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Article

Three-Dimensional Printed Auxetic Insole Orthotics for Flat Foot Patients with Quality Function Development/Theory of Inventive Problem Solving/Analytical Hierarchy Process Methods

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Abstract: Foot disorders affect approximately 10% of adults, with plantar heel pain significantly impacting foot-related quality of life and altering walking patterns. Flat feet, characterized by a lack of longitudinal arches, can lead to fatigue during walking. This study aims to develop 3D-printed shoe insoles tailored to the needs of patients. The design process incorporates Quality Function Deployment (QFD), Theory of Inventive Problem Solving (TRIZ), and Analytic Hierarchy Process (AHP) methods to create insoles that alleviate concentrated loads while meeting patient requirements. The AHP analysis indicated that patients prioritize insoles that effectively manage pressure distribution to achieve optimal functionality. QFD and TRIZ facilitated the identification of four product alternatives and production specifications. The analysis indicated that 3D-printed insoles made from TPU filament with 20% auxetic infill best align with patient preferences. This auxetic TPU option emerged as the top choice, achieving a priority value of 0.2506 due to its superior functionality and comfort. Load distribution measurements confirmed that TPU with auxetic infill resulted in the lowest load distribution, with a standard deviation of 0.1434 and a 25.4% reduction in maximum load compared to conditions without the insole.

Keywords: insole; QFD; TRIZ; AHP; auxetic; 3D print

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1. Introduction

The foot is a crucial organ for walking and serves as one of the most important sensory organs in the human body. Improper use of the feet can lead to irreversible shape changes, affecting plantar pressure at various levels [1]. The arch of the foot plays a vital role in absorbing impact pressure and is responsible for the functional stabilization of the body during static and dynamic activities such as standing and walking [2]. The longitudinal arch is a key component in the biomechanics of the foot, helping to maintain stability while standing, facilitating weight distribution over a broader area, enhancing speed and agility during movement, and providing both stability and flexibility. The longitudinal arch is formed by the tarsal and metatarsal bones, ligaments, and tendons. Based on the structure of the longitudinal arch, human foot shapes are categorized into three types: normal feet, flat feet, and cavus feet [3].

Foot disease is a common problem that accounts for approximately 1 million patient visits per year, with approximately 60% of these to primary care physicians. This disease is the most common cause of heel pain in adults, with a lifetime incidence of approximately 10% and an increasing incidence in women aged 40 to 60 years. Plantar heel disease is associated with various types of sports but is mostly reported in recreational activities and professional runners (incidence 5% to 10%) [4]. The presence of plantar heel pain affects foot-related quality of life and changes the way people walk. Therefore, to effectively treat plantar heel pain, treatment must be optimized to reduce its burden [5]. Diseases of the soles of the feet can occur due to several factors, such as genes, accidents, and other diseases that cause changes in foot morphology. Examples of foot diseases are Pes Planus or flat foot [6].

Flat feet (Pes Planus) are known to be associated with a high incidence of lower extremity injuries in the population. The occurrence of flat feet can be caused by multifactorial causes. This disease can appear at birth (congenital Pes Planus) or develop later in life (acquired Pes Planus). Flat feet are an anatomical change that can occur in one foot (unilateral Pes Planus) or in both feet (bilateral Pes Planus) [7].

Foot orthoses are used to treat foot pathologies such as plantar fasciopathies. Foot orthoses are still frequently used to support the arch of the foot in individuals with flat feet and alter lower extremity biomechanics during walking, running, and jumping. Therefore, foot orthoses are still used by doctors to treat painful musculoskeletal leg injuries. Compared with traditionally manufactured foot orthoses, 3D-printed foot orthoses decrease plantar pressure under the heel and reduce the sagittal range of motion, dorsiflexion when the heel moves, and maximum eversion of the ankle when walking.

Three-dimensional printing, also referred to as additive manufacturing, is accomplished through layer-by-layer stacking techniques. According to the designed 3D model, complex and diverse physical entities can be produced [8]. Recently, biomedical applications have evolved significantly due to the dedication of scientists, medical practitioners, engineers, and researchers worldwide. With ongoing advancements in technology, researchers are striving to reduce the costs of 3D-printed components and simplify the fabrication process. Examples of 3D printing applications include the production of bones, spinal implants, prosthetics, skin, and organs [9]. Surgeons can develop patient-specific anatomical models for preoperative planning, which enhances surgical precision. Bioprinting has paved the way for the creation of functional tissues and organs, helping to address the shortage of organ transplants. The dental field has also benefited from 3D printing, enabling the production of precise dental crowns, braces, and aligners [8]. Three-dimensional printed foot orthoses were also as effective as traditionally manufactured foot orthoses in supporting arches, demonstrated by similar reductions in arch height. However, other studies reported no differences in peak hindlimb eversion angles and velocities or loading rates during running between 3D-printed and traditionally manufactured foot orthoses [10].

To obtain information effectively and accurately, various plantar pressure measurement systems have been implemented. In general, these systems can be classified into two types, platform systems and shoe insole systems, each of which has advantages in long-term use and mobility. However, shoe insole systems receive more attention than platform systems today due to their wide range of uses. The system maintains its function under repeated and sometimes severe deformations resulting from daily activities but does not cause discomfort when worn [11]. The concept of custom-designed orthotic insoles has gained popularity due to the importance of comfort and preventing injury.

Kuang-Wei Lin conducted research on 3D-printed foot orthoses, which caused a decrease in ankle evertor moment by changing the path of the center of pressure inward [12]. Malia Ho conducted research to determine the biomedical effects, comparing 3D printed insoles and traditional insoles. The results of the study indicated that, with the use of foot orthoses, there is less activation of the plantar flexor muscles. Foot orthoses using 3D printing are more effective in reducing the decrease in foot angle height compared to traditional orthoses [10]. Ramirez also conducted research related to the use of the four TRIZ principles—namely, segmentation, inversion, preservation of new dimensions, and porous materials—as a basis for making foot orthoses with the results that 4 people were uncomfortable, 12 people were less comfortable, 21 people were comfortable, and 8 people were very comfortable with the resulting orthosis soles [13].

The aim of this research is to develop insoles using 3D printing that suit the patient's needs and desires. For this reason, this research uses the QFD, TRIZ, and AHP methods in the process of designing shoe insoles that can reduce the concentrated load on the patient's feet and are in accordance with the patient's needs and desires. QFD is a systematic system used by industry to link consumer needs with product design specifications to be made using House of Quality as the main tool for mapping and analyzing product design requirements and targets. The use of QFD in the product development process can increase the efficiency of time, costs, and techniques required [14].

In selecting the technical methods to be used, this research uses TRIZ. The "Theory of Inventive Problem Solving", also known as TRIZ, was developed by Russian scientist Genrich Altshuller in the 1940s [15]. Spreafico and Russo conducted a critical study of more than 200 case studies from journals on the use of TRIZ in industry. They concluded that TRIZ is one of the most effective and accepted methods for implementing system innovation [16]. TRIZ includes analytical tools for problem solving as well as data-driven tools for system transformation and their theoretical foundations. The TRIZ analysis tool can be used to transform, model, and analyze a problem using all the information about the product problem. The main goal of the TRIZ method is to find the ideal or perfect solution [17].

