Fashion and Textiles

RESEARCH Open Access

Identifying key evaluation criteria and design attributes to optimize sports bra design for senior females

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Abstract

The sports bra plays an important role in providing adequate support and minimizing breast movement to prevent exercise-induced discomfort, pain, and potential damage. However, there has been limited investigation into the evaluation of sports bras specifically designed for senior females. Therefore, this study was conducted to identify key multi-criteria for evaluating the design attributes of sports bras for senior women. Another aim was to systematically and numerically assess sports bra performance based on human perceptions. To achieve these objectives, the Delphi study was employed to identify key criteria, and the Analytic Hierarchy Process was utilized to rank the importance of both design attributes and sports bra styles. Unlike traditional evaluation methods, this study stands out by first identifying the multi-dimensional criteria for sports bras and then assessing intangible perceptions based on both subjective and objective feedback. The results indicate that the top three important criteria for subjective self-evaluation were overall support, shaping effect, and tactile sensation. Meanwhile, the top criteria for objective third-party evaluation were appearance, underband stability, and fit. Furthermore, the findings suggest that the long-shirt encapsulation-style sports bra, featuring a high neckline and a double back layer, was more suitable for senior women than the other three styles tested. This design provides ample support, an excellent shaping effect, sufficient back support for maintaining good posture, and freedom of movement during physical activities. These findings can inspire designers and manufacturers to develop sports bras tailored specifically for senior women by combining optimal attributes and design features.

Keywords: Sports bra, Senior females, Delphi study, Analytic hierarchy process, Bra design

Introduction

According to the World Health Organization (WHO), the global proportion of people aged over 60 is projected to nearly double from 12% in 2015 to 22% by 2050, reaching approximately 2 billion (WHO, 2022). The rapid growth of the aging population

will undoubtedly place significant burdens on both individuals and society, including increased costs of illness and more frequent public hospitalizations (Lee et al., 2016). However, some societies are beginning to view aging as an opportunity, and certain super-aged countries are embracing the concept of the silver economy (D'Ambrogio, 2020). Silver consumers are now significant players in the economy due to their relatively high incomes and large needs. As senior females age, they experience several noticeable changes in their breasts, including dissatisfaction with their breast appearance, weakened support tissues, and a higher risk of breast diseases (Coltman et al., 2017). These changes have significant implications for both physical and psychological well-being, resulting in a substantial need for external support during activities, such as sports bras.

Development trends change of sports bra are aligned to the change of population structures change. Currently, researchers and companies are adapting their products to meet the elderly market (Guido et al., 2022). The new sports bra development should consider both senior females' viewpoints and other conjoint analysis. Developers are trying to identify important design attributes and constructions to cater to the segmented market. However, there is no consensus agreement on the preferred design features. For example, some research has suggested the importance of strong support (Zhou et al., 2023), but this support is often achieved at the expense of comfort (Zhou et al., 2023). Human perceptions are intangible and complex, making it difficult to determine the importance of a set of variables (O'Donnell et al., 2003). However, commonly adopted assessment methods include either subjective assessments through self-answered questionnaires, interviews (Brown et al., 2014), or objective quantitative measurements of biomechanical behavior (McGhee & Steele, 2020), human motion recognition (Lu & Tong, 2019), or electromyography signals (Li et al., 2009; Sun et al., 2017). It is of significant interest to combine self-answered subjective data and the third part relative objective feedback from users for comprehensive design of sports bra.

The Analytic Hierarchy Process (AHP), a decision-making method widely utilized in evaluating and selecting alternatives, is commonly applied in medical technology, healthcare assessment, and information systems management (Liberatore & Nydick, 2008). AHP facilitates a comprehensive and rational approach to address decision problems, assigning numerical weights to each evaluation element by converting underlying information into numerical values. It enables the identification of optimal solutions for multi-criteria decision-making problems (Widianta et al., 2018). Usually, before conducting an AHP, it is essential to identify the key criteria. The Delphi study is a systematic and interactive tool used to achieve a consensus for framework development by gathering opinions from experts. Consequently, the goal of this research is to subjectively and objectively identify the critical factors that highly affect sports bra design for senior females using the AHP methodology based on the Delphi study. By providing a comprehensive and rational framework of criteria for comparing the performance of various alternative solutions, ultimately defining preferred sports bra design features and identifying the most suitable sports bras from several alternative solutions. It offers a feasible means to enhance the design and use of age-friendly sports bras for senior

females, assisting them in making right decisions on the options of various sports bras for their exercise routines.

Literature Review

To identify the most suitable design of sports bras for senior women, the initial step involves determining the appropriate evaluation criteria. Subsequently, a comprehensive and systematic combination of these criteria should be conducted, guided by practical wear trials. Structured frameworks should be devised to facilitate their integration into the decision-making process for evaluating sports bras. When selecting criteria for age-friendly sports bra design, factors such as comfort, support, functionality, user-friendliness, and aesthetics are typically considered (Zhang, 2022). Given the unique physical and psychological characteristics of senior women, aspects such as shaping effect, appearance, coverage, color, and femininity are highlighted as primary considerations. The level of satisfaction or dissatisfaction with one's body parts is closely linked to individual self-image, self-concept, or self-esteem (Brown & Lohr, 1987). Consequently, sports bras should enhance self-image and express beauty, presenting an attractive body silhouette to motivate older women to wear them during exercise (Zhang et al., 2019). Support is equally essential to comfort. For senior women seeking to conceal signs of aging and appear more youthful, uplift and push-up features are key support factors (Schultz, 2004). As the body ages, the anatomical supporting system loses elasticity, rendering elderly women's breasts more susceptible to discomfort during vigorous movement. Additionally, health issues such as disrupted body movement, nipple migration, and lack of breast support systems necessitate enhanced support. The shoulder strap is often cited as the most problematic component of a sports bra. It may slide over the shoulder or dig into the skin due to improper fit. Incorrectly tightened straps can exert excessive pressure on shoulder tissues, leading to discomfort or nerve dysfunction (Lee et al., 2024; Zhou et al., 2023). Solutions such as cushioned straps, wider width, and adjusted position can alleviate these issues. Furthermore, proper back configuration and underband width significantly impact user satisfaction.

