# A Fuzzy Number based Hierarchy Analytic Method and Application in Improvement of Rehabilitation Devices

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## ABSTRACT

Different methods have been developed to identify customer needs in product design. The needs are then transferred into technical attributes and product parameters in the design process. However, the transfer from product needs to design parameters is challenging. There is a lack of objective approaches in traditional methods of searching design parameters to handle inaccurate design information. This paper introduces an effective method to analyze and rank design parameters for optional solutions by combining benchmarking and quality function deployment methods in an improved fuzzy analytic hierarchy process. It forms a multi-criteria decision-making method for the evaluation of design solutions to reduce the subjective preference of decision-makers. The method has been applied in the improvement of exoskeleton rehabilitation devices.

**Keywords:** Product design, Multi-criteria decision-making, Fuzzy number, Rehabilitation device, Benchmarking.
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## 1 INTRODUCTION

A product is normally developed based on customer needs. Conceptual design is the most important process to transfer the customer needs into design parameters in product development [4]. The conceptual design develops options of design solutions based on product requirements. Product requirements may be decided from customer needs, benchmarks of competitive products, and market development trends. These requirements have to be transferred into measurable technical attributes that can be used to decide and analyze design solutions. Criteria must be set for measures of product performances to choose the best design solution. Alternatives of product solutions are searched in the stage of conceptual design based on design criteria and their relative importance levels.

At the stage of conceptual design, there may be multiple feasible design solutions. An objective and effective method is required for the evaluation and selection of alternatives to get an optimal solution [24]. An accurate evaluation of design alternatives is complicated and difficult as there may exist uncertainty and incompleteness of information at this stage. The solution evaluation is likely based on multi-criteria, which increases complexity of the evaluation process. Different methods have been proposed for the evaluation of design alternatives including the expert rating, grey evaluation, quality function allocation, and fuzzy analytic hierarchy process (FAHP) methods [13].

Benchmarking is a process to examine and compare similar products in the market for identifying the best product configuration and components in its kind [1]. The goal of benchmarking is to find the best practical solution of product design and eliminate trial and error in order to speed up the design improvement and increase efficiency of the new idea development [3]. The integration of benchmarking and FAHP method can improve accuracy of the searching process.

Traditional rehabilitation methods depend on the physical therapists, which is not only time-consuming and laborious, but also lack of quantitative and objective evaluation of the rehabilitation [22]. As a new research field, rehabilitation devices have been developed to help physical therapists providing patients flexible and reliable rehabilitation therapy [6]. An effective rehabilitation device is commonly operated by the computer and equipped with corresponding mechanical mechanism and sensor systems. The rehabilitation device assists patients with task oriented, repetitive and intensive training process to improve rehabilitation.

The existing design of rehabilitation devices are mainly based on a particular need of the rehabilitation or designers' experience. There is a lack of the systematic method to guide the design process to form an adaptable device for different needs of rehabilitation. As a result, an effective method is required for analysis and selection of design solutions. This paper introduces a FAHP method integrated with benchmarking in design of upper limb rehabilitation devices. It can guide designers to search solutions based on multi-criteria under uncertain information.

Following parts of the paper are organized as follows.  The next section reviews the exiting research on the evaluation of design solutions. Advantages and disadvantages of the existing methods are analyzed. A FAHP method integrated with benchmarking and quality function deployment is then proposed for evaluation and improvement of upper limb rehabilitation devices, followed by conclusions and further work.

## 2 RELATED RESEARCH

This paper searches for an effective method in the evaluation of design concepts. The existing methods of the conceptual design evaluation include the expert rating, grey evaluation, quality function deployment, and FAHP methods as follows [13].

a) Expert rating

The expert rating is a scoring method using qualitative descriptions. It uses selected evaluation measures for specific requirements of the evaluation object. Representative experts in the field are employed to develop evaluation criteria based on their experience for design evaluation. Design solutions are then evaluated and selected based on the evaluation criteria [25]. This method is suitable for the design assessment when there are many uncertain factors and other methods are difficult for the quantitative analysis. The expert rating method has following characteristics: 1) Its concept is simple, an appropriate evaluation can be determined for the formulated evaluation grade and standard based on the specific evaluation object; 2) It is intuitionistic, each measure is reflected in the form of scoring; 3) The process is easy in application. The main limitation is that results of the evaluation depend on the subjective judgment of decision-makers. There may be a lack of objectivity [27].