After finding the required criteria using QFD and alternative methods that will be used using TRIZ, this research uses AHP to determine the priority importance of each criterion in QFD and select alternatives that will be used in the shoe sole design process using 3D printing. AHP is a hierarchical weighted decision analysis method that applies network systems theory and multi-objective comprehensive evaluation methods and combines qualitative and quantitative methods to solve multi-objective complex problems [18]. After identifying the criteria to follow, the alternatives are selected in the process of making shoe soles using 3D printing. Therefore, the next stage is the product manufacturing process. With the combination of the three methods above, it is hoped that the shoe sole products made will be in accordance with consumer needs and can increase the efficiency of the development process.

2. Materials and Methods

2.1. Subject

In this study, we examined 5 patients with flat feet, detailed as follows in Table 1.

Table 1. Research subjects.

Subject	Gender	Age	Weight (Kg)	Shoe Size (UK)
Patient 1	Male	26	70	43
Patient 2	Female	31	60	41
Patient 3	Male	31	85	43
Patient 4	Male	16	60	44
Patient 5	Female	21	45	39

2.2. Methods

The methods used in this study can be seen in Figure 1.

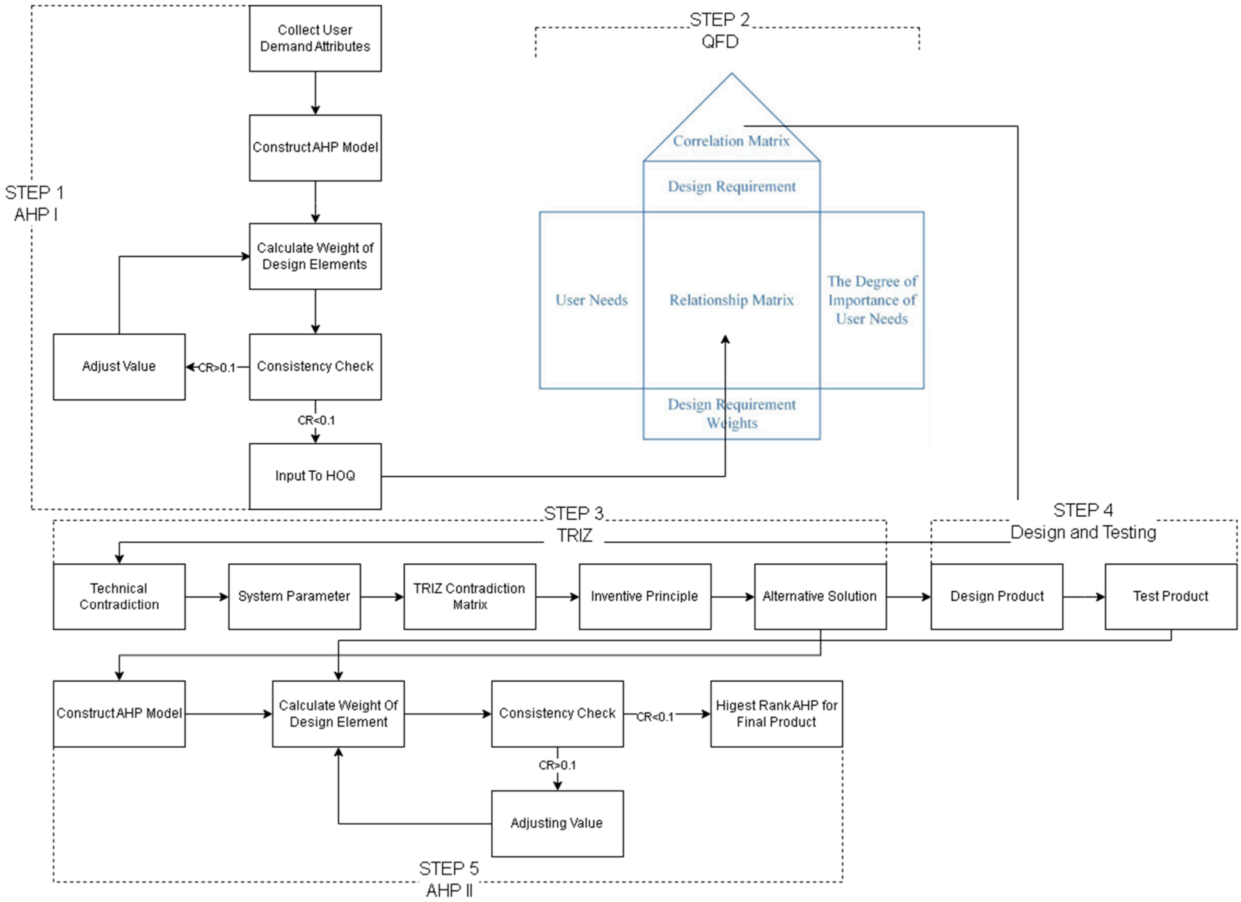


Figure 1. Research flowchart.

2.2.1. AHP I

This stage aims to determine the ranking of the importance of customer needs to be included in the House of Quality under the user needs and relationship matrix. The AHP stages are as follows:

1. Create pairwise comparisons using a scale of 1–9;
2. Establish the comparison matrix;
3. Determine the weight of each element and calculate the eigenvector;
4. Calculate the consistency ratio; if CR > 0.1, the weight values for each pairwise comparison will be recalculated;
5. Rank the consumer needs to be included in the QFD relationship matrix.

Interviews were conducted with consumers to obtain the criteria for consumer needs based on the research conducted by Suchada Rianmora, in her research titled "*Product Characteristics versus Customer Perceptions on a Health-Related Product*", which identifies six criteria for consumer needs in the development of insoles for individuals with flat feet [19]:

1. Instant pain relief;
2. Odorless;
3. Lightweight;
4. Easy to clean;
5. Durable;

6. Made from various materials.

2.2.2. QFD

This stage aims to determine the correlation between customer needs and the existing technical designs, as well as to identify the correlation matrix among each technical design, which will be resolved using TRIZ. In the study titled "*Product Characteristics versus Customer Perceptions on a Health-Related Product*", Suchada Rianmora identified five technical designs to produce insoles for individuals with flat feet, which are as follows [19]:

1. Weight
2. Dimension;
3. Material used;
4. Mean lifetime;
5. Shape.

These five technical design criteria served as a reference in this research. The QFD stages are as follows:

1. Enter customer desires into the user needs table;
2. Enter the available technical designs into the design requirement table;
3. Determine the correlation matrix among each technical design;
4. Establish the relationship matrix between customer needs and design requirements. For the customer needs values, use the results from AHP I;
5. Calculate the ranking of the design requirements.

