this study uses the two-dimensional quality model presented by Noriaki Kano. A questionnaire was designes containing 24 pair of Positive-Negative. The positive questions ask, "How would you feel if this feature were present?" while the negative questions ask, "How would you feel if this feature were absent?" Answers use a standard 5-point scale (① I like it very much; ② It should be that way; ③ I don't care; ④ I can tolerate it; ⑤ I don't like it).

A total of 116 questionnaires were collected. The respondent demographic was diverse: Wheelchair users constituted the majority (60.3 %, n = 70), followed by Caregivers/Family members (34.5%, n=40), ensuring a balanced perspective between subjective experience and objective caregiving needs. In terms of age, 44.0 % were aged 60-70, and 35.3 % were over 71, aligning with the target geriatric profile. Regarding health status, 54.3% had no history of pressure injuries, while 37.9 % had healed injuries, indicating a strong potential demand for preventive products. According to the KANO evaluation table, each subject's responses to each indicator (e.g., "Positive: Like" + "Negative: Dislike") were mapped to specific quality attributes as follows:

- Must-be Attributes: Absence causes extreme dissatisfaction, while presence is taken for granted (e.g., leak-proof).
- Performance Attributes: The better the performance, the higher the satisfaction (e.g., breathability).
- Attractive Attributes: Absence is not an issue, but presence brings pleasant surprise (e.g., vibrating massage).
- Indifferent Attributes: Presence or absence makes no difference (e.g., color selection).
- Reverse Attributes: Presence actually leads to dissatisfaction (e.g., complicated alarm sound).

Relying solely on attribute frequency makes it difficult to quantify the specific impact of each indicator on satisfaction.Therefore, this study introduces the Better-Worse coefficient for in-depth analysis. The calculation formula is as follows[19]:

$$Better(SI) = (\frac{A+O}{A+O+M+I}) \tag{1}$$

$$Worse(DSI) = [\frac{O+M}{A+O+M+I} \times (-1)] \tag{2}$$

Where {A, O, M, I} represent the frequency with which the indicator is classified under the corresponding attribute.

Better coefficient (range 0~ 1): Reflects the "value-added potential" of the function. The closer the value is to 1, the stronger the increase in satisfaction brought by providing this function (mainly identifying attractive factors).

Worse coefficient (range −1~0): Reflects the "basic guarantee power" of the function. The closer the value is to − 1, the stronger the dissatisfaction caused by not providing this function (mainly identifying must-have pain points).

This study implements a nuanced screening mechanism tailored to the 'latent demand' nature of the target group. Given that elderly users with sensory loss often classify critical functions as Indifferent (I) due to lack of awareness, a simple exclusion of all I attributes would discard essential physiological protections. Therefore, a Coefficient-Based Filtering Rule was adopted

- Retention Rule:

Indicators classified as I but possessing a high Better coefficient (>0.25) (indicating potential satisfaction, e.g., S4, S6) or a high absolute Worse coefficient (>0.15) (indicating basic necessity, e.g., P6, P2) are retained as 'Latent Requirements'.

- Exclusion Rule:

Only I indicators with negligible impact (both Better < 0.2 and |Worse| < 0.1), such as 'Multimedia (U6)' and 'Voice Feedback (S3)', are excluded to reduce cognitive load.

By means of this quantification and screening funnel, the initial 24 indicators were refined into a core set of key design factors (excluding low-impact items like S3 and U6). This process not only reduces the computational complexity of the subsequent ANP model but also ensures that the final design strategies focus on addressing primary user needs, avoiding the trap of "function overload." And the specific data of the screening results will be shown in detail in the Results section.

The key indicators retained after screening with the KANO model do not exist independently but instead form a close coupled relationship, and the indicators have an internal dependent relationship. The traditional Analytic Hierarchy Process (AHP) was founded under the condition that the indicators are free. But this assumption is broken by the Design of Dynamic Anti- Decubitus Cushions. For instance: “high-frequency dynamic pressure relief” can improve the physiological care results, but also it will raise the “air pump operating noise” problem, and shorten the “battery life”, which has classic “a single move affects the whole” feedback relationship [20]. To take into account these bidirectional dependencies and feedbacks in a scientific way, this study took on the Analytic Network.

