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An Integrated Musculoskeletal Motion Analysis and Quality Function Deployment in Lower Limb Leisure Exercise Product Design

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Abstract. The promotion of social living quality has expedited the development of leisure exercise products. However, most young people usually accomplish their tasks by sitting in front of the computers. This situation makes many people seriously deficient in exercises that may cause muscle skeleton declination. In review of current related products, most of them are primarily designed by designers' intuition or only for a specific purpose. The objective of this research is to involve the motion analysis of physical musculoskeletal system in the integrated development process of quality function deployment for the design of lower limb leisure exercise products. A four-stage of development procedure including performance ranges of muscle-joint activities, AIO life style questionnaire, factor analysis, and quality function deployment is conducted. The implementation of quality function deployment helps to link customer requirements with product characteristics and derives design criteria for generating design alternatives. Two design alternatives based on the design criteria are generated by the computer-aided design software. It is expected that this research will provide designers with a reference or norm on designing most suitable lower limb leisure exercise products for people.

Keywords. Lower Limb Leisure Exercise Product, Human Musculoskeletal System, Quality Function Deployment, Computer-Aided Design

Introduction

Sitting posture has a close relationship with the physical health and becomes a popular issue for medical, ergonomic and design research [1]. In current society, many people usually sit in the office chair and work for a long period of time. Mueller, Chen and Riedel [2] indicated that the coming industry 4.0 will give a trend of automation in smart design and manufacturing associated with more people working on the computer operation. This situation will cause diseases of the muscle skeleton system. Chaffin and Anderson [1] stressed that unlike people who work in a heavy load environment and get a high risk of injury, those people who sit in a chair for work without enough time of physical exercise will incur a chronic low back disorder. Since this kind of low back disorder is painful and needs a complicated treatment for rehabilitation, people gradually notice the importance of taking exercise to the physical health [3]. With the

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increasing health consciousness of the general public, the world-wide market for leisure exercise or fitness products has grown steadily. Currently a wide variety of these kinds of products are in great demand and also very competitive. Cross [4] noted that many manufacturers have devoted considerable efforts to upgrading the quality of their products and enhancing the efficiency of their designs and manufacturing processes.

The rapid growth of leisure exercise or fitness has made the related product development become diversification. In general, there are a variety of leisure exercise products which possess available functions for specific parts of physical body including head, neck, lumbar regions, and four limbs. Based on the investigation and collection of existing leisure exercise products, the research found that most of them are suitable for lower limbs and have similar functions. It might be because the activities of lower limbs can simultaneously connect with the activities of lumbar regions and achieve the relief effect of the low back burden. However, existing product design strategies for leisure exercise of lower limbs have been restricted to general conceptual or philosophical aspects of the design process, or to very limited application areas in physical activities. Besides, the designer often has his or her own subjective opinion and many new products are merely partial improvements or modifications of the existing products. It is noted that systematic approaches to the product design process will assist the designer to identify design problems and design criteria, and enhance the effectiveness of evaluation of the final design solution [4-5]. As such the objective for this research effort is to employ an integrated process of quality function deployment for making a suitable connection between customer requirements and lower limbs leisure exercise product characteristics to help explore the feasibility of building an optimum lower limbs leisure exercise product design model. The proposed method will be used to generate lower limbs leisure exercise product design alternatives. Note that the customer requirements will refer to the AIO life style questionnaire [6] and statistical factors analysis [7]; while the product characteristics will refer to the musculoskeletal motion analysis [1]. The procedures developed as a result of this research should assist designers in more closing linking the product design process with customer requirements.

1. Lower Limb Leisure Product Development Procedures

Product design is a creative process of integrating design components into a complete product characteristics which satisfies customer requirements. Since competition in every world market has increased, sound product design can play in securing competitive advantages in product quality and production efficiency. Based on the observation of current and potential competition in lower limb leisure exercise product design, the research noted that through the analysis of human musculoskeletal structure and activity characteristics will provide designers and manufacturers with opportunity of designing diverse and suitable products for users. As such, the development procedure of this research is divided into four stages. They are (1) collection of lower limb aspect of human musculoskeletal motion activity ranges and current existed leisure exercise product characteristics, (2) application of an AIO (A: activity, I: interest, O: opinion) type of questionnaire associated with factor analysis in the exploration of lower limb leisure exercise product requirements, (3) development of a quality function deployment process to link lower limb leisure exercise product requirements with physical activity characteristics to determine critical lower limb

leisure exercise product design criteria, and (4) generation of conceptual design alternatives and propose optimum lower limb leisure exercise product alternatives. The following sections will describe how the development process will work for the design of leisure exercise products.

2. Collection of Lower Limb Activities and Existing Leisure Exercise Products

In the ergonomic areas, designers mainly focus on the proper interaction and rational combination of human, machine, and environment to improve design efficiency and product safety. It means that the designer should design products for people to meet the capability and limitation requirements. Therefore, the human motion analysis on the musculoskeletal structure *sy*stem may play an important role in secure the quality and efficiency of product design [8]. The research first collected some lower limbs related anthropometric motion ranges and current existing leisure exercise products for exploring their corresponding relationships. To help develop the lower limb leisure exercise products, the research also observed and recorded operational activities from users when performing the exercise products. The conduction of motion analysis will help identify some critical points of motions for further product development.

2.1. Collection of human lower limb activities

The ranges of joint motions refer to the most range that the joint activity can reach on its extremity. In general, the range of joint motion will occur in two types of activities: (1) active activity, and (2) passive activity. The active activity is defined as the random contraction of skeletal muscle that causes a curvy movement of joint exercise; while the passive activity is related to a curvy movement that an external force renders on the joint exercise [9]. Note that different joint exercises will have different ranges of joint motions. Table 1 illustrates a collection of ranges of joint motions based on a various sources of ergonomic data [1][9]. According to the observation of current leisure exercise products, ball joint, plane joints, hinge joints, and ellipsoidal joint illustrated in Table 1 are considered as important factors to the design of leisure exercise products.

