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Designing Pressure-relieving Eyeglass Frame Using Analytic Hierarchy Process, Quality Function Deployment, and Theory of Inventive Problem Solving (TRIZ)

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Individuals with myopia need to wear eyeglasses, which causes pressure and discomfort on the bridge of the nose and behind the ears. Therefore, we designed a pressure-relieving eyeglass frame to provide comfort to users. For the development of the eyeglass, user demand was assessed using the analytic hierarchy process and converted into design requirements through quality function deployment. The theory of inventive problem solving was also applied to solve the problems faced in the design process. In the substance-field analysis, 40 inventive principles were applied. The eyeglass frame developed reduces pressure on the nose bridge and ears, providing comfort during wear. Therefore, user satisfaction with the eyeglass was also significantly enhanced. The design process of the eyeglass frame offers a reference for designing similar products to enhance the quality of life by integrating a rapidly developing technology.

1. Introduction

Sensor technology plays a crucial role in enhancing the functionality and user experience of eyeglasses, particularly in smart eyeglasses and those designed for virtual reality (VR), augmented reality (AR), and mixed reality (MR). The integration of sensors such as ultrasonic sensors, gyroscopes, accelerometers, and cameras increases the weight of the eyeglass, which results in users experiencing discomfort due to the added weight.(1,2) Therefore, it is important to design the eyeglass frame, including nose bridges, nose pads, temples, hinges, and temple tips.(3)

Wearing eyeglasses with such components presses the nose bridge, causing fatigue and soreness, and increasing the discomfort of wearing.(4) In 2020, approximately 30% of the global population had myopia. As the prevalence of myopia is increasing nowadays, such designs of frames are becoming critical.(5,6)

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The frames of eyeglasses are designed to expand the functionality and enhance the aesthetics of eyeglasses. In particular, eyeglasses with an advanced technology, such as smart interactive eyeglasses,(7) smart guide eyeglasses,(8) multi-material personalized eyeglasses,(9) ergonomic eyeglasses,(10) and customized and personalized eyeglasses,(11) require optimized designs of the frameworks for their purposes. The most important design element is to improve wearing comfort by alleviating the pressure of the eyeglass on the nose bridge.

Conventionally, to reduce the weight of the eyeglass, high-refractive-index lenses or thin and light lenses are used. Nose pads made of sponge or similar light materials are also selected for the frame. However, using such lenses and materials increases production costs and consumer prices, and does not guarantee the comfort of users. The eyeglass frame without nose pads is designed but inappropriate for users with relatively flat noses, such as Asians, mainly because eyeglasses without nose pads are prone to falling off.

To develop an eyeglass frame of higher quality for people with myopia and those using smart devices, an innovative design is required. Such a design alleviates the pressure of eyeglasses on the nose at an appropriate price and comfort. In this study, we designed the eyeglass frame to address the existing issues based on the results of the analytic hierarchy process (AHP), quality function deployment (QFD), and the theory of inventive problem solving (Teoriya Resheniya Izobretatelskikh Zadach, TRIZ). The proposed design in this study can be applied to diverse applications, including smart eyeglasses and VR/AR/MR devices, as well as to eyeglasses for myopia.

2. Materials and Methods

AHP is used in decision-making by analyzing and ranking plausible options. It is used to identify the objective demands of users by quantitatively evaluating the weights of different factors, thereby avoiding subjective biases occurring in traditional decision-making processes.(12,13) The QFD method is used to convert user demands into design requirements, avoiding the effect of subjective experience on the evaluation of user demands. The "house of quality" is a key tool for the translation and analysis of user demands to convert the results into design requirements that satisfy real user demands.(14,15) TRIZ is used for solving inventive problems and addressing difficulties in product innovation by analyzing invention principles, engineering parameters, and contradiction matrices.(16,17)

In this study, we utilized the AHP/QFD/TRIZ-combined design methodology to optimize the eyeglass frame, minimizing pressure on the nose and ears to significantly improve wearing comfort. AHP was used to evaluate the weights of related factors and accurately obtain the objective user demands without subjective biases. The QFD method was used to transform user demands into design requirements. TRIZ was used to solve difficulties in producing the designed frames. Applying these theories enabled decision-making on the designs of the frames.(17,18) This integrated method enabled a new design of the pressure-relieving glass frame that satisfies user demands for wearing comfort. The AHP/QFD/TRIZ-combined design methodology is presented in Fig. 1.