2.2.3. TRIZ

This stage aims to resolve contradictions among technical designs by utilizing the 40 inventive principles obtained from the TRIZ contradiction matrix. The TRIZ stages are as follows:

1. Identify the contradictory technical designs from the QFD results;
2. Select the system parameters for each technical contradiction;
3. Use the TRIZ contradiction matrix to determine the inventive principles that will be applied to resolve the technical contradictions;
4. Create alternative specifications/decisions based on the inventive principles obtained from the contradiction matrix.

2.2.4. Design and Testing

This stage aims to facilitate the product development process in accordance with the alternative specifications proposed by QFD and TRIZ. The resulting product will undergo testing with consumers to determine the weight of design elements that will be used in AHP II as the basis for selecting the final product.

Steps in the design phase:

1. The subject's foot was scanned in three dimensions using a 3D scanner (EinScan Scanner). To prevent the subsidence of the elevated navicular bone during contact with the ground, the scanning was conducted in a non-weight-bearing state, with the subject seated on a chair and the foot suspended in the air. In this non-weight-bearing condition, the inner arch of the foot did not collapse, allowing the height of the arch to be maintained, which further enhanced its shock-absorbing capability [20];
2. A 3D model of the insole was created using the Gensole website and the product was finalized using Blender software (version 4.2);
3. The product was sliced using the Bambu Lab slicer (version 1.9.7.52);
4. The product was 3D printed using the Bambu Lab X1C 3D printer.

The steps in the testing stage occurred as follows:

1. Product testing was conducted with consumers to gather feedback on the insole's performance and comfort;
2. The pressure distribution on the consumer's foot was checked using the **RPPS-2500 array sensor pressure distribution system**. RPPS-2500 has a 370 × 385 sensor size, with 350 mm × 350 mm sensor sensing area size, actuation force 0.1~5 kg, single sensing point 10 mm rubber. The process of checking the distribution of the foot arch using the RPPS-2500 can be seen in Figure 2. The results from the testing phase were used as the basis for the next steps.

Figure 2. Testing the distribution of load using the RPPS 2500 array sensor distribution system.

2.2.5. AHP II

This stage aims to make the final selection from several alternatives proposed by QFD and TRIZ, where the weights of the elements are derived from direct surveys conducted with consumers who have used all the offered alternatives. The outcome of this AHP process is the final product, which represents the highest value of the priority vector.

3. Results

3.1. STEP 1. AHP I

Suchada Rianmora, in the research titled "*Product Characteristics versus Customer Perceptions on a Health-Related Product*", identified six consumer needs criteria for the production of insoles for individuals with flat feet, which are as follows [19]:

1. Instant pain relief;
2. Odor-free;
3. Lightweight;
4. Easy to clean;
5. Durable;
6. Made from various types of materials.

This development is based on interviews conducted with five individuals suffering from flat feet, which yielded additional criteria to ensure a more comprehensive insole design that meets consumer needs:

1. Good durability;
2. Lightweight;
3. Short production time;
4. Reasonable price;
5. Comfortable to use;
6. Easy to clean;
7. Performs well.

A hierarchical AHP model is created based on these seven primary consumer needs, as illustrated in Figure 3.

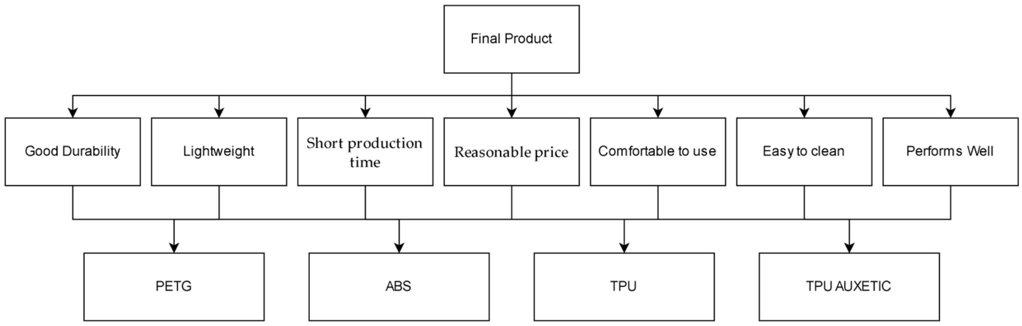


Figure 3. AHP Hierarchy I: comparison between criteria.

From the AHP Hierarchy I: for the comparison between criteria, pairwise comparisons are conducted for each criterion needed by consumers, as shown in Appendix A. The results from these pairwise comparisons will be divided by the total in each column to obtain the AHP normalization matrix. The results from each row in the normalization matrix are presented in Tables A1–A5 at Appendix A. The normalization matrix will then be divided by the total number of criteria to obtain the priority values for each criterion. To determine the eigenvector values, the priority results for each criterion will be divided by the total of the columns in the pairwise comparison matrix.

The AHP was conducted on the five consumers, and the results of the consistency ratios (CRs) are presented in Table 2.

Table 2. The consistency ratio (CR) for each consumer.

Consumer	Consistency Ratio
1	0.091
2	0.076
3	0.095
4	0.070
5	0.053

Based on the consistency ratio results for each consumer, it was found that CR < 0.1, indicating that the AHP results for each consumer are consistent. Once the AHP for each consumer was confirmed to be consistent, the values of each cell in the AHP for each consumer were combined into a consolidated AHP using the geometric mean formula in Excel, as shown in Table 3.

Table 3. Comparison of criteria among the combined five consumers with Geomean.

Criteria	Durability	Lightweight	Production Time	Price	Comfort	Easy to Clean
Durability	1.000	3.178	7.560	5.619	1.644	6.949
Lightweight	0.315	1.000	4.522	3.554	0.392	4.939
Production time	0.132	0.221	1.000	0.415	0.209	1.246
Price	0.178	0.281	2.408	1.000	0.257	2.371
Comfort	0.608	2.551	4.782	3.898	1.000	1.165
Easy to clean	0.144	0.202	0.803	0.422	0.859	1.000
Performs well	2.766	4.573	8.586	7.634	2.862	7.432

The comparison of criteria among the five consumers will involve normalizing the matrix by dividing each cell by the total of its respective column. To obtain the total for each row in the normalized matrix, the sum of the criteria will be used to derive the priority for each criterion. To calculate the eigenvector values, each priority will be multiplied by the total of each criterion in the comparison matrix, as presented in Table 4.

Table 4. Priorities and eigen values for the combined five consumers.

Criteria	Priority	Eigen Value	Rank
Durability	0.232	1.19333	2
Lightweight	0.114	1.37258	4
Production time	0.032	0.95439	7
Price	0.053	1.1923	5
Comfort	0.143	1.03264	3
Easy to clean	0.044	1.10287	6
Performs well	0.382	0.8823	1

The results of AHP I indicate that the comparison among criteria is consistent, as the CR value for each consumer is less than 0.1. The ranking of priorities, from the most important to the least important, is as follows: maximum functionality, high durability, comfort in use, lightweight, affordable price, ease of cleaning, and short production time. The values of each priority for the criteria will be incorporated into the House of Quality in the QFD phase.