b) Grey evaluation

The grey evaluation method refers to a theory of the grey system. It evaluates the state of an evaluation object at a certain stage for an intended target [30]. Grey evaluation can be processed at multiple levels, and the evaluation process can be recycled. An evaluation result of the previous process can be used as input data for the latter process evaluation [18]. Therefore, through the multi-level grey evaluation, evaluation requirements of a complex system can be conducted. The grey evaluation method can improve the accuracy and effectiveness of evaluation, but there are following shortcomings: 1) There is not an objective index system for evaluated objects; 2) the evaluation index cannot provide a solution to the target weight [20].

c) Quality function deployment

Quality function deployment (QFD) provides a tool to translate customer needs (CNs) into product technical requirements (TRs), and subsequently into parts characteristics, process plans, and production requirements. The translation uses a form chart, called the house of quality (HoQ). HoQ contains information for what to do related to CNs, and how CNs to do related to TRs, relationships of CNs and TRs, and benchmarking data. QFD is an effective tool of product design for identifying important technical requirements and design solutions [10]. The design starts at mapping customer needs into design parameters by identifying and converting these needs from qualitative criteria to quantitative parameters. QFD has been widely used for developing product characteristics in the process from function requirements to design parameters [16]. A limitation of QFD is that the weight used to rate the CNs and TRs directly affects the accuracy of the solution. A more objective method is required to improve the weight accuracy.

d) Fuzzy analytic hierarchy process (FAHP)

FAHP provides a multi-standard decision-making tool for decision-makers. It can be flexibly combined with other methods such as linear programming, quality function expansion, and fuzzy logic. But it is difficult to decide the performance level and weight for each design factor. Information is usually inaccurate [11]. The traditional FAHP method has been improved using the fuzzy set theory [26]. There is a large number of research solutions in the area [19]. Although this method is applied widely, it has following defects: 1) Due to the use of inaccurate quantitative data, it is hard to convince, 2) In the process of evaluation, some calculations are complex, leading to a low efficiency of the evaluation process.

These existing methods have different pros and cons. A common limitation is the lack of an objective evaluation method to handle inaccurate information. This research proposes an improved method for analyzing, ranking and prioritizing design solutions. The method integrates the FAHP and benchmarking method for multi-criteria decision-making in the evaluation of design solutions. Benchmarking provides objective details of products to reduce the subjective preference of decision-makers and influence of uncertain factors in decision-making. The FAHP analyzes factors that affect the competitiveness of products using a hierarchy of the design scheme evaluation. Using triangular fuzzy numbers instead of scales in the conventional analytic hierarchy process, the method can fully consider various factors to reduce risks in product development.

## 3 PROPOSED METHED

### 3.1 Fuzzy multi-criteria model

Fuzzy sets were introduced as an extension of the classical notion of sets [33]. In classical set theory, a set of elements is a crisp set because an element only has two membership possibilities, an element either belongs or does not belong to the set. However, fuzzy sets are sets whose elements are characterized by membership degrees represented with the aid of a membership function valued in the real unit interval [0, 1], where 0 represents the minimum degree of membership, 1 is for the maximum degree of membership, and the other values in [0,1] represent different degrees of membership. Fuzzy sets theory provides mathematical foundations to treat imprecision, inexactness, ambiguity, and uncertainty data that appear in real problems [32].