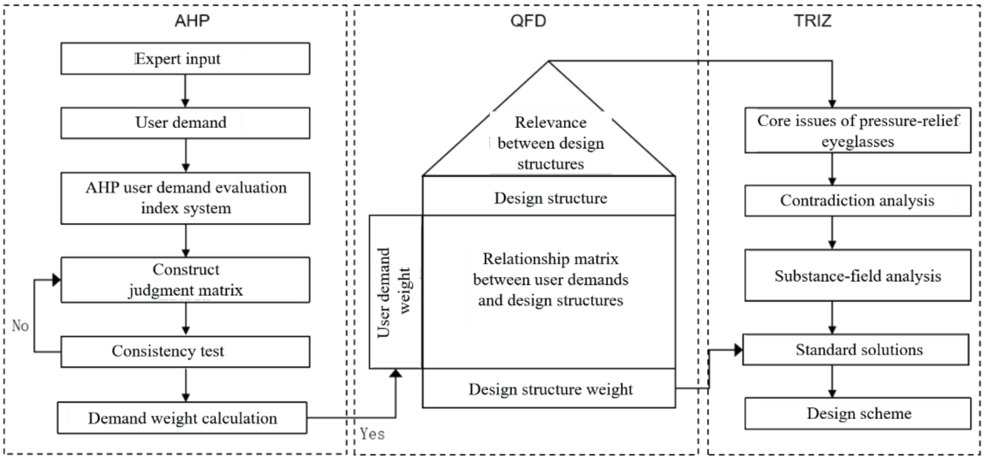


Fig. 1. Design process of pressure-relieving eyeglass frames.

2.1 Design process

The design of the pressure-relieving eyeglass frame was optimized using AHP, QFD, and TRIZ. First, the AHP hierarchical model was structured, and the judgment matrix was established on the basis of the hierarchical structure model. Thirty-six user demands were identified through the user demand analysis and categorized into five demand levels through interviews and questionnaire surveys. The weights of the demands at each level were calculated on the basis of expert's opinions. The user demands were imported into the house of quality model to determine contradicting pairs and were analyzed by using TRIZ to obtain the optimal solution and improve the design of the frame with enhanced comfort and durability.

2.2 User demand analysis

We interviewed 18 participants who wore eyeglasses every day. Fifty-two user demands were identified, of which 36 were finally selected. A questionnaire on a five-point Likert scale was created and distributed.[19] Five hundred eighty-six valid questionnaires were collected, and the data were validated using the Kaiser–Meyer–Olkin (KMO) and Bartlett's sphericity (Table 1). The KMO sampling adequacy was 0.917 and the approximate chi-square was 2388.467. The degree of freedom was 630 and Bartlett's sphericity significance was 0.00. This result indicated that the data were adequate for factor analysis.

The rotated component matrix in factor analysis contained 28 user demands, which were clustered in five demand levels. The first demand level consisted of nine user demands (easy to wear, stable frame, portable design, eyeglass frame fit, replaceable, fashionable appearance, stain resistance, loose and comfortable temple, and fine craftsmanship). The first demand level (A1) was related to the appearance and structure of pressure-relieving frames. The second demand level (A2) consisted of six user demands (anti-static, simple and easy to clean, radiation protection, personalized design, adjustable temples and nose pads, and rust resistance), related to safety and stability. The third demand level (A3) included four user demands (suitable proportion, lightweight and comfortable, durable, and low-sensitivity materials), related to quality and

Table 1
KMO and Bartlett's test results.