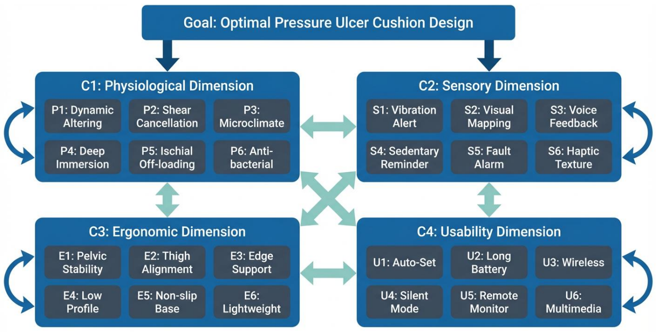

Fig. 2. ANP network structure model for pressure ulcer cushion design

Process (ANP), which was introduced by Saaty in 1996. In this way hierarchical goal connections can be made between the control and network, as for the network, indicator cluster networks with dense bidirectional feedback loops is established, reflecting the interconnectivity and trade-offs of the design indicators. This structure enables the formulation of design strategies that not only consider “who is more important,” but also scientifically reveals “who influences whom,” providing strong support for comprehensive performance optimization. As shown in Figure 2, we decompose the problem into two core layers: 1. Control layer. The overall goal is set as “the optimal design strategy for wheelchair anti-decubitus cushions for the elderly.” 2. Network layer. This includes four indicator clusters identified by the KANO screening: C1 Physiological Care, C2 Sensory Compensation, C3 Ergonomics, and C4 Usability. In this way, not only is a unidirectional connection established from the control layer to the network layer, but also dense bidirectional feedback loops are formed within the network layer. For example, C1 is set to affect C4 (function determines power consumption), while C4 also constrains C1 (power consumption limits functionality).

Using the Super Decisions software (v3.2, Windows 10 environment), a network model was constructed, and the aforementioned MDT expert group (7 members) was invited to conduct evaluations.

- Step1.Constructing the Unweighted Supermatrix :

The experts used Saaty’s 1−9 scale to perform pairwise comparisons on the interdependent criteria. The questioning paradigm was: “When considering the criterion of ‘Physiological Care’, which has a greater impact on ‘Battery Life’ — ‘Dynamic Pressure Relief’ or ‘Breathability’?” Based on the experts' scores, a comparison matrix was generated to calculate the eigenvectors, and these local priority vectors were inserted into the corresponding columns of the supermatrix. At this stage, column normalization of the matrix has not yet been completed.

- Step2.Constructing the Weighted Supermatrix :

In order to ensure that the sum of each column in the matrix is stochastic (equals 1), the experts were required to compare the importance of the clusters themselves. The cluster weight matrix was multiplied by the unweighted supermatrix to obtain the weighted supermatrix:

$$\bar{W}_{ij} = (W_{ij} \times C_{ij}) \tag{3}$$

- Step 3.Calculating the Limit Supermatrix :

To simulate the process in which the influence among indices is repeatedly disseminated throughout the network until stabilization, the weighted supermatrix was raised to powers.Once convergence is achieved, the values in each column of the resulting matrix represent the global priority weights of each criterion.

$$W^{\infty} = (\lim_{k\to\infty} (\bar{W})^{k}) \tag{4}$$

Due to the subjective ambiguity of human judgment, it is necessary to perform a consistency check on each pairwise comparison matrix. The calculation formula is as follows:

$$CI = (\frac{\lambda_{max} - n}{n - 1}) \tag{5}$$

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

where λ_{max} is the maximum eigenvalue, n is the order of the matrix, and RI is the random consistency index. In this study, all judgment matrices are required to have CR < 0. 1. In actual practice, during the first round of scoring, the CR values of two matrices (mainly involving the interactive effects between "sensory compensation" and "usability") were 0.12 and 0.15, respectively. The research team then organized a second round of Delphi discussion, providing feedback to the experts on the inconsistent nodes. After further investigation and modification, all the values of the CR in the matrices were finally reduced to less than 0.08. In order to have good logical unify and scientifically reasonable final weight data.