Tab. 1 shows membership functions of triangular fuzzy numbers in the form of triples (a1, aM, a2). Symmetric triangular fuzzy numbers 1 to 9 are used to indicate the relative strength of elements in the hierarchy [21]. Although the use of the discrete scales of 1 to 9 has the advantage of simplicity, it does not consider uncertainty associated with mapping of decision maker's perception, or judgement to a number. A fuzzy number $\tilde{x}$ expresses the meaning of 'about x'. Here each characteristic function is defined by three parameters of the symmetric triangular fuzzy number, the left point, middle point and right point of the range where the function is defined.

| *Triangular fuzzy number* | *Membership function* |
|---|---|
| $\tilde{1}$ | (1, 1, 3) |
| $\tilde{x}$ | （x-1, x, x+1）for x=2, 3, 4, 5, 6, 7, 8 |
| $\tilde{9}$ | (8, 9, 9) |

**Table 1**: Triangular fuzzy numbers and their corresponding membership functions.

According to the Dempster-Shafer theory of evidence [7], the upper and lower means of fuzzy number A are deduced as follows.

$$E_*(\tilde{A}) = \int_{-\infty}^{+\infty} x\, dF^*(x) \;,\; E^*(\tilde{A}) = \int_{-\infty}^{+\infty} x\, dF_*(x) \qquad (1)$$

In Eqn. (1), $F^*(x)$ and $F_*(x)$ are right continuous functions that describe the upper bound and lower bound distribution functions of fuzzy number A, respectively. The average value of A is a closed interval composed of expected values calculated by the upper and lower distribution functions, which is $E(\tilde{A})=|E^*(\tilde{A}),\ E_*(\tilde{A})|$.

When optimism q∈ [0, 1], attitude $E_q(\tilde{A})$ for fuzzy number A mapped to the real number field can be defined as a combination of $E_*(\tilde{A})$ and $E^*(\tilde{A})$ as follows.

$$E_q(\tilde{A}) = qE_*(\tilde{A})+(1-q)E^*(\tilde{A}) \qquad (2)$$

In Eqn. (2), $E_q(\tilde{A})$ indicates that fuzzy number $\tilde{A}$ is evaluated under optimism q. The larger q, the more important upper mean $E_*(\tilde{A})$ of fuzzy number A is. Therefore, q is used to represent the optimism of decision makers. q = 0 corresponds to the least optimistic, q = 1 means the most optimistic [29]. Considering triangular fuzzy number $\tilde{A}$ = (a1, aM, a2), we have follows.

$$E_q(\tilde{A}) = (1-q)(a1+aM)/2+q(aM+a2)/2 \qquad (3)$$

### 3.2 Fuzzy analytic hierarchy process (FAHP) method

The FAHP method is used to determine relative weights of different quality measures [31]. It is to evaluate performance of a group of products based on assigned values of fuzzy numbers of design criteria. For example, given three products A, B, C, the method of the fuzzy number based fuzzy hierarchy ranking process includes following steps.

Step 1. Forming a hierarchical model of the performance evaluation [15].

Step 2. Calculating fuzzy evaluation vectors at different levels, respectively. Fuzzy evaluation vector $\tilde{A}_i$ at different levels is calculated using Eqn. (4).

$$\tilde{A}_i = \tilde{C}_i \otimes \tilde{w}_i^{\,T} = \begin{bmatrix} \tilde{C}_{i,11} & \tilde{C}_{i,12} & \cdots & \tilde{C}_{i,1n} \\ \tilde{C}_{i,21} & \tilde{C}_{i,22} & & \tilde{C}_{i,2n} \\ \vdots & & \ddots & \vdots \\ \tilde{C}_{i,m1} & \tilde{C}_{i,m2} & \cdots & \tilde{C}_{i,mn} \end{bmatrix} \otimes \begin{bmatrix} \tilde{w}_{i,1} \\ \tilde{w}_{i,2} \\ \vdots \\ \tilde{w}_{i,n} \end{bmatrix} = \begin{bmatrix} \tilde{C}_{i,11}\otimes\tilde{w}_{i,1} \oplus \tilde{C}_{i,12}\otimes\tilde{w}_{i,2} \oplus \ldots \oplus \tilde{C}_{i,1n}\otimes\tilde{w}_{i,n} \\ \tilde{C}_{i,21}\otimes\tilde{w}_{i,1} \oplus \tilde{C}_{i,22}\otimes\tilde{w}_{i,2} \oplus \ldots \oplus \tilde{C}_{i,2n}\otimes\tilde{w}_{i,n} \\ \vdots \\ \tilde{C}_{i,m1}\otimes\tilde{w}_{i,1} \oplus \tilde{C}_{i,m2}\otimes\tilde{w}_{i,2} \oplus \ldots \oplus \tilde{C}_{i,mn}\otimes\tilde{w}_{i,n} \end{bmatrix} \quad (4)$$