KMO sampling adequacy	0.917
Approximate chi-square	2388.467
Degrees of freedom	630
Significance of Bartlett's sphericity	0.000

durability. The fourth demand level (A4) comprised five user demands (multi-functional design, lens adaptability, smooth frame, detachable design, and low price), related to function and price. The fifth user demand level (A5) consisted of four demands (mild pressure distribution, scratch and abrasion resistance, convenient storage, and easy production), related to convenience and practicality (Fig. 2).

A judgment matrix is essential to obtain the weight of user demands. Ten experts with product design experience and five experts engaged in eyewear design were invited as the expert group. They scored the selected user demands using the Saaty nine-point scale. The five demand levels were examined using the QFD house of quality for appearance and structure (A1), safety and stability (A2), quality and durability (A3), function and price (A4), and convenience and practicality (A5). The judgment matrix [A, (1)] for the five demand levels is constructed, where a_{ij} represents the comparison result of the ith factor to the jth factor.

$$A = (a_{ij})_{n*n} = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix} \tag{1}$$

The vector V_i of each row of matrix A was calculated by geometric averaging (square root method). Then, the data was normalized to obtain the average weight (W_i) of each factor and the weight vector W (2, 3).

$$V_i = \sqrt[n]{\prod\nolimits_i^n a_{ij}} \tag{2}$$

$$W_i = \frac{V_i}{\sum_{i=1}^{n} V_i} \tag{3}$$

$$W = \left(W_1,\, W_2,\, \ldots\ldots,\, W_n\right)^T \tag{4}$$

The consistency of the survey results was tested after obtaining the aforementioned data. Consistency index (C_I) = 0 indicates complete consistency, whereas C_I close to 0 denotes satisfactory consistency. The larger the C_I, the higher the inconsistency. The random index (R_I) was calculated using the consistency ratio (C_R) and C_I. C_R less than 0.1 indicates low consistency.