III. Result

Based on 116 valid questionnaires collected, attribute classification was conducted for 24 initial indicators according to the KANO evaluation table. Table 2 presents the frequency distribution and final attribute assignment. The analysis results reveal a telling pattern: the vast majority of indicators fell into the Indifferent (I) category. This suggests a widespread "latent demand"—users are largely unaware of what they are missing due to sensory loss.

TABLE II. BETTER AND WORSE COEFFICIENT

Code	Indicator	Category	Better (SI)	Worse (DSI)	Decision
S4	Sedentary Reminder	I	0.424	-0.059	Retained
P6	Anti-bacterial	I	0.378	-0.311	Retained
S6	Haptic Texture	I	0.365	-0.302	Retained
S2	Visual Mapping	I	0.338	-0.014	Retained
P1	Dynamic Altering	I	0.286	-0.071	Retained
E6	Lightweight	I	0.277	-0.181	Retained
E2	Thigh Alignment	I	0.267	-0.058	Retained
U3	Wireless	I	0.265	-0.084	Retained
U1	Auto-Set	I	0.261	-0.058	Retained
U4	Silent Mode	I	0.256	-0.122	Retained
S5	Fault Alarm	I	0.244	-0.081	Retained
S1	Vibration Alert	I	0.237	-0.062	Retained
U2	Long Battery	I	0.233	-0.2	Retained
P4	Deep Immersion	I	0.211	-0.156	Retained
P2	Shear Cancellation	I	0.188	-0.176	Retained
U5	Remote Monitor	I	0.176	-0.027	Retained
U6	Multimedia	I	0.167	-0.012	Excluded
E1	Pelvic Stability	I	0.157	-0.048	Retained
E3	Edge Support	I	0.148	-0.037	Retained
S3	Voice Feedback	I	0.133	-0.013	Excluded
E5	Non-slip Base	I	0.128	-0.051	Retained
P5	Ischial Off-loading	I	0.125	-0.075	Retained
E4	Low Profile	I	0.117	-0.091	Retained
P3	Microclimate	I	0.084	-0.072	Retained

Specifically, P1 (dynamic alternating pressure relief) and P2 (shear force offset) were both classified as Indifferent (I), with relatively low Worse coefficients of 0.071 and0.176. While this might seem surprising, it actually highlights a critical issue: for elderly users with sensory loss, the threat of shear force is "invisible." They simply do not feel the danger, leading to indifference. This gap between user perception and clinical reality makes the expert-driven ANP weighting in the next phase even more vital — it is a matter of survival, even if the user doesn't realize it.

On the other hand, the data revealed what users do consciously desire. As shown in the KANO results, S4 (sedentary reminder) and S6 (haptic texture) achieved the highest Better coefficients (0.424 and 0.365), ranking top in satisfaction potential. S2 (visual pressure cloud map) followed closely (0.338). This indicates that while users ignore the mechanics, they have a strong craving for "sensory empowerment" — gentle reminders and comfortable touch that make them feel cared for and in control.

At the same time, consistent with our predictions, U6 (multimedia entertainment function) remained at the bottom (Better0.167, Worse0.012), confirming it as a redundant distraction. Similarly, S3 (voice status broadcasting) was also eliminated (Better0.133). Interviews revealed the reason: public voice announcements felt "embarrassing," reinforcing the stigma of being a "sick person." Therefore, we eliminated voice interaction in favor of the more desired tactile and visual feedback to protect the elderly's social dignity.

Based on these quantitative insights, we refined the indicator set to a core group of key design factors (excluding low-impact items like S3 and U6) to advance to the next stage of ANP weight calculation.

Based on the iterative calculations performed by the Super Decisions software, the weighted supermatrix converges after computation, with the values in each column stabilizing to form the limit supermatrix. Table 3 presents the relative weight distribution of the four control-layer dimensions.