Research indicates that effective sports bras feature a short vest style, high neckline, slings, and cross-back or Y-back strap configuration, among other factors (Zhou et al., 2023). Another study suggested that the most comfortable sports bras are made of medium modulus, soft/spandex blend knit fabrics, with no fasteners and inserts around the cup for freedom of movement (Cheung, 2022). Given that various components of sports bras may conflict with each other, it is essential to tailor the selection process to meet the needs of the target users. While the appropriate selection of components yields benefits, the wrong materials may lead to performance reduction or failure. This dilemma underscores the need for advanced methodologies for optimal product design and decision-making. Therefore, this study aims to systematically and numerically identify and evaluate the key design attributes of sports bras for senior women based on their perceptions.

The combination of the Delphi study and AHP was selected for this research. The Delphi method, pioneered by Dalkey and Helmer at the Rand Corporation in the 1950s (Dalkey & Helmer, 1963), aims to achieve a reliable consensus among a group of experts regarding a specific topic by iteratively reviewing several rounds of feedback to make

effective decisions. In this method, experts independently work through a set of identical questions, and their feedback is collected anonymously. The results are then summarized, and the process iterates until consensus is reached. The Delphi method enables the exploration of underlying information, leading to different judgments and refining initial judgments (Blau, 1977). In the fashion and textile industry, the Delphi method is valuable for addressing complex issues professionally. For example, Huang and Tan (2007) conducted a market survey using the Delphi study to evaluate and prioritize important apparel design factors that affected the quality of apparel design. The Delphi and AHP research method has also been applied to develop frameworks for sustainable textiles design (Gbededo & Liyanage, 2020) and identify key elements for supply chain management in the sustainable fashion-apparel industry (Garcia et al., 2022).

The AHP model is typically constructed through several steps. First, define the target problem that needs to be addressed. Second, construct the hierarchical structure, which is built from the top level to the middle and bottom levels. This structure encompasses the goal of the decision, the selected evaluation criteria, and the alternatives, defined as the object layer, ruler layer, and factor layer, respectively. Third, perform pairwise comparisons; the matrices are compared pairwise to assess their relative importance. Finally, calculate the weights; the weightings of each evaluation criterion are calculated, allowing for the quantification and comparison of each criterion's relative importance for decision-making. Hence, AHP is important for systematically structuring key criteria, ensuring a direct, rational, and logical assessment without unnecessary complexity or procedures (Widianta et al., 2018). When faced with multiple criteria, reducing dimensionality to achieve a comprehensive assessment within a single dimension becomes important yet challenging. AHP has been proposed and demonstrated its reliability and robustness in prioritizing factors and alternatives, and it is extensively applied in fashion and textiles. Previous studies underscore the efficacy of these methodologies in addressing the complexities inherent in product design and decision-making processes, particularly in qualitative analysis. For instance, Kapuria and Karmaker (2018) utilized AHP-based quality function deployment to ascertain optimal design criteria associated with material parameters, manufacturing processes, and chemical treatments, all aimed at enhancing the quality of textile products. Similarly, Bizuneh and Kifle (2024) conducted a survey to determine and prioritize users' requirements using factor analysis and fuzzy AHP.

There is a lack of investigation into the evaluation of sports bras specifically designed for senior females. Moreover, existing research on performance evaluation is limited, either focusing on qualitative questionnaires or biomechanical analysis within a few attributes (Zhou et al., 2022). However, this study considers a comprehensive scope, prioritizing and narrowing down the attributes with ranked importance, and quantifying human perceptions that are intangible and complex, making it difficult to judge the importance of a set of variables. Hence, this study focused on sports bra design for senior women based on the analysis of subjective and objective evaluations of four self-developed sports bra prototypes. Experiments were conducted to identify the key multi-criteria for evaluating the design attributes of sports bras for senior women. Another aim is to systematically and numerically assess sports bra performance based on human perceptions. Accordingly, the following research questions are proposed:

RQ1: What are the key evaluation criteria for sports bras for senior women from the perspectives of professionals and senior women themselves?
RQ2: What are the priority design attributes according to professionals and senior women in the evaluation of sports bras?
RQ3: Based on the results from RQ2, what is the ranking of the four self-evaluated sports bra prototypes?

The first research question (RQ1) was addressed by reviewing the literature and employing the Delphi method to extract common design attributes. Ratings from professionals and users on the selected attributes were structured into a 9-level Likert scale and analyzed using AHP. Similarly, evaluations of sports bra prototypes were conducted using AHP, prioritizing the key criteria. This approach is important for satisfying the needs of senior female consumers and enhancing the sales of the intimate apparel industry.

Methods

Te following procedures as outlined in Fig. 1 will be carried out to achieve our targets. The process starts to develop the preliminary criteria list in evaluating sports bra designs for senior females, summarizing from previous research. Subsequently, a Delphi study will be undertaken to identify the most appropriate criteria by reaching a consensus among a panel of experts, expanding upon the initial set of criteria. The refined framework derived from this will form the foundation for constructing the AHP hierarchical structure. According to the AHP model, one senior female participants were asked to perform selected poses and complete questionnaires,