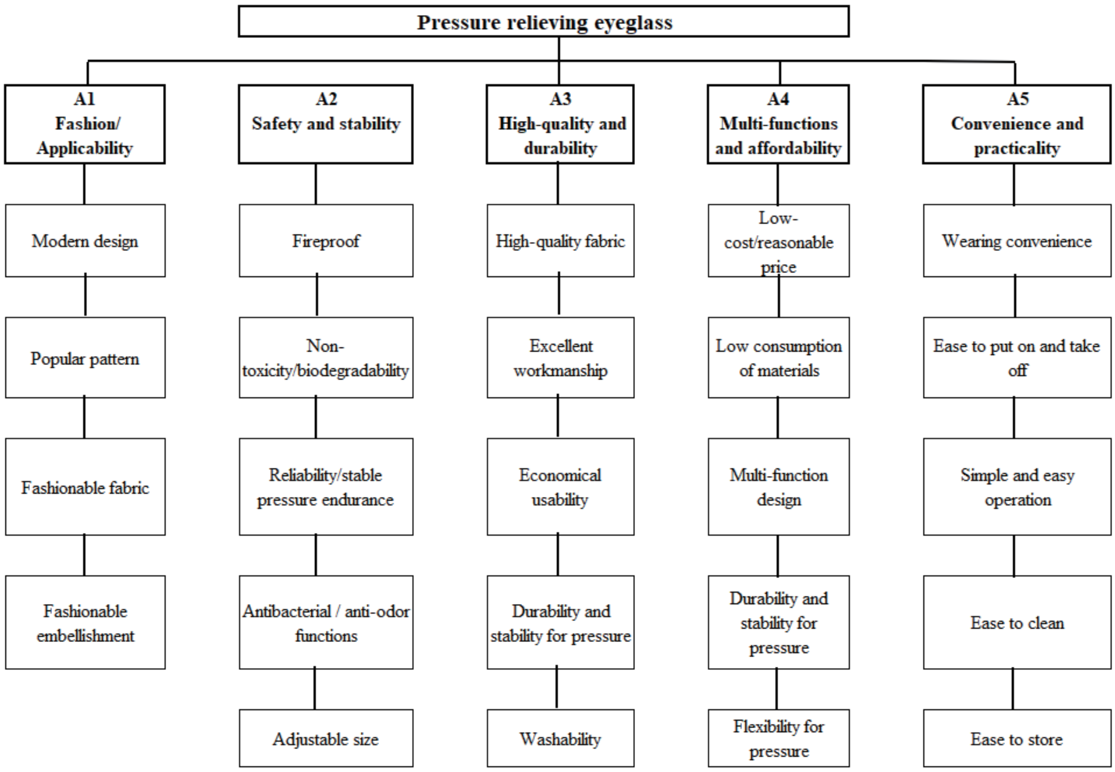


Fig. 2. AHP judgment matrix of pressure-relieving eyeglass frame.

$$\lambda_{max} = \sum_{i=1}^{n} \frac{(AW)_i}{nw_i} \tag{5}$$

$$C_I = \frac{\lambda_{max} - n}{n-1} \tag{6}$$

$$C_R = \frac{C_I}{R_I} \tag{7}$$

Here, the maximum eigenvalue of the characteristic equation is λ_{max}, n is the order of the judgment matrix A, C_R is the calculated consistency ratio, C_I is the test coefficient, and R_I is the average random consistency index.

Table 2 shows the results of the consistency test, eigenvectors, and weights of demand levels. The results indicated the consistency of the calculated weights. A2 and A3 showed the highest proportions. In terms of materials, thermoplastic rubber (TR) and titanium alloy are used in the frame. TR has advantages such as being lightweight and comfortable, durability and safety, a flexible design, and diverse colors. In contrast, titanium alloy has high strength and heat resistance, and excellent corrosion resistance.[20] Both materials are regarded as ideal for the eyeglass frame.

Table 2
Analysis table of weights of five levels of AHP hierarchy of stress-relieving eyeglass.

Item	Eigenvector	Weight	Maximum eigenvalue	C_I
A1	0.648	0.129		
A2	1.689	0.338		
A3	1.125	0.226	5.161	0.040
A4	0.440	0.088		
A5	1.098	0.219		

2.3 QFD quality house model

The QFD model links user demands to product characteristics for design optimization using the quality house. The quality house comprises the following components: the left wall, the roof, the room, and the basement. The user demands and their weights belong to the left wall of the quality house, the structural characteristics to meet user demands to the roof, the correlation between user demands and quality characteristics to the room, and the weights of structural characteristics to the basement of the quality house.[21]

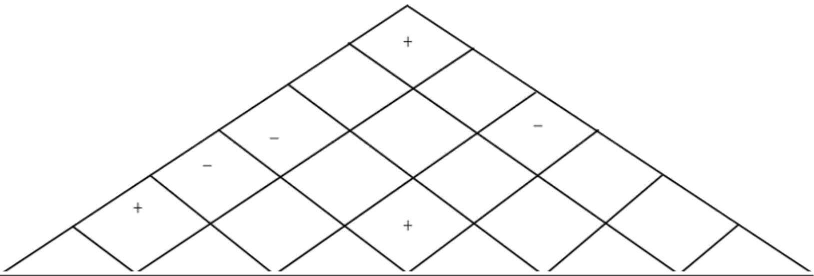
After constructing the AHP judgment matrix A and conducting factor analysis, the weights of user demands were calculated and imported into the left wall of the quality house. The ceiling of the quality house was set as the design structure, which was used to modify the frame structure of traditional glass. To design a stress-relieving eyeglass frame, pressure-relieving nose pads, stress-relieving frames, and stress-relieving temples were selected as main features, while foot covers, hinges, and frame beams were selected as auxiliary features. The design features were assigned to the quality house. Eight experts experienced in product design and eyeglass frame design rated the features as 5 for strong correlation, 3 for medium correlation, 1 for weak correlation, and zero for no correlation. The importance of the design features was expressed as "+" for positive correlation and "–" for negative correlation in the roof relationship matrix (Fig. 3).