TABLE III. WEIGHT DISTRIBUTION OF DIMENSIONS

Dimension	Code	Weight	Rank
Physiological Care	C1	0.463	1
Sensory Compensation	C2	0.245	2
Ergonomics	C3	0.178	3
Usability	C4	0.114	4

The results show that the C1 Physiological Care dimension carries a weight as high as 0.463, accounting for nearly half of the total. This once again quantitatively confirms that "pressure ulcer prevention" is a core attribute of medical devices. Following closely is C2 Sensory Compensation (0.245), a weight significantly higher than that of the traditional C3 Ergonomics (0.178) and C4 Usability (0.114).

This counterintuitive weight distribution (Sensory Ergonomics) is a significant finding, indicating that experts believe — for wheelchair-bound seniors with sensory loss — the value of active interaction functions that can "awaken perception" (such as vibration alerts) even surpasses that of passive physical comfort (such as ergonomic fit).

By normalizing the elements in the ultimate supermatrix, the global composite weights for the key indicators were obtained. Figure 3 shows the top key indicators and their cumulative weights. Data analysis revealed the true priorities in design:

P2 Shear Force Mitigation (0.184) takes the top spot, right after is P1 Dynamic Alternating Pressure Relief (0.152), and in third place we have P3 Microclimate Breathability (0.095). Together, these three indicators account for 43.1% of the total system weight. This indicates that, regardless of how smart the cushion is, if it fails to deliver on the three physical fundamentals of "shear resistance, pressure relief, and temperature and humidity control," the entire design will be rendered unsuccessful.

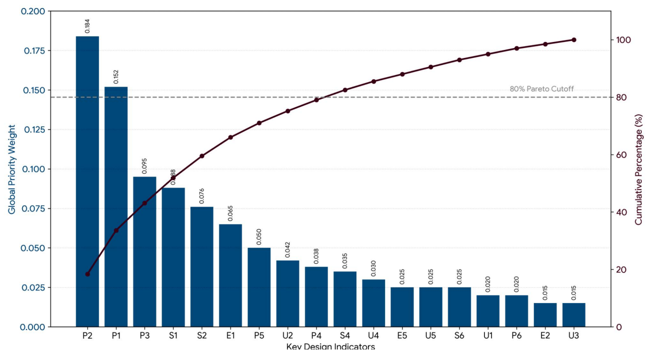

Fig. 3. Pareto chart of global weights for key design indicators

It is noteworthy that S1 Abnormal Pressure Vibration Alert (0.088) and S2 Visualized Pressure Cloud Map (0.076) have squeezed into the top six, even surpassing E1 Pelvic Support (0.065) in weight. This strongly supports the "sensory compensation" hypothesis of this study: that equipping elderly individuals with "perception" through technological means is considered an efficient pathway to pressure ulcer prevention.

To verify the necessity of introducing "dependency" in the ANP model, we compared it with the traditional AHP calculation results, which do not consider feedback relationships.

In the AHP model, since the "function-power consumption" constraint is not taken into account, the weight of U2 Ultra-long Battery Life is underestimated (ranking only 12th).

In contrast, in the ANP model, because the negative feedback from C1 (powerful air pump) to C4 (battery) is considered, the weight of U2 Ultra-long Battery Life rises to 8th place (0.042).

This indicates that the ANP model accurately captures engineering reality: the more powerful the physiological intervention function, the greater the need for strong energy support. Such weight adjustment based on real-world constraints makes the design strategies derived from the ANP model more feasible for engineering implementation.

IV. STRATEGY

A. *Strategy 1 Physiological Compensation: Active Anti-Shear and Dynamic Intervention*

KANO analysis, the expert panel assigned it the highest weight (w0.184) in the ANP model. This starkly highlights the significant gap between user perception and clinical reality. This discrepancy reinforces the necessity of the Dual-Layer Decoupled design, which must operate as an automated intervention system to provide protection without requiring conscious user engagement.