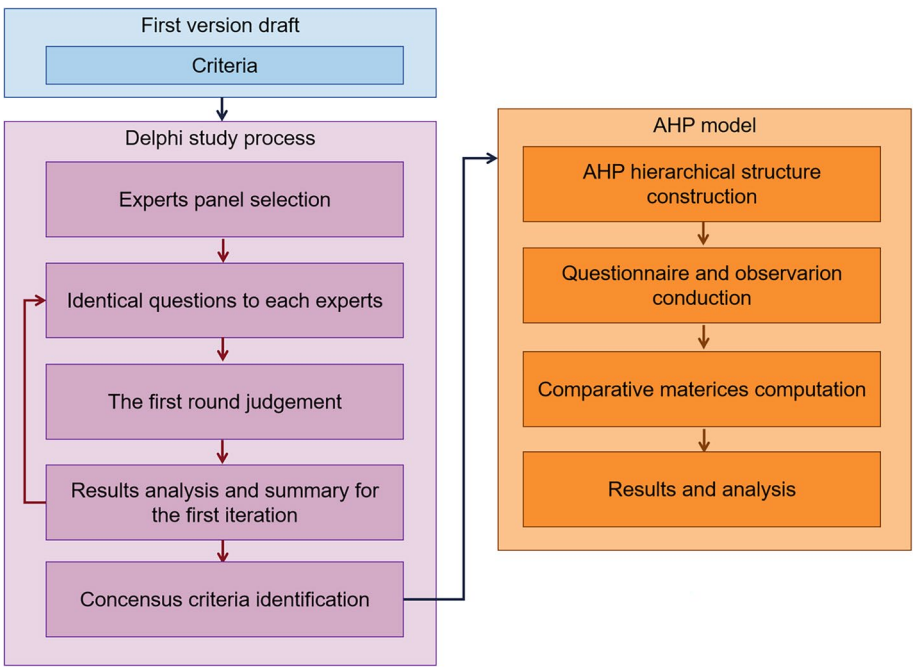


Fig. 1 The framework for conducting the Delphi study and AHP model

while observations will be conducted by a research assistant acting as an impartial third-party.

Experts panel selection

According to recommendations from previous literature, a suitable group size for avoiding irrelevant opinions or complexity in reaching a consensus is typically between 9 and 18 participants (Vidal et al., 2011). Therefore, we selected 10 experts who met the following criteria: 1). Diverse perspectives; 2). Sufficient knowledge and experience; 3). Willingness to volunteer and available time for participation. Of the several experts approached, 10 finally participated in the study, with half coming from the industrial sector and the other half from academia. The academic experts were chosen based on their in-depth knowledge, publication records and research backgrounds in fashion technology or related disciplines. The industrial practitioners included fashion designers, intimate apparel designers, and managers in roles related to manufacturing, merchandising, and marketing within the industry. For detailed profiles of the participating experts, please refer to Table 1.

Performing a Delphi study to build up the AHP hierarchical structure

Before starting the Delphi study process, the first version of the criteria for evaluating sports bra performance was drafted based on previous studies (Yick et al., 2010; Zhang et al., 2022; Zhou et al., 2023). These criteria were categorized into 11 sections: aesthetics, shoulder straps, neckline, back, armhole, underbust, cup, side panel, closure, wing, and fabric, as outlined in Table 2. The criteria were structured into a 9-level Likert scale to assess the importance of each criteria in evaluating sports bras for senior females, with a rating of 1 indicating minimum importance and 9 indicating maximum importance.

Table 1 The profiles of participating experts

Experts/ Scholars No	Year of related experience	Section	Job title	Research field
1	30	Industry	Fashion Designer	Sports bra design
2	11	Academia	Academic	Underwear optimization
3	23	Academia	Academic	Fashion technology
4	12	Academia	Academic	Functional and particular garment development
5	22	Industry	Senior manager	Quality control, practical manufacture problem solving, resource planning, inventory management
6	16	Industry	Senior manager	Merchandising operation and management, marketing, trend prediction
7	10	Academia	Academic	Psychology, human behavior, exercise motivation
8	8	Industry	Team leader	Fashion design
9	12	Industry	Technician	Textile fabrication
10	36	Industry	Underwear Designer	Cutting and prototyping

Table 2 Criteria for evaluating design features for sports bras

Component	Design criteria
Aesthetic	·Not embarrassing ·Shaping effect
Shoulder straps	·Tightness
Neckline	·Coverage ·Tightness
Back	·Support ·Tightness
Armhole	·Large movement space
Underbust	·Support ·Tightness
Cup	·Shaping effect ·Fitting ·support
Side panel	·Shaping effect ·Thermal management
Closure	·User-friendly
Wing	·Support ·Coverage ·Shaping effect ·Thermal management
Fabric	·Thermal comfort ·Tactile comfort ·Elasticity
Color	·Bright contrast colors make senior women feel energetic and youthful ·Dark colors, such as black, make them look slim

Sports bra samples

Four types of sports bras developed by ourselves were used, which have two styles: short shirt style and long shirt style. The sports bra samples were manufactured to incorporate the current representative features of sports bras, as shown in Table 3. The bra sizes ranged from 80B to 90D. Each participant wore each sports bra for the evaluation.

Build up the AHP hierarchical structure

In the evaluation of sports bra alternatives, the AHP was employed to facilitate the complex decision-making process, which was divided into three hierarchical layers. These layers were organized from top to bottom and included the object layer, the rule layer, and the factor layer. In this study, the first layer, namely the object layer, represents sports bra performance. The the rule layer as second layer was established through expert consensus using the Delphi study process and consisted of eight elements assessed through both subjective self-answered questionnaires and objective observations from a third-party. The self-answered questionnaire encompassed criteria such as shaping effect, underband comfort, fitting, overall support, strap comfort, the ability to stay in place, tactile sensation, and back support. Meanwhile, the third-party observation included assessments of the ability to stay in place, shaping effect, fitting, uplift effect, underband stability, overall appearance, coverage, and back support. The third layer comprised the four selected sports bra alternatives.

Table 3 The design specification and different views of developed sports bra

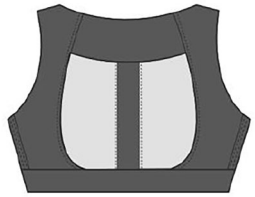
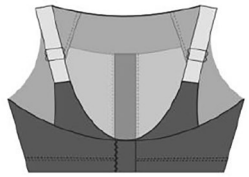
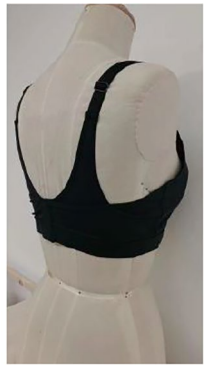
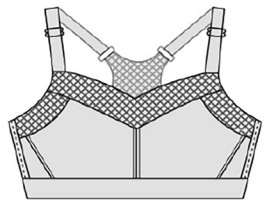
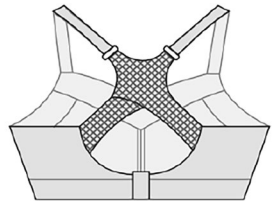
No	Design features	Design sketches and photographs
Sports bra 1 (B1)	·High neckline ·Encapsulation style ·Low armhole ·U-shaped double back support ·Moisture-wicking, quick-drying material	     
Sports bra 2 (B2)	·V-shaped neckline ·Compression style ·Mesh fabrics for neckline and armhole ·Special back design ·Moisture-wicking, quick-drying material	 