Where $\tilde{C}_i$ is a fuzzy judgment matrix of each index in each level; $\tilde{w}_i$ is the fuzzy weight vector of each index in the level corresponding to $\tilde{C}_i$; $\tilde{w}_{i,j}=\tilde{1},\tilde{2},\tilde{3},\tilde{4},\tilde{5},\tilde{6},\tilde{7},\tilde{8},\tilde{9}$; $\tilde{C}_{i,kj}=\tilde{1},\tilde{2},\tilde{3},\tilde{4},\tilde{5},\tilde{6},\tilde{7},\tilde{8},\tilde{9}$; k=1,2 … m; j=1,2 … n; i represents the ith criterion; m and n are the numbers of rows and columns, respectively.

Step 3. Establishing a general fuzzy rating vector $\tilde{R}$, the total level of evaluation vector $\tilde{R}$ is obtained from Eqn. (5).

$$\tilde{R}=\tilde{A}\otimes\tilde{O}^{T}=[\tilde{A}_1,\tilde{A}_2,\ldots\tilde{A}_n]\otimes[\tilde{O}_1,\tilde{O}_2,\ldots\tilde{O}_n]^{T}=[\tilde{r}_1,\tilde{r}_2,\ldots\tilde{r}_m]^{T} \quad (5)$$

Where $\tilde{A}$ is a fuzzy judgment matrix in the general level. It is composed of fuzzy vectors of different levels in the previous step. $\tilde{O}$ is a weight vector of each criterion. Its value is decided according to the result of the quality house and benchmarking analysis.

Step 4. Calculating the average of fuzzy numbers of the overall fuzzy evaluation vector $\tilde{R}$, and the fuzzy mean $E_q(\tilde{r}_1)$ of the optimistic degree of reaction for decision makers under the optimistic degree q using Eqn. (3).

Step 5. Normalizing $E_q(\tilde{r}_1)$ using Eqn. (6).

$$N_q(\tilde{r}_i) = E_q(\tilde{r}_i)/[E_q(\tilde{r}_1) + E_q(\tilde{r}_2) + \ldots + E_q(\tilde{r}_m)] \quad (6)$$

The largest $N_q(\tilde{r}_i)$ in the product concepts will be the best design solution.

### 3.3 Benchmarking method

Although the fuzzy multi-criteria model can help searching design solution based on fuzzy numbers, the value assignment of fuzzy numbers to each design criterion is subjective, mainly based on the knowledge of designers [9], [12]. Without references, it is difficult to decide them precisely due to the lack of knowledge and data of the product in the conceptual design. Using benchmarking, design parameters can be searched from some similar products selected from the market as benchmarks. The benchmarks are decomposed into subassemblies and components for detail analysis based on priorities and weight factors derived from design measures [14]. Therefore, the benchmarking method can provide an objective solution of fuzzy numbers for each design criterion. The benchmark products selected are analyzed based on their preformation to meet each design criterion. Results are normalized to match the range of the proposed fuzzy numbers. These numbers are then assigned to performance levels of each design criterion.

## 4 CASE STUDY

The proposed method is used to improve design of the existing upper limb rehabilitation devices. Three rehabilitation products are selected as benchmarking products to provide design references. An improved design of the exoskeleton device is developed to verify the feasibility and effectiveness of the proposed method. Following sections of the paper introduce the method application.

### 4.1 Design needs

Design of an upper limb rehabilitation device is a complex process with multi-criteria. Although a variety of limb rehabilitation devices is available in the market, these devices have some limitations in either adaptability, user friendly, economy, or safety as discussed in Section 1. Following design needs are identified to improve the existing devices based on the analysis of existing rehabilitation products and rehabilitation operations [2].

(1) Safety: This is a primary need to avoid the secondary injury in affected limbs during rehabilitation. The device operation should be controlled within the range of physical activities of patients' capability.