3.2. STEP 2. QFD

In our study, we have developed eight technical designs based on broader consumer needs, which include the following:

1. Stable structure;
2. Foot-shape compatibility;
3. Comfort in use;
4. Effective heat absorption;
5. Lightweight;
6. Low production cost;
7. Ease of production;
8. Aesthetic shape.

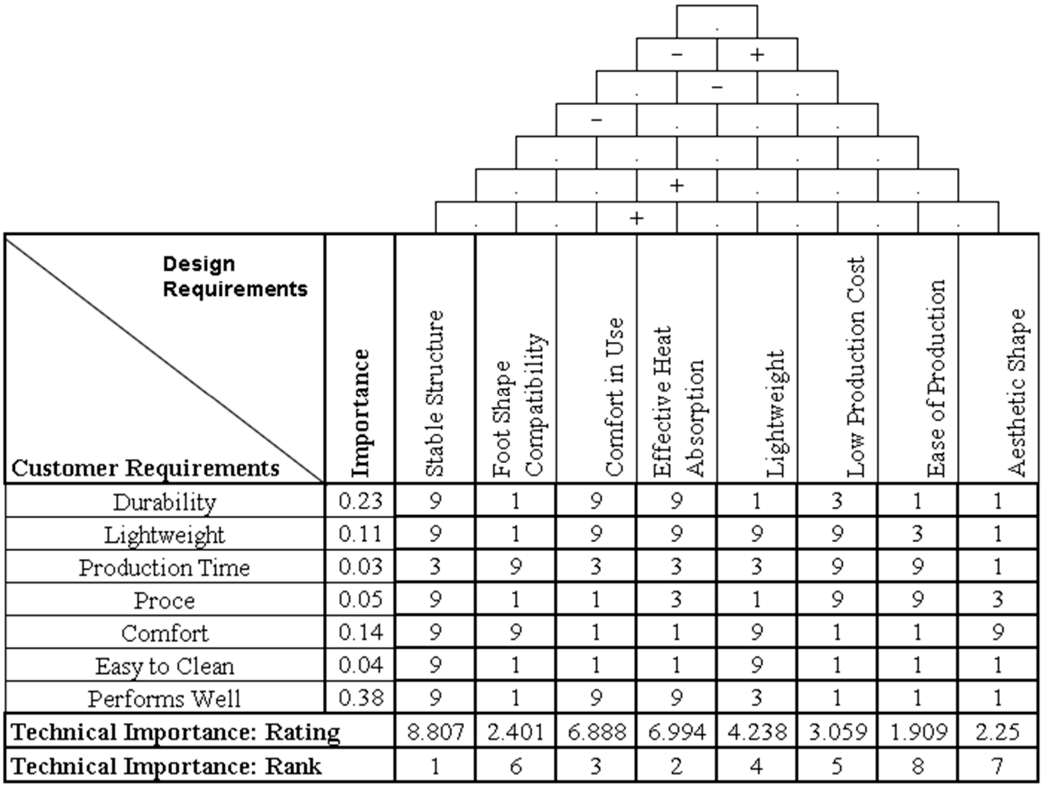
From the eight technical aspects, a relationship matrix will be created to illustrate the connection between consumer needs and technical aspects, as shown in Table 5. The values will be categorized into three criteria, which are as follows:

1. High relationship between needs and technical aspects: 9;
2. Medium relationship between needs and technical aspects: 3;
3. Low relationship between needs and technical aspects: 1.

Table 5. Relationship matrix between consumer needs and technical aspects.

Relationship Matrix	Stable Structure	Foot-Shape Compatibility	Comfort in Use	Effective Heat Absorption	Lightweight	Low Production Cost	Ease of Production	Aesthetic Shape
Durability	9	1	9	9	1	3	1	1
Lightweight	9	1	9	9	9	9	3	1
Production time	3	9	3	3	3	9	9	1
Price	9	1	1	3	1	9	9	3
Comfort	9	9	1	1	9	1	1	9
Easy to clean	9	1	1	1	9	1	1	1
Performs well	9	1	9	9	3	1	1	1

The values in each relationship matrix, as shown in Table 5, will be multiplied by the respective priority values from AHP I to be incorporated into the relationship matrix in the House of Quality, as illustrated in Figure 4. The results from the House of Quality in this study indicate that having a stable structure is the primary priority among the technical aspects in the production of orthotic insoles.



Customer Requirements \ Design Requirements	Importance	Stable Structure	Foot Shape Compatibility	Comfort in Use	Effective Heat Absorption	Lightweight	Low Production Cost	Ease of Production	Aesthetic Shape
Durability	0.23	9	1	9	9	1	3	1	1
Lightweight	0.11	9	1	9	9	9	9	3	1
Production Time	0.03	3	9	3	3	3	9	9	1
Proce	0.05	9	1	1	3	1	9	9	3
Comfort	0.14	9	9	1	1	9	1	1	9
Easy to Clean	0.04	9	1	1	1	9	1	1	1
Performs Well	0.38	9	1	9	9	3	1	1	1
Technical Importance: Rating		8.807	2.401	6.888	6.994	4.238	3.059	1.909	2.25
Technical Importance: Rank		1	6	3	2	4	5	8	7

Figure 4. House of Quality structure.

At this stage, the relationships among the technical aspects are also determined, which can be observed in the roof section of the House of Quality. Here, (+) indicates a strong positive relationship between technical aspects; (.) signifies no relationship; and (−) denotes a contradiction among the technical aspects. Any contradictions identified among the technical aspects will be addressed using TRIZ in the subsequent TRIZ phase.

3.3. STEP 3. TRIZ

In the results of the House of Quality, there are three technical parameters that exhibit contradictory relationships. Each technical parameter with a contradictory relationship has its own system parameter from the 39 TRIZ system parameters, which are referenced in Table 6.

Table 6. Technical contradictions and system parameters.

Technical Contradiction	Technical Variable	System Parameter
1	Stable structure Lightweight	Stress or pressure Weight of moving object
2	Ease of production Aesthetic shape	Ease of manufacture Device complexity
3	Stable structure Ease of production	Stress or pressure Ease of manufacture

From each system parameter in Table 6, alternative improvements can be identified using the TRIZ contradiction matrix. The contradiction matrix is a structured arrangement of 39 improvement parameters and 39 worsening parameters (a 39 × 39 matrix). This is organized as a grid with 39 rows and columns, serving as a tool for analyzing the interactions between these features. In the intersection boxes where the parameters of two features converge, inventive principles for addressing the specific problem are organized by frequency, where each cell entry provides the most frequently applied inventive principles to resolve or eliminate contradictions within the technical domain [21].

At this stage, the selected parameters for each technical contradiction from the previous section are cross-referenced in the matrix to identify a set of inventive principles. The contradiction matrix table can present effective solutions to be utilized in addressing technical problems. The results of the matrix table for resolving the technical contradictions in this study can be seen in red frame at Figure 5.