Table 3 (continued)

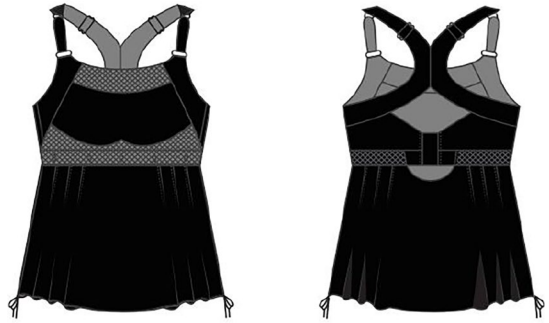
No	Design features	Design sketches and photographs
		
Sports bra 3 (B3)	·High neckline ·Compression style ·Butterfly-shaped back design ·Detachable long shirt ·Magnet opening and closure ·Moisture-wicking, quick-drying material	

Table 3 (continued)

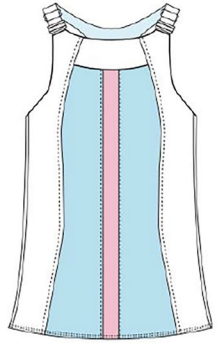
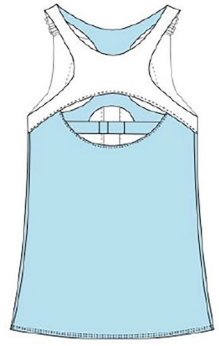
No	Design features	Design sketches and photographs
Sports bra 4 (B4)	·Detachable slider ·Encapsulation style ·Light color ·Double-layer racerback ·Zip up from the bottom at the side seam ·Moisture-wicking, quick-drying material	  

Table 3 (continued)

No	Design features	Design sketches and photographs
		

Table 4 Nine-level scale rating for AHP

Scale	Definition of importance	Explanation
1	Equal	Two factors contribute equally to the objective
2	Slight	
3	Moderate	Judgement slightly important one over another
4	Moderate plus	
5	Strong	Judgement strongly importance one over another
6	Strong plus	
7	Very strong	Judgement is very strongly over another
8	Very, very strong	
9	Extreme	Judgement is of the highest possible order of affirmation over another

Remark: if factor i is attributed by a non-zero numbers when compared with the factor j, then j has the reciprocal value when compared with i

Based on this information and analysis, a hierarchical structure was established. To assess the relative importance of the criteria, a nine-level scale rating was employed (Sun, 2010), as detailed in Table 4, where a rating of 1 indicated equal importance, 5 signified strong importance, and 9 represented extremely high importance. The senior female participants and the third-party were tasked with judging both the criteria and sports bra alternatives. Pairwise comparisons were conducted, starting from the lowest level, to determine their relative significance or importance.

In the context of the sports bra evaluation for senior females, the criteria and four selected sports bra styles were assessed through pairwise comparison matrices. Subsequently, an A-matrix (n×n) was formulated, as illustrated in Function 1.

$$\mathrm{A} = \begin{bmatrix} 1 & \mathrm{a}_{12} \cdots & \mathrm{a}_{1\mathrm{n}} \\ \vdots & \ddots & \vdots \\ 1/\mathrm{a}_{1\mathrm{n}} & 1/\mathrm{a}_{2\mathrm{n}} \cdots & 1 \end{bmatrix} \tag{1}$$

where n represents the number of alternatives, i refers to the base criteria for comparison corresponding to row i, and j indicates the criteria being compared to criteria i (Leal, 2020). In this reciprocal matrix that $a_{ji} = 1/a_{ij}$, matrix A then can be converted into Function 2.

$$\begin{bmatrix} 1 & a_{12} \cdots & \mathrm{a}_{1\mathrm{n}} \\ \vdots & \ddots & \vdots \\ 1/\mathrm{a}_{1\mathrm{n}} & 1/a_{2n} \cdots & 1 \end{bmatrix} \begin{bmatrix} W_1 \\ W_2 \end{bmatrix} = \lambda_{\max} \begin{bmatrix} W_1 \\ W_2 \end{bmatrix} \tag{2}$$

$$\mathrm{AW} = \lambda_{\max} \mathrm{W} \tag{3}$$

In accordance with Function 3, the eigenvector can be computed to establish the weight of criteria, where W represents the criteria weight matrix, and λ denotes the largest eigenvalue. The final evaluation results were derived by aggregating the rankings of each alternative, determined based on their performance scores in each criterion. Before analyzing the results obtained from the AHP, it's essential to assess the reliability of the pairwise comparison matrix by calculating the Consistency Random (CR). This is

done to ensure the consistency of judgments, in other words, to confirm that the judgments are logical. Illogical situations, such as A being more important than B, B being more important than C, but C being more important than A, should be detected and addressed. To calculate the CR, it's necessary to calculate the consistency index (CI) and the random consistency index (RI) first. The CR is defined by computing the CI and the Random Index (RI), as demonstrated in Function 4, Function 5 and Function 6.

$$\mathrm{CI} = \frac{\lambda_{max} - n}{n - 1} \tag{4}$$

$$\mathrm{RI} = \frac{\lambda_{max,avg} - n}{n - 1} \tag{5}$$

$$\mathrm{CR} = \frac{CI}{RI} \tag{6}$$

where λ_{max} represents the largest eigenvalue, and $\lambda_{max,avg}$ is the average value of λ_{max} for the matrix A (n × n). The accepted CR (Consistency Ratio) value should be less than 0.1. If the CR value exceeds 0.1, the assessment result is considered unacceptable, and it is advisable to repeat the analysis for better consistency.

Case study

In the experiment, 55 physically active participants with an underband size of 85 cm and C + bra cup size (mean ± SD: age = 60 ± 5 years; range = 51—69 years; height = 156 ± 20 cm; weight = 61.9 ± 7.35 kg) were selected. The participants were professionally fitted with sports bras based on the Metric Bra Sizing System (Zheng, 2006). Participants were selected based on several criteria, including being postmenopausal, having a history of breastfeeding but without surgery. Before the experiment, participants were informed about the study and provided their consent by signing a consent form. This study was approved by the Hong Kong Polytechnic University Research Ethics Committee (Approval No. HSEARS20200205001). The participants volunteered for this study and provided informed consent prior to data collection.