(2) Economy: Affordability should be considered for the product production and use.

(3) User friendly: A good interactive interface is required between the device and user, such as easy to wear, lightweight, interest and comfortable experience during the device application.

(4) Adaptability: This is to meet rehabilitation needs of different patients and injures. The size of the device should be adjustable to meet different users in height and limb size, such as using a changeable length of forearm and upper arm.

Each requirement can be further detailed to facility design of the device. Such as the safety is affected by the device structure, components, and operations. The economy depends on the material, structure and number of degrees of freedom of the device. The user friendliness involves the interactivity, sensitivity and accuracy of the device. The adaptability is influenced by structure of the device. In order to consider these multi-criteria in design, a fuzzy multi-criteria model is built to help design of an upper limb rehabilitation device to meet the identified needs.

## 4.2 Data collection

For the evaluation of design solutions of upper limb rehabilitation devices using the proposed method, three upper limb rehabilitation products are selected as benchmarks. They are: A) CADEN-7 exoskeleton robot [23], b) ARMin exoskeleton upper limb rehabilitation training robot [5], and C) EXO-UL7 dual arm exoskeleton robot [8]. These devices are popular upper limb rehabilitation products in the market with the competitive function and price to meet user requirements. These selected upper limb rehabilitation products are similar in functions and applications with the identified requirements. The selected benchmarks are analyzed for each criterion in the performance evaluation of matching requirements. Components of benchmarks are also analyzed to decide the product detail. Data are collected to apply the proposed method that integrates FAHP, QFD and benchmarking methods. Data contents and hierarchical design evaluation are shown in Fig. 1.

The benchmarking method is used to decide weight factors of triangular fuzzy numbers for design criteria by comparing their importance based on each requirement. Tab. 2 shows an example of the function performance comparison of upper limb rehabilitation devices. In Tab. 2, product performances are coded with A to L respectively, their importance levels are compared in pairwise. The code shown in the table is the one with the more important level in the benchmark products. A final weight of the criterion is the value of its performance score divided by the total score.

## 4.3 Performance and demand analysis

House of quality (HoQ) is an analysis tool of QFD [17]. It is a graphical method to identify relations between customer needs and performances of corresponding products or services [28]. As shown in Tab. 3, the relation is analyzed for customers' demands and product functions, where, ● shows a strong relation with a value of 9; ○ indicates a general relation using a value of 3; △ is a basic correlation with a value of 1. The importance rank is based on results of the analysis of Tab. 2.

According to the analysis of the HoQ in Tab. 2, the strength, degrees of freedom and adjustability are more important than other functions for the product design. From Fig. 1, the strength affects the safety, degrees of freedom, and adjustability of the product adaptability. From Tabs. 1, 2 and 3, triangular fuzzy numbers $\tilde{1}, \tilde{2}, \tilde{3}, \tilde{4}, \tilde{5}, \tilde{6}, \tilde{7}, \tilde{8}, \tilde{9}$ are assigned to related contributions of various indicators based on results of benchmarking in the product function comparison analysis. The fuzzy index scores and weights of each index of the benchmark products are shown in Tab. 4.

Using Eqns. (1-6), results of the benchmark evaluation are calculated as follows.

$$N_q(A) = \frac{E_{q[\widetilde{r_1}]}}{E_{q[\widetilde{r_1}]}+E_{q[\widetilde{r_2}]}+E_{q[\widetilde{r_3}]}} = \frac{425+451.5q}{1407+1370.5q} \qquad (7)$$

$$N_q(B) = \frac{E_{q[\widetilde{r_2}]}}{E_{q[\widetilde{r_1}]}+E_{q[\widetilde{r_2}]}+E_{q[\widetilde{r_3}]}} = \frac{461+433q}{1407+1370.5q} \quad (8)$$

$$N_q(C) = \frac{E_{q[\widetilde{r_3}]}}{E_{q[\widetilde{r_1}]}+E_{q[\widetilde{r_2}]}+E_{q[\widetilde{r_3}]}} = \frac{521+486q}{1407+1370.5q} \quad (9)$$