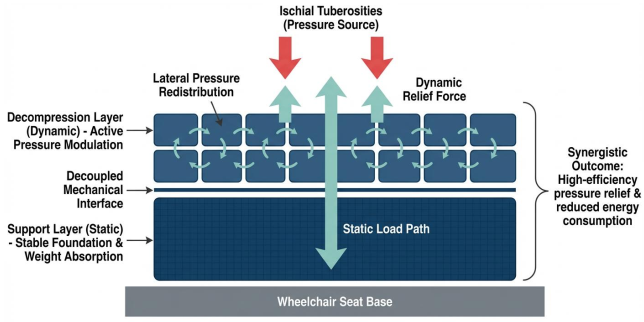

Fig. 4. Conceptual Model of Dual-Layer Decoupled Synergy Mechanism

We put forward a "two-layer decoupling" structured strategy to achieve physical decoupling and coordination of the cushion's vertical support function and the horizontal shear resistance function. As Figure 4 shown,vertically (dynamic) P1 index is dealt with by cycle the inflation and deflation of the airbag arrays simulates muscle pumps, so that "zero-pressure time window" is produced at the compressed areas to improve the microcirculation and blood perfusion of the local area. Horizontally (Sliding) it is addressed through a low-friction adaptive layer to absorb the lateral stress generated by body sliding at the P2 index. This 1+1 moving and slided, such that the base which should have received the shear force transmission is unable to pass on to something more distant, such an approach may be helpful with an elderly person who no longer functions physiologically[21] .The control algorithm operates as follows: an integrated pressure sensor array continuously monitors the pressure distribution. When a specific region exceeds a pre-set pressure-time threshold (e.g., >32mmHg for >5 minutes), the system identifies the corresponding air cells. To maintain postural stability, the algorithm then executes a 'Neighbor-Compensated Deflation' sequence: it slightly increases the pressure in the adjacent cells before slowly decreasing the pressure in the target cell, ensuring the user's weight is smoothly redistributed rather than causing a sudden drop. The cycle then proceeds in an A-B-C pattern across the entire surface to ensure systematic off-loading.

In fact, dual-layer decoupling cushion design integrates the dynamic alternating pressure relief of the vertical dimension with a sliding low-friction surface of the horizontal dimension to reduce both vertical compression and harmful shear force. In this mechanical innovation, we take advantage of the active load change and shear force decoupling to achieve the protection of the vulnerable deep tissue parts, and solve the problem of pressure ulcers and deep tissue injury for the elderly who cannot turn over independently in a wheelchair, which cannot be solved by passive cushioning.

Recognizing the safety risks associated with active surfaces, the dynamic altering strategy incorporates several safety protocols. The rate of inflation/deflation is algorithmically limited to a slow, gradual transition to prevent abrupt movements that could cause shear or destabilize the user. Furthermore, the system includes a 'Static Mode' manual override. Users or caregivers can press a single, easily accessible button to instantly deactivate all dynamic movements, converting the cushion into a stable, static surface. This is critical during transfers (e.g., from wheelchair to bed) or when the user requires absolute postural stability. This feature directly addresses standard safety requirements for active medical assistive devices.

B. Strategy 2 Sensory Empowerment: Multimodal Perceptual Reconstruction

The factors S1 high-weighted factor abnormal pressure alert (0.088), S2 visual feedback (0.076) have screened the important neglected neurological aspect in pressure ulcer prevention among the external manifestations of loss of pain sensation due to afferent nerve blockade. To this key problem, the core strategy is to achieve the goal through "sensory enhancement", which means using the elderly's existing sensitive senses, such as touch and sight, to build an external artificial reflex arc to compensate for the failed biological pain pathways.

Responding to the KANO analysis request for eliminating "voice interferences" and destigmatizing alerts, this strategy uses a low cognitive load, multiple modes of interaction logic. Non-invasive gradient vibration signals are used as the main warning signals, including a gentle first-level vibration which is breathing / adjustment, and a more urgent second-level vibration which simulates pain / warning. This tactile feedback directly excites the limbic system, causing defensive reflexes in private situations, but at the same time preserving the user's social dignity[22].

In other words, besides a, an interface can numerically render the invisible pressure distribution as an intuitive "risk heat map" which makes it clear to the users immediately, thus moving the pressure ulcer treatment from guessing to data-backed preemptive management. Innovations in sensing are together,early detection,tactile feedback cues help in taking prompt responses in case of the individual having a loss of sensation,thus reducing the risk of the pressure ulcers [23].