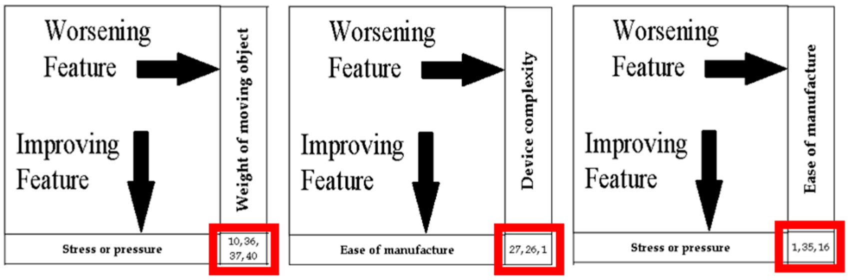


Figure 5. Alternative improvements based on the TRIZ contradiction matrix.

The first contradiction issue can be resolved using the principles of preliminary action (10), phase transitions (36), thermal expansion (37), and composite materials (40). The second technical issue can be addressed through the principles of cheap-short-lived (27), copying (26), and segmentation (1). The third technical issue can be resolved by applying the principles of segmentation (1), parameter change (35), and partial or excessive action (16).

Based on the resolution of the first contradiction, the application of preliminary action, phase transitions, thermal expansion, and composite material ensures that the product manufacturing process is not adversely affected by thermal expansion. In this study, three types of alternative materials were utilized: ABS (Acrylonitrile Butadiene Styrene), PETG (Polyethylene Terephthalate Glycol-Modified), and TPU (Thermoplastic Polyurethane). These materials were selected due to their lightweight properties and adequate pressure resistance, making them suitable to produce orthotic insoles.

For the second technical contradiction, several alternative solutions are available, including cheap-short-lived, copying, and segmentation. This study employs 3D printing as the manufacturing process for insoles. The use of 3D printing technology in this research was chosen due to its ability to create insoles with complex geometries. This technology offers a wider range of material options, along with lower production costs and faster manufacturing times compared to traditional methods [22]. Orthotic insoles can be produced using foot impressions in a foam box; however, this method often suffers from low precision and accuracy when the insoles are fitted to the patient's foot shape, frequently resulting in less comfortable orthotic footwear [23]. A comparison of the production processes for insoles can be seen in Table 7.

Table 7. Comparison of insole production processes.

Categories	Traditional	3D Printing (FDM)	Podograph Insole Machine
Geometric Complexity	Low	High	High
Insole Material Type	Low	High	Low
Additive Material	Low	High	Low
Material Cost per Insole	High	Low	Low
Equipment Cost	Low	Low	High
Customization Ease	Low	High	Low

The type of 3D printing used in this study is Fused Deposition Modeling (FDM). One unique advantage of FDM technology is its ability to adjust the infill density of the object, which significantly reduces weight compared to other 3D printing technologies. The key benefits of FDM technology include its low cost, lightweight, and process simplicity compared to other 3D printing methods [24].

The third technical contradiction has alternative solutions, including segmentation, parameter change, and partial or excessive action. To address this issue, auxetic structures can be utilized as infill in 3D printed products. Auxetic infill is a distinctive porous structure that exhibits lateral expansion under axial tension while contracting laterally under compression. This concept is based on the research conducted by Tong Chen titled "*A Novel Porous Structural Design of the Orthotic Insole for Diabetic Foot*", which employed auxetic infill in flat insoles and regular infill in load-bearing areas, resulting in a lighter product with a stronger structure [25].

The results from the TRIZ analysis in this study identified four types of alternative products that will proceed to the design and testing phases, namely:

1. Using ABS material;
2. Using PETG material;
3. Using TPU material;
4. Using TPU material with an auxetic structure.

Auxetic structures function optimally in the plastic phase of materials [26]. Therefore, in this study, auxetic structures are only applied to elastic materials, specifically TPU (Thermoplastic Polyurethane). Meanwhile, ABS (Acrylonitrile Butadiene Styrene) and PETG (Polyethylene Terephthalate Glycol-Modified) are classified as brittle materials, making them unsuitable for the application of auxetic structures. Thus, the focus of this research is on the use of auxetic structures in materials that possess adequate elasticity properties to support the desired performance and functionality [27,28].

3.4. STEP 4. Design and Testing

The first stage in the product design process involves scanning the consumer's foot using a 3D scanner to obtain the morphological shape of the foot. After the foot morphology is scanned with the 3D scanner, the scan results are exported as an STL file type to be uploaded to the insole creation website, www.gensole.com (accessed on 5 October 2024). Using this website, the insole is designed to follow the contours of the consumer's foot morphology. Once the insole design is completed using Gensole, the design is imported into the Bambuu Lab application for slicing, enabling it to be printed using a 3D printer, as illustrated in Figure 6. The product will be printed at a 0-degree angle following the shape of the product to achieve the highest Young's modulus value [29].

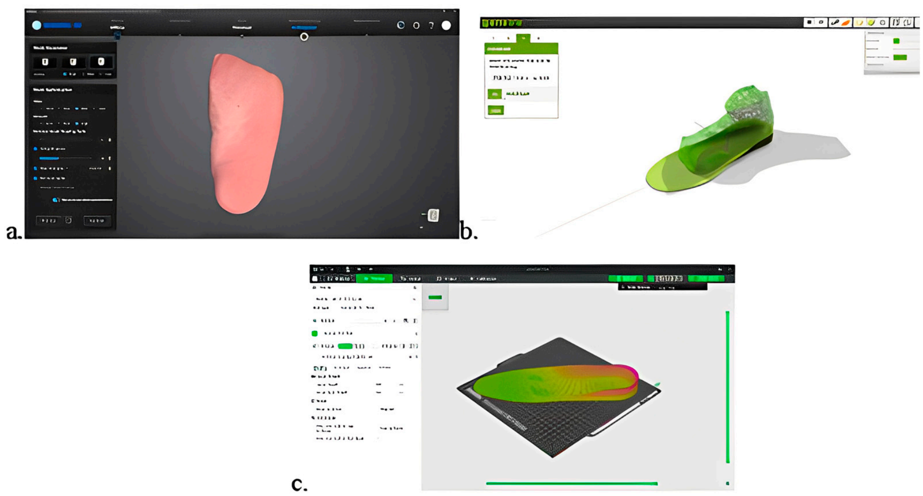


Figure 6. Insole production process: (**a**) 3D scanning of the consumer's foot; (**b**) insole design using the Gensole website; (**c**) slicing process using Bambuu Lab.

Since there is currently no 3D printing slicer that includes an auxetic infill pattern, this study designs the auxetic infill using Blender software (version 4.2). After the auxetic infill design is created with Blender, the infill design is combined with the insole design to achieve the desired insole infill structure, as shown in Figure 7.