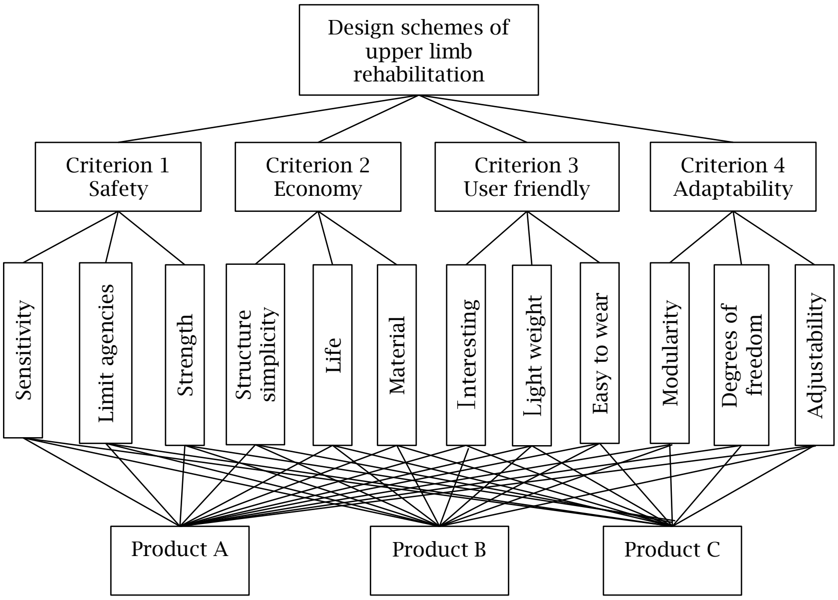


**Figure 1**: Hierarchical structure of the design evaluation.

| Criteria | | Sensitivity A | Limit agencies B | Strength C | Structure simplicity D | Life time E | Material F | Interesting G | Light weight H | Easy to wear I | Modularity J | Degrees of freedom K | Adjustability L |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | Sensitivity | | B | C | A | A | F | G | A | A | A | A | L |
| B | Limit agencies | | | C | D | C | F | G | B | B | B | K | L |
| C | Strength | | | | C | C | F | C | C | C | C | K | C |
| D | Structure simplicity | | | | | D | D | G | D | D | J | K | L |
| E | Life time | | | | | | F | G | E | I | J | K | L |
| F | Material | | | | | | | F | F | I | F | K | F |
| G | Interesting | | | | | | | | G | G | G | K | L |
| H | Light weight | | | | | | | | | H | J | K | L |
| I | Easy to wear | | | | | | | | | | J | K | L |
| J | Modularity | | | | | | | | | | | K | L |
| K | Degrees of freedom | | | | | | | | | | | | L |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| L Adjustability | | | | | | | | | | | | |
| Total Hits | 6 | 4 | 10 | 5 | 1 | 8 | 7 | 1 | 2 | 5 | 9 | 9 |
| Weightings | 0.09 | 0.06 | 0.15 | 0.075 | 0.015 | 0.12 | 0.106 | 0.015 | 0.03 | 0.075 | 0.136 | 0.136 |

**Table 2**: Product function performance comparison based on benchmarks.

| | Sensor feedback | Buffer Design | Limit Block | Selection | Motor placement | VR Games | Emergency stop Stop button | Number of DOF | Structural | Modular design | Gravity compensation | Importance rank |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sensitivity | ● | ● | | | | | | | | | | 5 |
| Limit agencies | | | ● | | | | △ | | | | | 4 |
| Strength | | ○ | | ● | | | | | | | ○ | 9 |
| Structure simplicity | | | | | ○ | | | | | | | 4 |
| Life | | | | | | | | | | | | 2 |
| Material | | | | ● | | | | | | | | 7 |
| Interesting | | | | | | ● | | ○ | | | | 6 |
| Light weight | | | | | | | | | | | | 2 |
| Easy to wear | | | | | △ | | | | ● | | | 3 |
| Modularity | | | | | | | | | | ● | | 4 |
| Degrees of freedom | | | | | | | | ● | | | | 6 |
| Adjustability | | | | | | | | | ● | ○ | | 7 |
| Importance | 5 | 4 | 6 | 7 | 5 | 8 | 4 | 7 | 6 | 5 | 4 | |
| Ideal value | | | | ⊙ | | | | ↑ | | | | |

| | | |
|---|---|---|
| ● | Strong correlation | 9 |
| ○ | Moderate correlation | 3 |
| △ | Weak correlation | 1 |
| ↑ | rise | |
| ⊙ | aims | |
| ↓ | decline | |