And this will be the engineering practical message of the embodied cognition theory. Turning the cushion into an extension of the elderly person's body perception, endowing it with proactively sensing and feedback functions, to enable the user's position of passively receiving care to change to an active role in participating in their own health management. In this shift not only reduce risk from lack of perception, also considerably strengthening of the elderly individual's self-efficacy, i.e. their confidence and feeling of control over taking effective preventive measures for self. There are studies that have shown that when we improve patients' self-efficacy then it will be able to promote them to have self-care behavior that will continue and effectively prevent pressure ulcers and also help to enhance their health management as a whole [24].

To address the risk of alarm fatigue, the proposed multimodal system operates on a 'Graduated Alert' principle, distinguishing between gentle guidance and critical warnings.

- Level 1 (Guidance): For non-critical events like prolonged sitting (as per indicator S4), the system provides a subtle, non-intrusive haptic cue (e.g., a slow 'breathing' vibration) intended as a private reminder, not an alarm. This aligns with our KANO finding that users prefer gentle guidance over disruptive alerts.
- Level 2 (Warning): A high-priority alarm (e.g., a sharp, pulsed vibration) is triggered only when a critical pressure threshold is breached for a sustained period, indicating imminent tissue damage risk.
- Caregiver Notification: To avoid desensitizing the primary user, critical alerts can be configured to be sent directly to a caregiver's mobile device via the App (as per indicator U5), bypassing the user entirely, especially during sleep. This tiered, context-aware approach ensures that warnings remain meaningful and actionable, thereby mitigating the risk of alarm fatigue for both users and caregivers."

C. Strategy 3:Microenvironmental Ecological Governance

Similarly, although P3 (Microclimate) demonstrated the lowest user interest in the survey (Better SI = 0.084), its role in preventing skin maceration is scientifically indisputable according to the 'Four Forces Model'. This cognitive dissonance supports the implementation of an Active Airflow system, which should operate autonomously based on sensor thresholds rather than relying on manual user control.

In response to the limitations of passive breathable materials, this strategy proposes the principle of " active negative-pressure circulation " : it advocates for an "extraction" airflow mode rather than "direct blowing" in order to avoid the "cold-damp effect" that could harm elderly individuals, while efficiently removing moisture and heat from beneath the hips. Addressing the " function vs. energy consumption (C1 vs C4)" trade-off identified in the ANP, the strategy recommends the introduction of a threshold-triggered algorithm (such as activation when humidity exceeds 80%). This kind of on-demand working mode, it can reach an optimum degree in the improvement of effectiveness of the microenvironment for the system and its efficiency of using the energy within the system itself.

V. Discussion

A. Theoretical Validation: Mapping to the "Four-Force Model "

The design strategies derived from the KANO-ANP hybrid model establish a theoretical correspondence with the 'Four Forces Model' of modern pressure sore pathology, thereby demonstrating that this combination of technologies adheres to scientific methods for clinical applicability.However,our findings reveal a significant discrepancy between expert clinical judgment and user perception. While the KANO analysis indicated that users classified both Shear Cancellation (P2) and Dynamic Alternating Pressure Relief (P1) as 'Indifferent' due to a lack of sensory awareness, the ANP expert evaluation assigned them the highest weights (0.184 and 0.152, respectively). This discrepancy underscores the necessity of our approach: the model addresses not only the expressed desires of users but also the "invisible" clinical risks they cannot perceive, such as the 'subcutaneous iceberg effect' of Deep Tissue Injury (DTI) as described by NPUAP[25].