Data collection

The self-answered questionnaire and the observation list were prepared and thoroughly explained to the participants and a research assistant. The experiment took place in a controlled laboratory environment with a temperature set at 24 ± 0.5 °C and humidity at 65 ± 3%. The participants were instructed to perform six different poses, beginning with standing still, followed by the postures in the following order: half-moon pose, high lunge, warrior II, and extended side angle pose, as depicted in Fig. 2. While the participants were performing these poses, a well-trained research assistant was responsible for conducting observations. After completing the poses, participants were asked to fill out the hierarchical structured questionnaire.

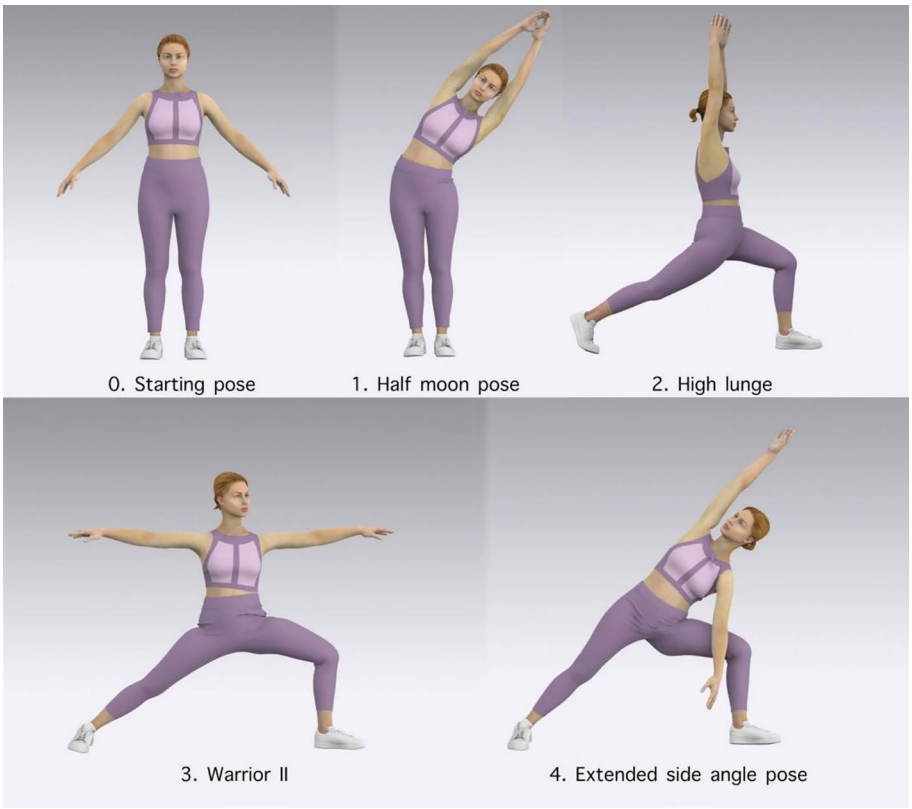


Fig. 2 Four Yoga poses performed by the participants

Table 5 The refined sport bras evaluation framework

Criteria No	Self-evaluation	The third-party observation
1	Shaping effect	The ability to keep in place
2	Underband tightness	Shaping effect
3	Fitting	Cup appearance
4	Overall support	Uplift effect
5	Strap tightness	Cup fitting
6	The ability to keep in place	Underband stability
7	Tactile sensation	Coverage
8	Back support	Back support

Results and Discussion

Results of the Delphi study and the refined framework

In this study, the aggregation of criteria judgments will be used to assess the extent of agreement (Delbecq et al., 1974). It was reported that, after two rounds, the mean standard deviation of the responses was less than 1, and the minimum number of iterations for a Delphi study is two (Vidal et al., 2011). Therefore, two rounds of the Delphi study were conducted. The first iteration was designed to utilize Likert scale ratings for the provided criteria by each expert, enabling a comparison of differences among the experts' opinions. The second iteration sought to refine and characterize the key criteria

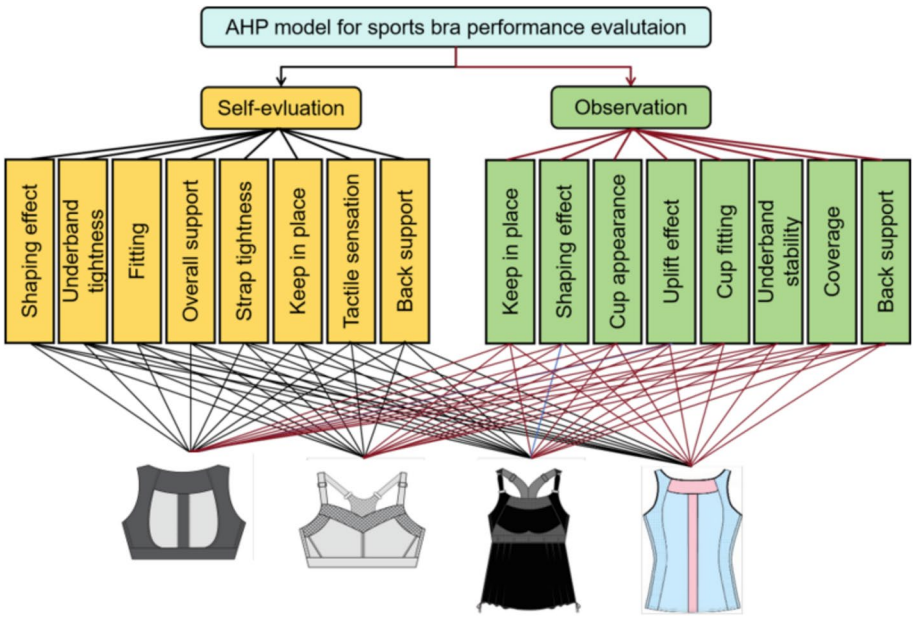


Fig. 3 A combined evaluation system of the sports bra evaluation

based on the insights gained from the first iteration. The top 8 criteria for self-evaluation and the third-party observation with the score larger than 2.5 were kept in the refined sport bras evaluation framework, as shown in the Table 5.