**Table 3**: HoQ of function and demand.

| Functional indicators | Product demand | $\widetilde{\omega_i}$ | A | B | C |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| Safety $\widetilde{\omega_1}$ | Sensitivity | $\tilde{5}$ | $\tilde{2}$ | $\tilde{1}$ | $\tilde{3}$ |
| | Limit agencies | $\tilde{4}$ | $\tilde{3}$ | $\tilde{2}$ | $\tilde{2}$ |
| | Strength | $\tilde{9}$ | $\tilde{2}$ | $\tilde{1}$ | $\tilde{3}$ |
| Economy $\widetilde{\omega_2}$ | Structure simplicity | $\tilde{4}$ | $\tilde{3}$ | $\tilde{2}$ | $\tilde{1}$ |
| | Life | $\tilde{2}$ | $\tilde{2}$ | $\tilde{1}$ | $\tilde{2}$ |
| | Material | $\tilde{8}$ | $\tilde{2}$ | $\tilde{2}$ | $\tilde{2}$ |
| User friendly $\widetilde{\omega_3}$ | Interesting | $\tilde{6}$ | $\tilde{1}$ | $\tilde{3}$ | $\tilde{3}$ |
| | Light weight | $\tilde{2}$ | $\tilde{2}$ | $\tilde{2}$ | $\tilde{1}$ |
| | Easy to wear | $\tilde{4}$ | $\tilde{3}$ | $\tilde{3}$ | $\tilde{1}$ |
| Adaptability $\widetilde{\omega_4}$ | Modularity | $\tilde{3}$ | $\tilde{1}$ | $\tilde{1}$ | $\tilde{3}$ |
| | Degrees of freedom | $\tilde{6}$ | $\tilde{2}$ | $\tilde{2}$ | $\tilde{3}$ |
| | Adjustability | $\tilde{7}$ | $\tilde{3}$ | $\tilde{3}$ | $\tilde{2}$ |

**Table 4**: Fuzzy index scores and weights.

Where q∈[0,1], $N_q(A)$∈[0,1], $N_q(B)$∈[0,1], $N_q(C)$∈[0,1], values of $N_q(A)$, $N_q(B)$ and $N_q(C)$ represent the optimization of products A, B and C, respectively, under the optimist q of the decision-maker. The bigger the value of Nq is, the more possible it is to be selected. From the results, it is found that $N_q(A) < N_q(B) < N_q(C)$. Therefore, product C has the best performance in overall.

## 4.4 Design improvement

Based on the further analysis of component evaluations, it is found that benchmark product A has the simplest structure; product B uses the most portable material and has the best performance of human-machine interactions; product C has the maximum degrees of freedom, it can also be used in both left and right arms. Considering anatomy of the human upper limb, the motion range of each joint, and evaluation results of benchmark products, a new design using five degrees of freedom for an upper limb rehabilitation device is proposed by combining advantages of the three benchmark products as shown in Figs. 2 and 3.

The proposed device has a lightweight with the ensured safety. Most of the rehabilitation devices on the market including the three benchmarks use a rigid structure [2]. Since the device only carries weight of the forearm, the aluminum alloy is used to have a lightweight and the enough strength required. Aluminum alloy #6610 is selected for the main structure of the device based on the comparison of mechanical properties of different grades of aluminum alloys.

There are mainly three types of driving methods using hydraulic, pneumatic or electric power, respectively. In this design, electric motors are used. The advantage of the hydraulic drive is the large torque, but this design does not require a large driving torque. The hydraulic drive is costly and its maintenance is relatively complex. Pneumatic drive requires an air compressor or air compressor station to supply air. It is also not suitable for a portable rehabilitation device. In comparison, the selection, use, and control of the electric motor are convenient. Therefore, the electric motor is chosen for driving methods of the device. Considering the application of the rehabilitation device, the stepper motor can easily meet the accurate positioning for different patient requirements in rehabilitation.