Even more importantly, the study goes beyond the Four Forces Model by empirically validating a fifth, often-neglected dimension: 'perception'. While the ANP assigned high priority to alarm-based functions like Vibration Alerts (S1), the KANO analysis revealed that users have a stronger latent demand for gentler, more engaging forms of feedback. For example, Sedentary Reminder (S4) and Haptic Texture

(S6) achieved the highest Better coefficients. This suggests that a truly effective 'digital nervous system' should not only warn of danger but also provide positive, behavioral guidance and comfort. Our multimodal strategy, therefore, integrates both urgent alerts (from ANP) and desirable interactions (from KANO) to create a more holistic and human-centered sensory experience, transforming the device from a mere treatment tool into a cooperative human-machine defense system

As for this study has shown that, this kind of strategy model built on dynamic support surface has great possibility to be turned to clinical use, partly because of "sensory empowerment", with "sensory empowerment" it makes up for patient missing pain signal, with vibration, visual feed back it deals with the "compliance problem" in nursing care. It can be learned that empowerment is an important part of nursing that refers to helping patients and their caregivers acquire decision-making ability and autonomy and positively affecting compliance and quality[26]. Empowerment is not just about psychology or society; it also includes the improvement of patients' perceiving capability and risk awareness through specific operational environment and technology, so patients can take care of the affairs themselves[27].

Further more, by presenting the pathological risks as "visual" as well as "tactile", we can also have patients and carers perceive the risks in real time. This directly solves problems in nursing where patients who have no sensation refuse to cooperate with turning over. This Design effectively replaced the traditional passive care model and help to enhanced patient adherence and the outcome of care [28].

B. Clinical Potential and Limitations

Despite the rigor of the logical framework, this study still has the following limitations that need to be examined in future work:

First and foremost, the primary limitation of this study is its conceptual nature. The proposed design strategies, while rigorously derived from user needs and expert judgment, have not yet been validated through a functional prototype or empirical pressure-mapping experiments. Consequently, claims regarding 'superior pressure distribution' or 'enhanced blood perfusion' remain theoretical deductions based on biomechanical principles. Future work must prioritize the development of a high-fidelity prototype and conduct comparative clinical trials against high-end static air-cell cushions, using objective metrics such as interface pressure, tissue oxygenation (using transcutaneous oximetry), and long-term pressure injury incidence rates.

Second, regarding strategy design research based on expert scoring (ANP) and user needs analysis (KANO), there is still a lack of large-scale clinical pressure mapping measurements and longitudinal controlled trials of pressure ulcer incidence, as well as insufficient sample sizes, which aligns with the phenomenon of inadequate integration between design research and clinical validation noted in existing literature. For example, some studies have pointed out that although various strategies for pressure ulcer prevention have been designed, there is still a lack of extensive clinical trial verification and limitations in sample size. In addition, although pressure mapping technology has been applied in wheelchair cushion selection and seated pressure management, its stability and clinical practicality are still being improved, and there is not yet sufficient data to support large-scale clinical applications[29].

Third, regarding the potential failure of sensory compensation strategies for groups with severe cognitive impairment (such as late-stage Alzheimer's disease), research by the Alzheimer's Association and others has shown that patients with advanced cognitive dysfunction have a significantly reduced ability to understand abstract symbols (such as red light warnings), and may also display agitated behaviors, which limits the effectiveness of abstract symbol applications[30]. Adaptive strategies for groups with advanced cognitive impairment need to take specific differences in cognitive abilities into account and subdivide user profiles in order to design more precise and simplified interventions[31].

Lastly, regarding the "function – energy consumption" constraints revealed by the ANP model and concerns that a double-layer air cushion structure may increase cushion thickness and affect the wheelchair's center of gravity and stability, engineering literature indicates that although double- layer or multi-layer air cushions can optimize pressure distribution, they inevitably increase physical thickness, thereby affecting the wheelchair's stability and operational performance. Although new types of high-strength, ultra-thin materials (such as TPU composite fabrics) can reduce thickness, actual engineering applications still face tough trade-offs between material performance and ergonomics. Moreover, the current international standard ISO 7176－16 imposes limitations on cushion thickness, so technical implementation must proceed in compliance with these standards[32].

VI. CONCLUSION

A. Summary of Research Findings

This study takes a dynamic decompression pad Design strategy based on KANO - ANP hybrid model to solve the aging problem which relies on wheelchairs and sensory function has been reduced. It proves the point of "mechanical substitution for the human brain".