3. Results

3.1 Contradiction analysis and solution based on TRIZ theory

Three pairs of positive and negative correlations were obtained on the roof of the quality house. Negative correlations were observed between the nose pad and the temple, the nose pad and the foot cover, and the temple and the frame beam. The nose pad is connected to the frame beam, while the temple is connected to the foot cover and functional blocks. The three pairs of negative correlations were integrated into the feature of nose and temple supports, which was used as the pair of representative negative correlations in TRIZ.

Contradictions were divided into two groups: physical and technical contradictions. The nose and temple supports were the pressure points of the eyeglass frame distributed around the nose bridge and ears, respectively. The nose support was in direct contact with the nose bridge, and the temple support was in direct contact with the ears. Once the pressure on the nose support



Design/structure / User requirement	Weight	Pressure-relieving nose pad	Pressure-relieving frame	Pressure-relieving temple	Foot cover of eyeglasses	Hinge	Eyeglass frame beam
Fashion and applicability	0.129	1	5	5	3		3
Safety and stability	0.337	5	5	5		5	3
High quality and durability	0.225	3	5	5	3	1	3
Multifunctionality and affordability	0.087		3	5		1	
Convenience and practicality	0.219		1	5	1	3	1
Absolute weight of design and structure		248	429	498	128	265	229
Relative weight of design and structure		0.138	0.238	0.277	0.071	0.147	0.127

Fig. 3. QFD quality house model for developing pressure-relieving frame.

decreased, the pressure on the temple support increased, and vice versa. Therefore, the contradiction between the nose and temple supports was technical. The pressure-relieving frame was designed to reduce the pressure of the eyeglass on the nose, but, at the same time, the pressure on the ears must not be increased. The design of the frame must not be too unique to maintain the aesthetics of the eyeglass, leading to no significant changes in the shape of the eyeglass.

Considering the contradictions in the design of the pressure-relieving frame, the user demands were reflected in the frame design to determine appropriate design principles. To address the contradiction between the nose and temple supports, the object-field analysis method in TRIZ was used to analyze the relevant issues and find solutions. In this study, 40 inventive principles and 76 standard parameters of TRIZ were used to solve the problem.(22) The object-field model was constructed using the object-field analysis method. The object-field model consisted of the object of action (S1, functional receptor), the tool (S2, functional executor), and the action field (F) between them. Combined with the contradiction in the study, the basic object-field model of contradiction was constructed as shown in Fig. 4. This model comprised two substances and one energy field; the substances were the S1 nose bridge and S2 eyeglass, and the energy field was the F1 pressure field.

The common pressure-relief method for the nose pad is to add a sponge or soft cover. However, a sponge or soft cover does not reduce pressure on the nose bridge effectively because

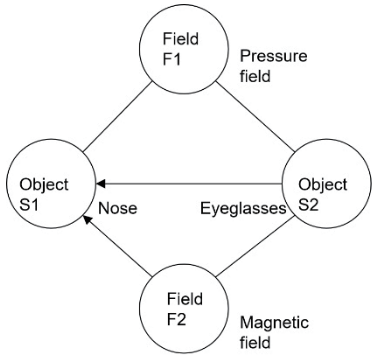


Fig. 4. Basic object-field model of eyeglass frame and nose.