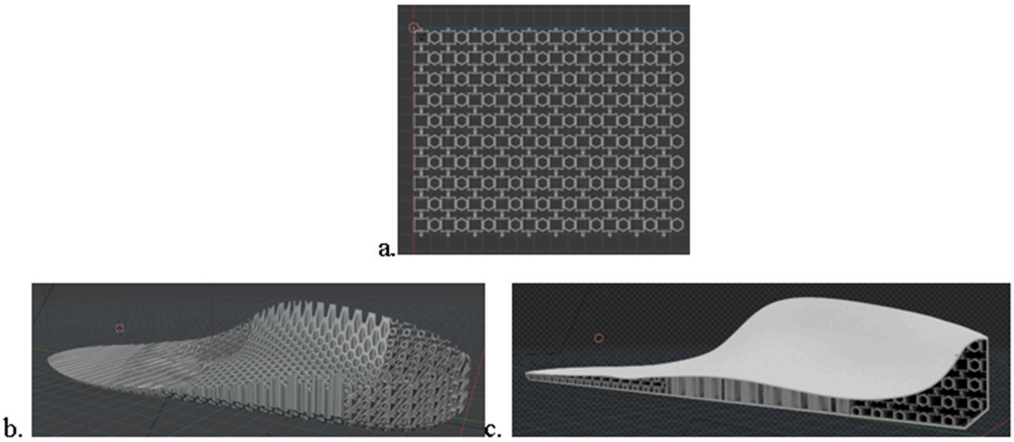


Figure 7. Auxetic insole design process: (**a**) auxetic structure design; (**b**) design structure for insoles; (**c**) combined structure and insole.

The insole is divided into two areas: a soft area located at the forefoot and rearfoot regions; and a support area situated in the midfoot region. The soft area exhibits an 18% greater deformation compared to a common flat structure under pressure. Standing experiments demonstrate that the support area reduces pressure in the forefoot and rearfoot regions by approximately 30% [25]. In this study, a modified auxetic honeycomb structure was utilized, based on research by Aniket Ingrole titled "*Design and Modeling of Auxetic and Hybrid Honeycomb Structures for In-Plane Property Enhancement*". The design selected is Auxetic-Honeycomb 1, as it exhibits the lowest Young's modulus while maintaining a high compressive strength. This makes it suitable for use in soft insoles, ensuring comfort for the user due to the soft material at the front and back of the foot. Additionally, the design provides optimal functionality in the midfoot area as it possesses a higher Young's modulus, ensuring that the contours of the insole retain their shape during use [30]. In this study, a hexagonal infill type is used because the hexagonal infill type has a higher elastic modulus compared to the grid infill type. A 25% infill using the hexagonal type is equivalent to a 50% infill using the grid type [31]. A wall thickness of 2 mm was utilized in this study because a greater wall thickness demonstrated improved performance in terms of stiffness and resistance to deformation under compressive loading [32].

The next step is the production of the products using a 3D printer. All alternatives are printed using the same parameter settings. The ABS, PETG, and TPU filaments used in this study were produced by SUNLU. The results of the printing for each alternative can be seen in Figure 8. After the printing process, all alternatives will undergo testing with consumers to obtain weight values for AHP II. The tests conducted will include comfort testing and functional testing. For the functional test, the Array 2500 sensor pressure distribution system will be used to observe the pressure distribution and the pressure focal points on the consumers' feet, as shown in Figure 9.

The black area in Figure 9 indicates that there is no pressure or very little pressure in that area, making it undetectable by the software. The teal area represents pressure levels between 0 and 0.5 kPa, while the green area indicates pressure levels between 0.5 and 1 kPa. The lavender area shows pressure levels between 1 and 1.5 kPa. The red area indicates that the pressure is above 1.5 kPa. The results without using insoles show a maximum pressure value of 2.167 kPa on the foot sole. In contrast, the maximum pressure value on the foot sole with the ABS insole is 2.020 kPa, with the PETG insole it is 1.806 kPa, with the TPU insole it is 2.088 kPa, and with the TPU insole auxetic infill, the maximum pressure value on the foot sole is 1.620 kPa.

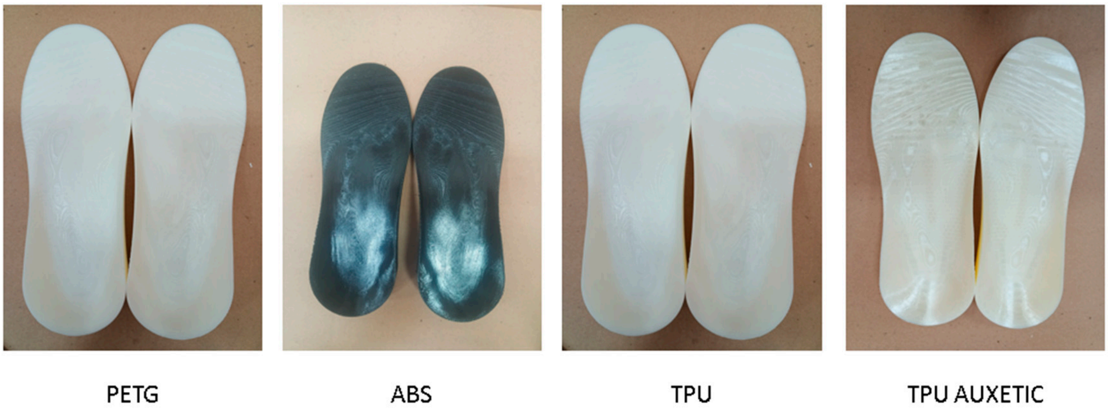


Figure 8. The results of the printing for each alternative.