While preferences for women's bras or sports bras were well-documented in previous literature (Zhou et al., 2022), it remains uncertain whether these preferences can be influenced by anatomical and psychological changes because of aging process. Through the Delphi study process, general evaluation criteria from the literature can be refined into both eight criteria for self-evaluation and eight for third-party evaluation, respectively, by a group of experts. The reason for dividing the criteria into two parts is that third-party observations can provide relatively objective comments and offer insights into sports bra performance that is difficult for participants to do self-assessment. And it is not easy to balance the functional factors in support, and aesthetic factors, such as appearance, shaping effect, underband stability, and underband tightness, often pose a dilemma. People frequently attempt to determine whether function is more important than support or whether comfort is more critical than stability. Hence, the criteria were evaluated using the following AHP to determine the importance ranking among the criteria.

Constructing the hierarchical structure and establishing the evaluation matrix

With the refined framework for sports bra evaluation criteria, a hierarchical structure is constructed and illustrated in Fig. 3. The ultimate objective is to assess sports bra performance for senior females. Eight criteria, corresponding to both subjective self-evaluation and objective third-party observation, have been identified.

Using the hierarchical structure, the relative evaluations based on pairwise comparisons conducted by the senior female participants and the research assistant to assess sports bra performance were collected and processed, as shown in Table 6 and Table 7.

Table 6 Relative evaluation for self-evaluation

Self-evaluation criteria No	1	2	3	4	5	6	7	8
1	1	3	2	1/4	3	4	2	2
2	1/3	1	1/4	1/6	2	1/2	1/4	1/5
3	1/2	4	1	1/5	3	2	1/3	1/3
4	4	6	5	1	7	3	3	4
5	1/3	1/2	1/3	1/7	1	1/2	1/3	1/3
6	1/4	2	1/2	1/3	2	1	1/3	1/2
7	1/2	4	3	1/3	3	3	1	2
8	1/2	6	3	1/4	3	2	1/2	1

Table 7 Relative evaluation for the third-party observation

The third-party observation criteria No	1	2	3	4	5	6	7	8
1	1	1/5	1/4	1/3	1/6	1/6	3	1/3
2	5	1	1/4	2	1/3	1/3	5	3
3	4	4	1	3	1/2	1/4	4	2
4	3	1/2	1/3	1	1/3	1/4	3	2
5	6	3	2	3	1	1/3	3	5
6	6	3	4	4	3	1	4	3
7	1/3	1/5	1/4	1/3	1/3	1/4	1	1/3
8	3	1/3	1/2	1/2	1/5	1/3	3	1

Table 8 The mean random consistency index

Rank	1	2	3	4	5	6	7	8
R.I	0	0	0.58	0.9	1.12	1.24	1.32	1.41
Rank	9	10	11	12	13	14	15	
R.I	1.45	1.49	1.52	1.54	1.56	1.58	1.59	

This relative evaluation enables the quantitative analysis after numerical processing and comparison. By implementing the AHP analysis, sports bra performance can be ranked in order from largest weighting to the lowest one based on the evaluation determinants.

The consistency test

The results of the consistency indicators have been calculated. The Consistency Index (CI) for the self-evaluation judgment matrix is 0.09, and the CI for the third-party observation judgment matrix is 0.135. Since there are 8 criteria, the matrix size is 8×8. The Random Index (RI) is 1.41, as shown in Table 8 (Rao Tummala & Ling, 1998). Referring to Function 6, the Consistency Ratio (CR) for the self-evaluation judgment matrix is 0.06, which is less than 0.1. The RC value for the third-party observation judgment matrix is 0.09, also less than 0.1. All these indices fall within the acceptable range. When CR is less than 0.1, the results can be considered reliable.

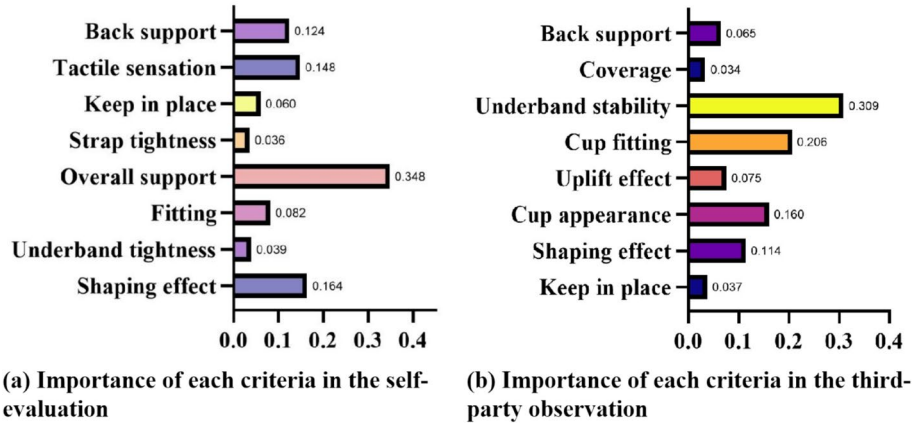


Fig. 4 The importance of each criteria in the (**a**) self-evaluation and (**b**) the third-party observation of the sports bra for senior females

AHP analysis for the weight of evaluation criteria

The weight of the criteria in the questionnaire is presented in Fig. 4 (a). The weights were ranked as follows: 0.348 for overall support, 0.164 for shaping effect, 0.148 for tactile sensation, 0.124 for back support, 0.082 for fitting, 0.060 for the ability to stay in place, 0.039 for underband tightness, and 0.036 for strap tightness. Specifically, the weight of overall support (0.348) is nearly twice that of shaping effect (0.164), tactile sensation (0.148), and back support (0.124). The underband tightness (0.039) and strap tightness (0.036) are relatively less significant. Regarding overall support, it is crucial for senior females to feel overall supported when wearing a sports bra. As women age, the anatomical support for their breasts weakens, increasing the need for external support from a sports bra. Additionally, the shaping effect is ranked the second place. Many senior females experience breast sagging and changes in body shape, which can impair the confidence. Thus, increasing the demand for the shaping effects is found. Tactile sensation also plays a significant role in evaluating sports bra performance. It is often influenced by factors such as the materials used, cutting and sewing, and stitching. For instance, materials like mesh or lace are commonly used for the places in the neckline, armpits, or wings to enhance breathability and moisture-wicking. However, according to the AHP analysis, mesh and lace can have a detrimental effect on tactile sensation, suggesting that they should be avoided in the course of sports bra design. Back support and fitting are closely related to the pattern design. Senior females require sports bras that offer good back support and fitting. It's also worth noting that strap tightness and underband tightness have the lowest importance, which contradicts previous studies suggesting that tightness is the most frequently complained about attribute in sports bra design (Bowles et al., 2012). This difference may arise from variations in exercise intensity between senior women and younger individuals, as seniors often engage in low-to-moderate-intensity activities. Therefore, the tightness is not a very critical factor for the senior women.