First, a significant disconnect exists between user perception and clinical necessity. While users classified core physiological functions like "Shear Cancellation (P2)" and "Dynamic Alternating Pressure Relief (P1)" as 'Indifferent' (I) due to a lack of sensory awareness, the expert-driven ANP evaluation emphatically assigned them the highest weights. This confirms that the physical mechanics of preventing Deep Tissue Injury (DTI) remain the non-negotiable foundation of the product's value, even if users themselves cannot perceive the risk[33].

Secondly, Sensory Compensation is a breakthrough for improving user experience. The thoughtful combination of some attractive features such as "abnormal pressure vibration warning (S1)", "visual pressure mapping (S2)" meet users' strong need for "restoration of perception" and allow users to re-perceive their physical status through touch and vision. It can also be found in the research related to intelligent wheelchairs and assistive devices, the feedback system can also improve the behavior of the user when it comes to stress relief and safety, and it encourages the user to monitor themselve

Finally, cognitive load reduction is an important aspect of age-friendly design and moral aspects. The KANO model discards indifferent attributes such as "voice broadcasting" and "multimedia entertainment", and it is indicated that the design should not lead to sensory overstimulation but should help lower the cognitive load of the elderly and protect their social status. So as to make medical aids that are practicable at the same time should be respectful of the social and psychological need of the elderly. This also fits in with minimizing the users cognitive load on the equipment .

To sum up, this study systematically integrates qualitative exploration, quantitative screening and network-based weightings, and builds a multi-level value system of "physical foundation - sensory improvement - cognitive optimization" in the design of dynamic decompression mats. This method is sure to have the physiological basis of preventing pressure sores, improve the sense of user experience and the compatibility with morality, and offer a much more complete and personal stress relief solution to wheelchair-olders.

B. Theoretical and Practical Contributions

Theoretically, this study has filled the traditional "four-force model" with the human factor dimension of "perceptual loss" that is often ignored by supplementing it with the "sensory compensation theory" of neural rehabilitation, enriching the perspective of elderly-friendly auxiliary equipment Design. It put forward an explanatory framework of " visual/tactile compensation for pain perception " , offering a new academic perspective for addressing the problem of " perceptual disconnection " in human-computer interaction, thereby expanding the theoretical foundation for preventing pressure sores.

In terms of methods, this study verified the feasibility of the KANO-ANP hybrid model in the Design of medical products. It is effectively breaks through the limit that is can not weigh the independent kano model and the mixed-independence coupling by single APHP models (Such as the coexisting energy-consumption contrary example of the functional module). It is worthy to be pointed out that the participation of wound, stom and incontinence nurses (WOCN) in the decision making process can correct the old Design research bias of "engineer is important, medicine is not " and also has established a scientific and rigorous paradigm of all in medical engineering decision making.

At the level of industrial practice, three core strategies proposed by this study, namely, dual-layer decoupling of shear resistance, sensory-empowered early warning, and active microclimate cycling, together with a "deskilled" care interaction logic, can provide practical R&D guidance for medical device companies. These strategies help promote the development of anti- pressure ulcer assistive devices from the stage of traditional material processing to the era of intelligent interaction, and also provide technical support for solving the problem of a shortage of professional nursing staff in an aging society, promoting the application and development of anti-pressure ulcer devices.

C. Final Remarks

These contributions are original and practical within the research on pressure injury prevention at present. Existing studies have emphasized that nursing interventions are important and the impact of insufficient nursing prevention measures and technical system Design for medical device related pressure injuries and so on [34]. Study also produced theoretical innovation, method integration and practical application as important reference promotion interdisciplinary innovative prevention pressure ulcer and In order to prevent pressure ulcer, but also a technical problem that appears in medical practice, It is also a problem concerning the dignity of the old people's life and moral issues. In the face of the global wave of aging, the design strategies proposed in this paper attempt to break away from the traditional image of assistive devices as "cold medical equipment", and integrate pathological mechanisms and smart interactive technology, and build an active intervention system with characteristics of being "perceptual, communicative and temperature-responsive"

Although further clinical validation is still needed, the direction highlighted by this research — empowering disabled elderly individuals through technology so that they shift from passive recipients of care to active health managers—will be a key path in meeting future caregiving challenges. We look forward to the light of technology pierce through the fog of perception, ensuring that every elderly person spends their later years in comfort and dignity.

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