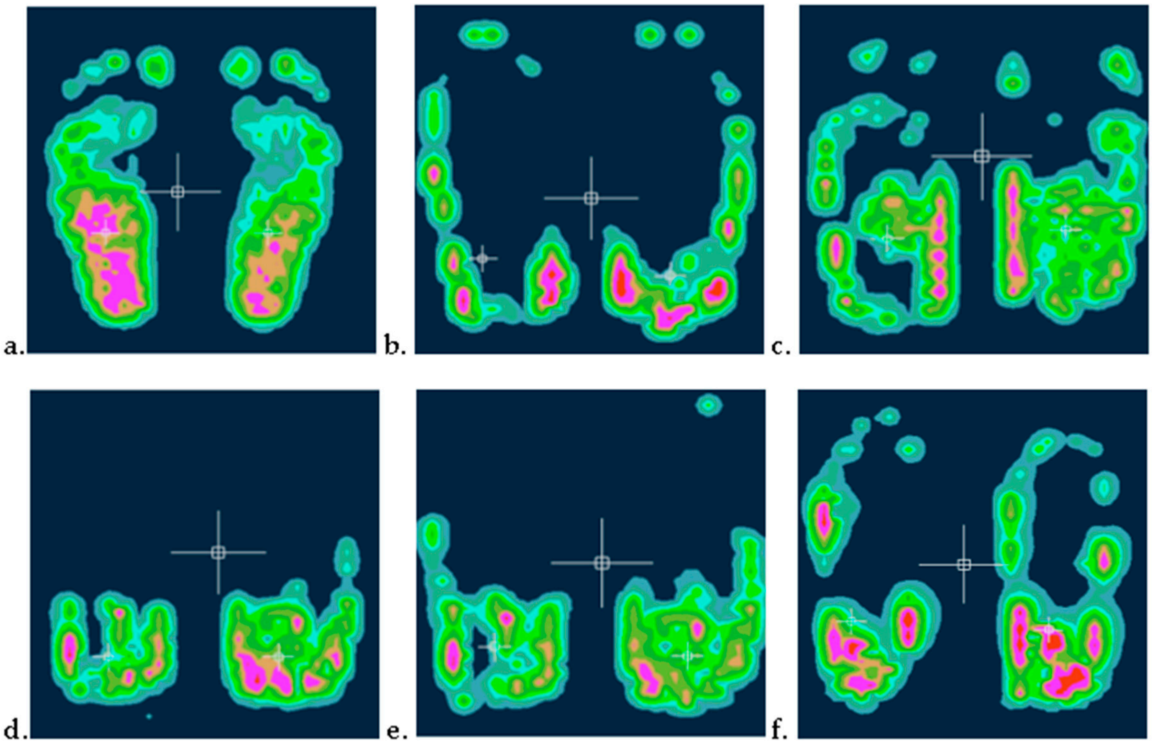


Figure 9. Results of the center-of-mass measurements and load distribution: (**a**) without footwear; (**b**) using ABS material; (**c**) using PETG material; (**d**) using TPU material; (**e**) using TPU material with auxetic structure; (**f**) using traditional insole from marketplace.

The results of this study indicate that the use of insoles leads to a decrease in the maximum load point on the foot. This is consistent with the paper "*A Review of the Plantar Pressure Distribution Effects from Insole Materials and at Different Walking Speeds*" [33].

The results of the pressure distribution testing on the foot were analyzed using an interval plot to assess the load distribution across the foot, as shown in Figure 10. The interval plot results indicate that the TPU auxetic exhibited the most uniform load distribution, with the smallest standard deviation of 0.1434.

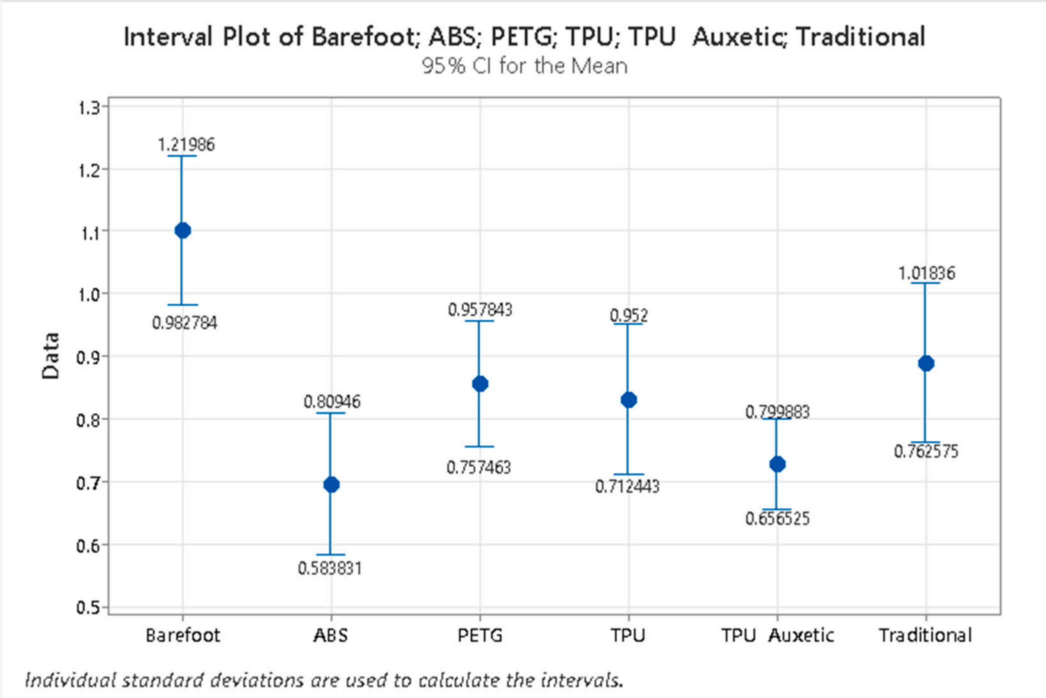


Figure 10. Interval plot of load distribution at each measurement point.

3.5. STEP 5. AHP II

Based on the results of the interviews and the outcomes of QFD and TRIZ, an AHP model was developed to determine the alternatives to be used as the final product, as shown in Figure 11.

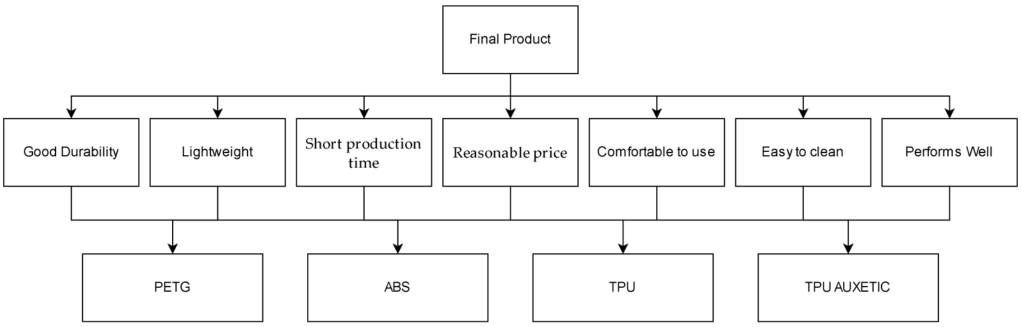


Figure 11. AHP Hierarchy II: comparisons between alternatives.

Using the same method as AHP I, AHP II determined the weights of each alternative for each criterion, with each criterion containing five consumer inputs and a consistency ratio (CR) for each consumer of less than 0.1. By combining the weight values from each consumer for the four materials, Table 8 presents the average weights calculated using the geometric mean for the comfort criterion, based on the results of interviews with patients to determine the weight of each alternative.

Table 8. Average comparison of alternatives for the comfort criterion.

Comfort	ABS	PETG	TPU	TPU Auxetic
ABS	1.000	1.246	0.237	0.117
PETG	0.803	1.000	0.232	0.114
TPU	4.227	4.317	1.000	0.308
TPU auxetic	8.559	8.790	3.245	1.000
Total	14.589	15.354	4.714	1.539

From the pairwise comparison weight matrix of the alternatives, the consistency ratio was calculated for each alternative, and the priority values for each alternative were determined, as shown in Table 9.

Table 9. Priority comparison for each alternative across all criteria.