the main pressure originates from the weight of the lenses. Considering the contradiction between the nose pad and the nose bridge, the standard parameter S1.2.4 was identified. With field F2, the harmful effect was counteracted. By adding a repulsive magnetic field in F2 to the connection between the eyeglass frame and the nose bridge, the pressure on the nose bridge was minimized. The lens frame was lifted by the magnetic force, without affecting the vision of the user. The segmentation principle was applied, and the temples were divided into two parts, namely, the front part connected to the lens ring and the rear part. Rotatable components were installed between the front and rear parts so that they could rotate at a certain angle. At the same time, repulsive magnets were added to the front and rear parts of the divided temples. The magnet installed in the rear part had a slightly stronger magnetic force than that in the front part to lift the front part of the temples, and the lens frame did not exert downward pressure on the nose bridge.

3.2 Pressure-relieving frame design

The design is shown in Fig. 5. Considering the intention of the pressure-relieving design, a lighter TR and titanium alloy were selected for the main frame of the eyeglass. The temples were divided into front and rear parts, with a rotatable joint and repulsive magnets at the connection to lift the lenses and reduce pressure on the nose bridge. Sponge and soft silicone covers were added at the contact with the ears to distribute the load and improve comfort. The prototype frame was fabricated by injection molding or 3D printing. The end of the front part of the temple (leg A) was surrounded by a magnet. The top of the rear part (leg B) was extended outward with a magnet. Leg A was connected to the frame, nose pad, and other components to lift these components simultaneously, thereby reducing the downward pressure from the frame and lenses and the friction and extrusion of the nose pad, providing stability. While the downward pressure was minimized, the pressure on leg B must be reduced; otherwise, the pressure on the ears increased and caused the temples to move forward. Therefore, we designed leg B on the basis of the flexible shell or membrane principle of TRIZ. By dispersing the load, we adjusted the surface hardness using a buffering device.

In the frame, we added a soft sponge and soft-grade silicone temple cover with an anti-slip design to the junction of leg B and the outer ear. The contact area between the temple and the

Fig. 5. (Color online) Temple magnet of pressure-relieving frame.

outer ear was increased to increase the friction. At the same time, the soft-grade material was employed to reduce pressure and increase wearing comfort (Fig. 6). The design of the whole frame is shown in Fig. 7.

4. Discussion

In this study, we designed a pressure-relieving eyeglass frame based on the theories of AHP/QFD/TRIZ. The designed frame reduced the pressure on the nose bridge and ears and improved wearing comfort. In designing the frame, user demands and resolving contradictions were considered.

AHP was used to accurately identify the user demands to avoid the effect of subjective biases of users. The user demands were effectively transformed into design requirements through the QFD model to meet the actual demands. TRIZ was applied to product innovation. The contradictions in the design of the frame were successfully resolved by substance-field analysis and inventive principles. We clarified the relationship between the user demand levels and the design structure by constructing the AHP judgment matrix and the QFD house of quality model. It was found that safety and stability, quality, and durability were important. Therefore, we established a method based on the substance-field analysis result of TRIZ to minimize the pressure on the nose bridge. We added a repulsive magnetic field at the junction of the frame and the nose bridge, and divided the temples to prevent the lens from pressing downward.

The design proposed in previous studies lacked evaluation by users. Therefore, we invited experts to evaluate the design and analyze the feasibility, scientificity, and rationality for further improvement. A chart was created on the basis of the average score of the experts in 11 evaluation criteria (pressure-relieving effect, stability and safety, material selection, ergonomic design, appearance design, functional practicality, manufacturing process, adaptability, innovation, cost-effectiveness, and sustainability) on a 10-point scale, as shown in Fig. 8.