The weight of the criteria in the third-party observation is illustrated in Fig. 4 (b). The weights were ranked as follows: 0.309 for appearance, 0.206 for cup fitting, 0.160 for cup appearance, 0.114 for shaping effect, 0.075 for uplift effect, 0.065 for the back support, and 0.034 for coverage. It's noteworthy that the weight of appearance (0.309) and cup

Table 9 The weights of all criteria evaluated through observation for the four sports bra alternatives

Criteria for self-evaluation	Weight			
	B1	B2	B3	B4
Shaping effect	0.579	0.471	0.294	**0.631**
Underband tightness	0.395	0.361	0.279	**0.644**
Fitting	0.367	0.335	0.315	**0.500**
Overall support	**0.588**	0.479	0.203	0.539
Strap tightness	0.377	0.236	0.390	**0.504**
Keep in place	**0.645**	0.331	0.334	0.409
Good tactile sensation	**0.613**	0.517	0.598	0.417
Back support	**0.596**	0.375	0.197	0.559
Total weight	**0.561**	0.437	0.302	0.530

fitting (0.206) collectively accounted for approximately 50% of the major criteria, surpassing the significance of other criteria. On the other hand, these results imply that the self-assessment by the participants themselves, as indicated in the self-answered results, may differ from the observations made by a third-party. In third-party observation, judgments are considered more objective, and certain performance aspects that participants may not detect can be readily observed by the observer. In particular, users frequently criticize the underband for being overly tight, which restricts chest movement and can even affect breathing. However, for senior females, underband stability holds high importance. Given that their exercise often involves significant stretching and extension, the underband is susceptible to riding up with skin movement during workouts. The second and third most important criteria are cup fitting and cup appearance. The unique sagging breast morphology of senior females results in gaps at the top of the bra cup, as they don't uniformly fill the cup in a round shape. Consequently, there is a greater need for sports bras that offer extra fit and support. Regarding the shaping effect, its importance is consistent on the results of observation (0.164) and self-evaluation (0.114).

AHP analysis for the weight of sports bra alternatives

Table 9 presents the results of the analysis of weights in the factor layer for subjective self-evaluations, including the four sports bra alternatives. A higher weight value indicates better performance according to the criteria. The bolded values represent the weights of the sports bras alternatives corresponding to the evaluation criteria that are greater than 0.5. To begin, when examining the results for the sports bra alternatives in terms of their shaping effect, the two highest weight rankings were 0.631 for sports bra number 4 (B4) and 0.579 for B1. It's also noticeable that the weight of B4 significantly exceeds the other three sports bra alternatives, B1, B2, and B3, in terms of underband tightness (B4: 0.644), fitting (B4: 0.500), and strap tightness (B4: 0.504). B1 demonstrates its higher importance compared to the other alternatives regarding overall support (B1: 0.588), the ability to stay in place (B1: 0.645), good tactile sensation (B1: 0.613), and back support (B1: 0.561).

Table 10 displays the results of the analysis of weights in the factor layer for objective third-party observations of the four sports bra alternatives. When evaluating the weight

Table 10 The weights of all criteria evaluated through observation for the four sports bra alternatives

Criteria for the third-party observation	Weight			
	B1	B2	B3	B4
Keep in place	0.580	0.520	**0.649**	0.586
Shaping effect	0.489	**0.558**	0.531	0.383
Cup appearance	0.441	0.347	0.347	**0.568**
Uplift effect	**0.503**	0.353	0.350	0.425
Cut fitting	**0.596**	0.311	0.347	0.480
Underband stability	**0.532**	0.403	0.466	0.508
Coverage	**0.642**	0.430	0.344	0.529
Back support	0.456	0.469	0.289	**0.575**
Total weight	**0.524**	0.399	0.412	0.499

of the sports bras' ability to stay in place, B3 obtained the highest weight (0.649), while B2 (0.520) was the least important in this regard. Regarding shaping effect, B2 (0.558) and B3 (0.531) held relatively higher importance compared to B1 (0.489) and B4 (0.383). B4 received higher weight values for cup appearance (0.568) and back support (0.575), while B1 had greater weight values (0.503, 0.596, 0.532, 0.642) for uplift effect, cup fitting, underband stability, and coverage, respectively.

The weights of subjective self-evaluations for all criteria are displayed in the radar map shown in Fig. 5 (a). The total weight for B1 (Blue line), as assessed by senior female participants across all criteria, was the highest at 0.561, followed by B4 at 0.530 (Green line). B2 (Red line) had a total weight of 0.437, and B3 (Light blue line) had a total weight of 0.302, indicating relatively lower overall importance. Both B1 and B4 are considered the most suitable designs for senior females with overall performance. B1 excels in terms of back support, tactile sensation, staying in place, and overall support, while B4 excels in terms of shaping effect, underband tightness, and fitting. When examining their designs, it becomes evident that B1's double-back layer, precise cutting and sewing, moisture-wicking textiles, and the encapsulation style contribute to its performance. The moisture-wicking fabrics provide sports bra with good heat and sweat transformation, hence have high performance in the evaluation. Such function materials, such as anti-yellowing effects (Yip et al., 2009) and compressional resistance and compressional resilience (Tong et al., 2015) also can be used for outer layer of sports bra for improving outdoor exercise experience. On the other hand, B4's long shirt design covers the out-of-shape body, and its side panel pattern creates a slimming effect, resulting in its excellent shaping performance. The radar map for the third-party observation is presented in Fig. 5 (b). B1 (represented by the blue line) shows a relatively high overall performance weight of 0.524, surpassing B2 (red line) at 0.399, B3 (light blue line) at 0.412, and B4 (green line) at 0.499. This pattern aligns with the self-evaluation results, where B1 shows the best performance, followed by B4. B4 demonstrates a relatively balanced importance across the eight criteria. However, its most notable shortcoming is the underband tightness. These two designs outperform others in terms of coverage, underband stability, cup fitting, and uplift effect. The excellent coverage performance can be attributed to their