Alternative	Durability	Lightweight	Production Time	Price	Comfort	Easy to Clean	Performs Well
ABS	0.34	0.09	0.33	0.08	0.068	0.12	0.14
PETG	0.42	0.10	0.45	0.11	0.06	0.17	0.15
TPU	0.13	0.03	0.14	0.04	0.24	0.36	0.19
TPU auxetic	0.11	0.03	0.08	0.02	0.62	0.36	0.53

The comparison data for each criterion across the alternatives will be multiplied by the priority values of each criterion and subsequently ranked according to their priorities, as presented in Table 10.

Table 10. Priority and ranking of each alternative.

Alternative	Total Priority	Rank
ABS	0.165747	3
PETG	0.196854	2
TPU	0.127457	4
TPU auxetic	0.250629	1

4. Discussion

In this study, QFD/TRIZ/AHP were utilized as methods for developing insole orthotics for individuals with flat feet. In the first stage, AHP was employed to translate patient desires into ranked priorities of patient needs, which was incorporated into the House of Quality. The results of AHP I indicate that the maximizing function is the most important criterion in the production of orthotic shoe insoles.

In the QFD stage, a relationship matrix was established between patient needs and existing technical aspects, resulting in the identification of three contradictory problems to be addressed using TRIZ. During the TRIZ phase, solutions for these three contradictory problems were identified as follows:

1. Utilize 3D printing as a production tool to ensure that the resulting product conforms to patient specifications while allowing for rapid production times;
2. Employ three types of alternative materials, ABS, PETG, and TPU, as the base materials due to their high durability and lightweight properties;
3. Implement an auxetic infill type as an alternative infill for TPU material to achieve a more stable structure that is easier to produce.

From these proposed solutions, four types of alternative products were developed for consumer testing to determine the weight of each alternative for use in AHP II. The results of the load distribution and center-of-mass assessment on consumers' feet indicate that using insoles improves load distribution, preventing body weight from concentrating on the central point of the foot, which helps reduce fatigue during walking.

In AHP II, it was determined that the material TPU with an auxetic structure is the primary product choice as it received the highest priority value of 0.2506. This is attributed to the fact that the TPU with auxetic infill offers optimal functionality and high comfort. These findings align with the load distribution measurements, where the TPU with auxetic infill exhibited the lowest load distribution, with a standard deviation of 0.1434, a maximum load of 1620 kPa, and a decrease of 25.4% maximum load.

5. Conclusions

This study aims to develop insole products for orthotics using the QFD/TRIZ/AHP methods. The results of this research identified seven patient needs along with eight technical specifications. The use of auxetic infill effectively resolves technical issues related to the contradiction between stable and lightweight structures. To address the challenge of producing a product that is easy to manufacture while maintaining an aesthetically pleasing design, the use of affordable 3D printing technology is proposed as a solution. Materials such as ABS, PETG, and TPU are recommended to tackle the issue of creating a lightweight product with good pressure resistance. The TPU with auxetic infill is the final product of this research, with a priority value of 0.2506. This product also demonstrates a reduction in value of 25.4% when compared to the condition without the insole. This study also found that structural stability is the most critical technical specification in the production of orthotic insoles. Testing of load distribution on the footbed demonstrated that the use of insoles effectively reduces load distribution on the foot. Overall, the QFD/TRIZ/AHP methodologies can be effectively applied in the product development process of orthotic insoles, prioritizing patient desires while maintaining the primary functions of the insoles.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board of the Komite Etik Penelitian Kedokteran Fakultas Kedokteran Universitas Jendral Soedirman (010/KEPK/PE/I/2024 and date of approval 20 March 2024).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The original data presented in the study are openly available in zenodo at https://doi.org/10.5281/zenodo.14752214.

Conflicts of Interest: Author Cokisela C L Tobing was employed by the company Dare Prosthetic & Orthotic Service, Bekasi, Indonesia 17147. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Table A1. AHP I for consumer 1.

Criteria	Durability	Lightweight	Production Time	Price	Comfort	Easy to Clean
Durability	1.000	3.000	7.000	7.000	2.000	8.000
Lightweight	0.333	1.000	5.000	3.000	0.333	5.000
Production time	0.143	0.200	1.000	0.333	0.200	3.000
Price	0.143	0.333	3.000	1.000	0.250	3.000
Comfort	0.500	3.000	5.000	4.000	1.000	7.000
Easy to clean	0.125	0.200	0.333	0.333	0.143	1.000
Performs well	3.000	5.000	9.000	9.000	3.000	8.000

Table A2. AHP I for consumer 2.

Criteria	Durability	Lightweight	Production Time	Price	Comfort	Easy to Clean
Durability	1.000	3.000	8.000	5.000	2.000	9.000
Lightweight	0.333	1.000	3.000	3.000	0.500	7.000
Production time	0.125	0.333	1.000	0.333	0.200	1.000
Price	0.200	0.333	3.000	1.000	0.333	5.000
Comfort	0.500	2.000	5.000	3.000	1.000	0.143
Easy to clean	0.111	0.143	1.000	0.200	7.000	1.000
Performs well	3.000	5.000	8.000	8.000	4.000	9.000

Table A3. AHP I for consumer 3.

Criteria	Durability	Lightweight	Production Time	Price	Comfort	Easy to Clean
Durability	1.000	4.000	7.000	5.000	3.000	9.000
Lightweight	0.250	1.000	3.000	3.000	0.333	7.000
Production time	0.143	0.333	1.000	0.333	0.200	4.000
Price	0.200	0.333	3.000	1.000	0.333	5.000
Comfort	0.333	3.000	5.000	3.000	1.000	0.143
Easy to clean	0.111	0.143	0.250	0.200	7.000	1.000
Performs well	3.000	5.000	8.000	8.000	4.000	9.000

Table A4. AHP for consumer 4.

Criteria	Durability	Lightweight	Production Time	Price	Comfort	Easy to Clean
Durability	1.000	3.000	9.000	4.000	0.500	5.000
Lightweight	0.333	1.000	7.000	3.000	0.500	4.000
Production time	0.111	0.143	1.000	0.333	0.200	0.500
Price	0.250	0.333	3.000	1.000	0.200	3.000
Comfort	2.000	2.000	5.000	5.000	1.000	5.000
Easy to clean	0.200	0.250	2.000	0.333	0.200	1.000
Performs well	3.000	4.000	9.000	5.000	2.000	7.000

Table A5. AHP for consumer 5.

Criteria	Durability	Lightweight	Production Time	Price	Comfort	Easy to Clean
Durability	1.000	3.000	7.000	8.000	2.000	5.000
Lightweight	0.333	1.000	6.000	7.000	0.333	3.000
Production time	0.143	0.167	1.000	1.000	0.250	0.500
Price	0.125	0.143	1.000	1.000	0.200	0.333
Comfort	0.500	3.000	4.000	5.000	1.000	3.000
Easy to clean	0.200	0.333	2.000	3.000	0.333	1.000
Performs well	2.000	4.000	9.000	9.000	2.000	5.000

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