Despite the results, we identified limitations in this study. First, we did not explore the optimal ratio for dividing the temples into two parts nor the impact of the magnetic force on the pressure-relieving eyeglass frame. These factors are important to maintain the stability and comfort of the eyeglass. Second, healthy young people tested the designed frame, which, to some extent, restricted the general use of the frame. In the design of the frame, diverse groups of

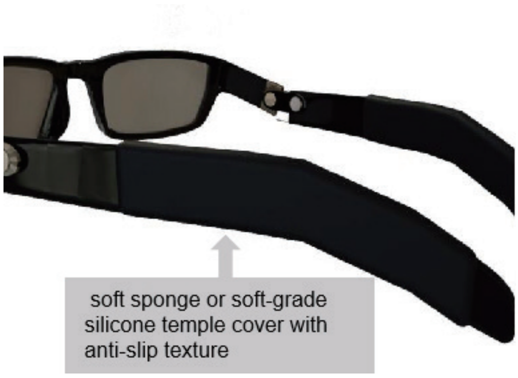


Fig. 6. (Color online) Temple cover.

Fig. 7. (Color online) Newly designed eyeglass frame.

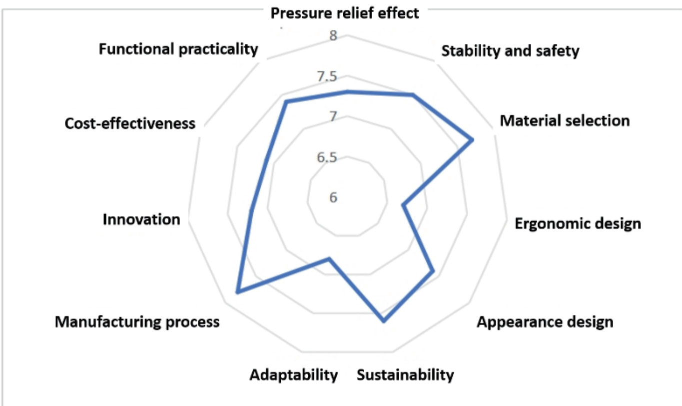


Fig. 8. (Color online) Evaluation chart of expert group.

people with different ages, genders, and physical conditions need to be considered, as they can have different demands and wearing experiences. Therefore, future research is required to evaluate the newly designed frame and refine its design to enhance pressure-relieving capabilities. At the same time, how to educate users needs to be considered, as the comfort of wearing depends on the user's understanding.[22] Additional factors need to be incorporated into the design and its analysis to enhance user demands and the design quality.

Along with this, it is necessary to explore how to integrate new components, such as magnets and sensors, to reduce pressure on the nose and ears in eyeglass frame design. While magnets or other devices enhance functionality (e.g., modularity, adjustability, or foldability), they increase the weight of the frame and might lead to discomfort, especially on pressure-sensitive areas, including the nose bridge and ears, if appropriately distributed. Therefore, ultralight materials, such as TR90, titanium, or carbon fiber composites, need to be used to include new components without compromising comfort. Then, designs must be improved by using hollow structures and integrating hinges to offset the weight of the added mechanisms. Advanced CAD modeling and wear testing are required to simulate the balance between added components and comfort. Through such thoughtful engineering, frames that are light and well balanced can be developed.

Designing the eyeglass frame involves multiple aspects, including user demands, aesthetics, and the psychology of users. Therefore, interdisciplinary research is necessary to integrate diverse knowledge and technology from engineering, marketing, science, and psychology. The frame design developed in this study can be continuously refined as the technology progresses and as people's expectations for an improved quality of life rise.

5. Conclusions

By integrating AHP, QFD, and TRIZ, we examined the issue of the eyeglass frame that applies pressure to the nose bridge and ears. On the basis of the results, we designed the frame considering theoretical principles, technical contradictions, wearing comfort, and the limitations of traditional eyeglass design. The demands of users and wearing comfort were analyzed, and applicable technological innovation was explored in the design. The design successfully balanced technological innovation with user experience. Despite several limitations, the proposed design provides a reference for the academic and industrial applications of the eyeglass frame, as well as the methodology used. The design elements of the frame can also be used to design and develop sensors for the smart devices of VR, AR, and MR, since the frame has been designed to minimize pressure and enhance wearing comfort.

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