In Fig. 2, J1, J2, J3 are for rotations of the shoulder adduction and abduction, flexion and extension, internal and external turn, respectively. J4 is for the elbow flexion and extension. J5 provides rotations of the forearm. In order to ensure safety, motion limits are set at each joint. For adaptability, the device is designed for a detachable connection at A to achieve the dual-arm versatility by changing the orientation of the forearm.

In order to enhance functionality of the device, such as the adaptability for patients with different body types, the improved device uses an adjustable length telescopic structure as marked B in Fig.

3. Some patients may have discomfort due to different heights in using the device if the height of the seat and support is fixed. Therefore, in the modified mechanical structure, the support is designed as an adjustable mechanism, the lifting column C, as shown in Fig. 3.

As shown in Fig. 4, in order to enhance interactions of the patient and device in the treatment process, sensors are placed at joints of the upper limb rehabilitation device to record the movement trajectory of patient's limbs. Using a concept of the "mirror image", a targeted rehabilitation training trajectory is designed for the patient by comparing the recoded trajectory with normal limb's trajectory. During the rehabilitation, patient's trajectory is recorded to compare with the designed trajectory in the real time to guide the process. Using virtual reality based simulation, different games can be designed to increase the interest and initiative of the patient rehabilitation according to the degree of injury of a patient. We have designed some rehabilitation games using the Vizard software tool and Perception Neuron motion sensors with different levels of difficulty for applications in rehabilitation.

Comparing the new design with benchmark products, the device improvement can be identified as follows. 1) The device structure is more compact as the use of the optimal structure design and light material. 2) Versatility is improved to meet the rehabilitation need of both arms. 3) Adaptability is improved as the adjustable structure for the forearm to accommodate patients of different sizes. 4) The device comfort is improved as the use of the lifting column. 5) The patient interest and pertinence are improved to play rehabilitation games as the use of motion sensors to track the process.

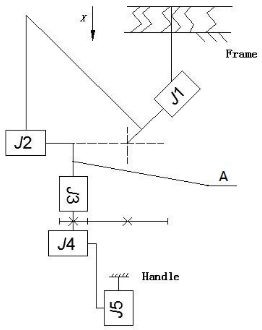


**Figure 2**: Device arm connections.

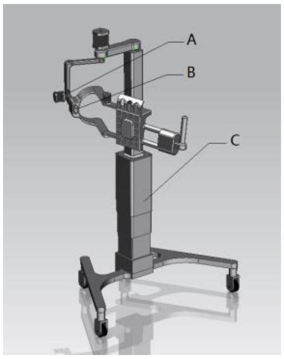


**Figure 3**: 3D model of the proposed rehabilitation device.

**Figure 4**: Rehabilitation demonstration.

## 5 CONCLUSIONS

Design evaluation for improvement is a key process of decision-making in product development. Due to the complexity of evaluation requirements and difficulty of quantification, design information may have the characteristics of vagueness, uncertainty and incompleteness, which increases the difficulty of decision-making. The FAHP method provides a simple and efficient process in the design evaluation for complex products with multi-criteria of performance measures. Benchmarking method helps reducing the subjective influence of decision-makers on the weight value of fuzzy numbers.

This paper presents the integration of fuzzy multi-criteria decision-making and benchmarking methods for the evaluation of design alternatives. Taking the upper limb rehabilitation products as example, the fuzzy set theory, analytic hierarchy process and multi-criteria decision theory are comprehensively applied to improve the design solution for diversified needs of the product.

The improved device, based on the design parameters search using the proposed methods, offers features of left and right arms interchangeability, sensor tracking treatment, lifting mechanism, and optimized structure to meet requirements of safety, economy, user friendly and adaptability. It provides a practical and effective reference for the design of upper limb rehabilitation devices.

Further work of this research will consider the diversity of product functions, and optimization of the rehabilitation plan. Virtual reality based games will be improved to increase the interactivity and interests of the device application in the rehabilitation.

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