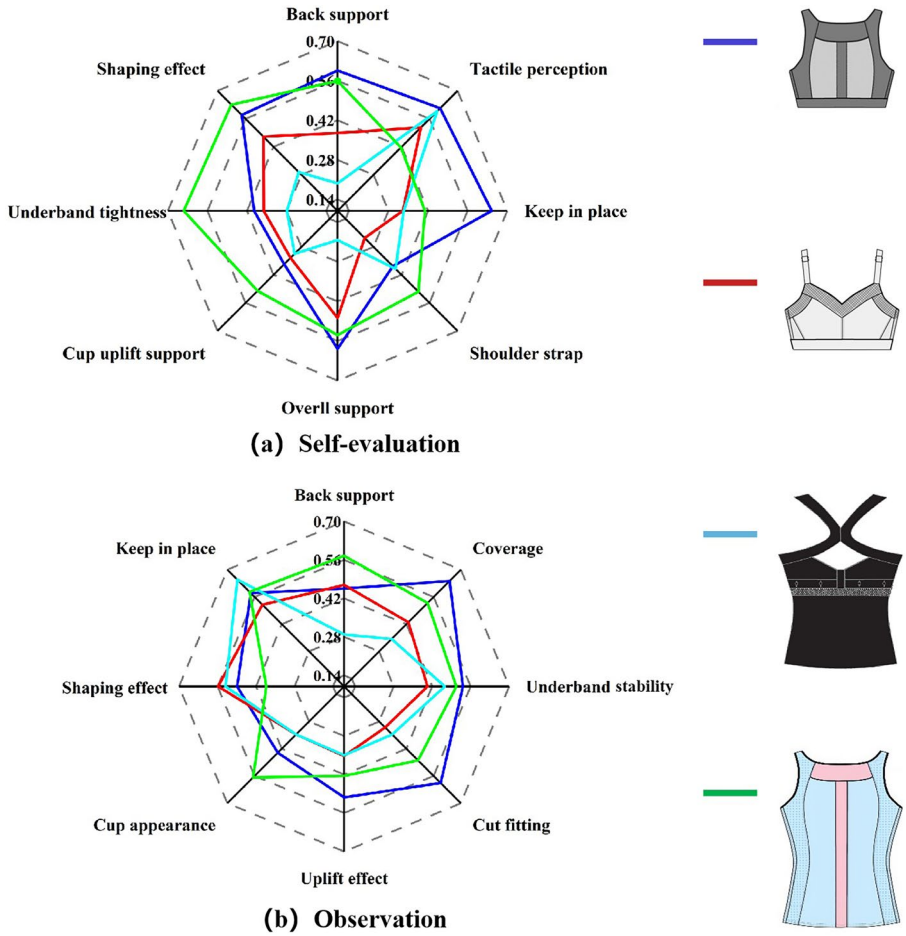


Fig. 5 Radar map of performance by (**a**) self-evaluation and (**b**) the third-party observation

high neckline design, which ensures adequate coverage during physical activities. The remarkable underband stability and back support may be a result of the double-back design. B2's racerback and B3's butterfly back were designed to allow more freedom of movement during stretching exercises, and they also prevent straps from slipping off the shoulders. However, the single-layer back design in these bras may not provide sufficient support, especially for senior females who often have poor posture and hunchback issues. Additionally, the encapsulation style of cup fitting performs better, as it separates each breast individually. By offering effective support and maintaining their shape during vigorous breast movement without excessive compression, this encapsulation style shows an attractive and supportive fit.

Conclusions

The current study focuses on evaluating sports bra performance for senior females by combining subjective evaluations from self-answered questionnaires and objective evaluations from third-party observations. The study is divided into two main parts. In the first part, evaluation criteria are developed through the Delphi study. For self-evaluations, the selected criteria include shaping effect, underband tightness, fitting, overall

support, strap tightness, the ability to stay in place, tactile sensation, and back support. In contrast, the eight criteria chosen for third-party observation are the ability to stay in place, shaping effect, fitting, uplift effect, underband stability, appearance, coverage, and back support. In the second part, the pairwise comparisons of these criteria were determined using the AHP method, allowing for the importance ranking of criteria with regards to each criterion. This process enables the establishment of evaluation criteria that encompass multidimensional aspect from the subjective and objective opinions of professionals and senior female participants. The top three important criteria for self-evaluation were overall support, shaping effect, and tactile sensation, while the top three important criteria for third-party observation were appearance, underband stability, and fitting. In terms of design, the long shirt encapsulation-style sports bra, designed with a high neckline and a double back layer, is found to be more suitable for senior females. This design provides ample support, excellent shaping effect, sufficient back support for maintaining good posture, and freedom of movement during physical activities. These results and conclusions are valuable for designing age-friendly sports bras and developing new markets for intimate industries and retailers, which draw significant implications for economic improvement.

Author contributions
J.Z. and N.L. were responsible for the entire experimental design, structure construction, data processing, and manuscript writing. T.C.H. and X.L. took charge of graph visualization, while R.L. provided comments. J.C. contributed comments and revised the manuscript. K.Y. and J.Y. guided the development of the research background, results, and conclusion, and also revised the manuscript. All authors read and approved the final manuscript.

Funding
This work was supported by the PolyU Project of Strategic Importance (Investigate the mechanisms underlying the efficacy of conservative management, ZE2H) and the project on Medical Textiles and Functional Clothing towards Personalized Therapy and Future Healthcare (1-WZ28).

Availability of data and materials
The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
This study was approved by the Hong Kong Polytechnic University Research Ethics Committee (Approval No. HSEARS20200205001).

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

Received: 11 November 2023 Accepted: 11 February 2025
Published online: 03 March 2025

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