2.2. Collection of existing leisure exercise products

There are a variety of lower limb leisure exercise products in the market, such as treadmill, elliptical training machine, bouncing machine, vertical knee raise apparatus, and leg extension machine. Sometimes, roller skating and skateboard are considered as the lower limb exercise apparatuses. However, most of the lower limb exercise products are related to treadmills and also involve activities of upper extremities and whole body. The research collected about 40 lower limb leisure exercise products and classified these products into three categories: (1) lower limbs, (2) lower limb and upper limbs, and (3) whole body. The representative products for these categories are illustrated in Figure 1. According to the investigation of the collected lower limb related leisure exercise products illustrated in Figure 1, the research found that most fitting for the whole body products are multifunctional training types and not suitable for the leisure exercise purpose. In general, a leisure exercise product with simple function and easy operation is most preferable to all ages, especially for the old ages. The research also found that the lower limb treadmills machines are accepted by the old

Table 1. Motion ranges of muscle joint exercises.

Physical Part of Body	Type of Joint	Type of Motion Activity	Range of Motion (in Degrees)
Buttocks	Ball Joint	Flexion	115-125
		Extension	5-10
		Abduction	45-50
		Adduction	20-30
		Revolution	360
		Rotation	90-100
Patella	Plane Joint	Up and Down Slide	5
Tibia	Hinge Joint	Flexion	155
		Extension	0
Proximal Tibiofibular Joint	Hinge Joint	Flexion	30-35
		Extension	40-45
Tarsal Bones	Plane Joint	Slide	0
Bunion	Ellipsoidal Joint	Flexion	25-35
		Extension	80-90
		Abduction	15-25
		Adduction	-
Apotelus	Hinge Joint	Flexion	90
		Extension	0

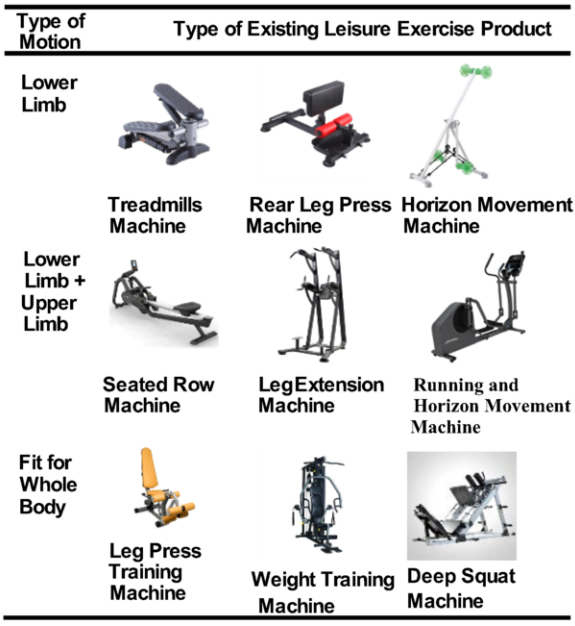


Figure 1. Representative lower limb leisure exercise products.

ages for their healthful functions. Therefore, the research will focus on the design of leisure exercise products having simple functions that fit for all ages. The design of treadmills machines is also considered. The research further analyzed the current lower limb exercise treadmills machines and noted that they can provide exercisers with seven types of step exercises including (1) thigh adduction, (2) knee flexion, (3) leg lift, (4) tight abduction, (5) knee extension, (6) calf aiming at the pedal, and (7) thigh and calf stamping on pedals. Based on the analysis of the lower limb exercise treadmills machines, it may conclude that certain factors will affect the tread exercise efficiency

including exertion method, frequency of getting hurt, leg length, calf length, seat depth, knee height, and seat height. These factors will be involved in the following analytic process.

3. The AIO Questionnaire and Factor Analysis

Life style in consumer behaviors reflects users psychological attitudes and inclination on buying. In contrast to the traditional questionnaire, life style questionnaire will much easier to help tested subjects understand the real meaning of questions and respond to the requirements of the tested subjects. The research designed an AIO life style questionnaire with "A" denotes activity, "I" denotes interest, and "O" denotes opinion, respectively [6]. To develop AIO lifestyle questions, the research considered the customer behaviors on purchasing preferences. According to the analysis of interviewing 10 experienced exercise product users, the research identify four key dimensions of construct associated with 22 requirement aspects as illustrated in Table 2. The 65 lifestyle questions regarding the about 22 requirement aspects were designed in an AIO format. Note that a popular Liker five-point measurement chart is used in the questionnaire evaluation process. The five points of 1, 2, 3, 4, and 5 denote the linguistic judgments of “not”, “very low”, “low”, “medium”, “high”, and “very high” on importance of requirement, respectively. The research used both Internet MySurvey and paper types to distribute the questionnaires to the voluntary tested subjects. A total of 105 effective results were forwarded to the factor analysis. The statistical software SPSS 17.0 was used. In this research, the principle component analysis was used and the varimax method was considered for orthogonal rotation [7]. The results showed that the KMO (Kaiser-Meyer-Olkin) value is 0.830 and Cronbach's α is 0.828 meaing that a Bartlett’s test is statistically significant. Table 3 illustrated the derived 5 factors associated with 12 preference requirement attributes. The identified preference requirement attributes will be involved in the quality function deployment to make a proper connection with the lower limb leisure exercise product characteristics.

Table 2. Four key dimensions of constructs of user requirements.

Key Dimension	Question for User Requirement					
Interactive Exchange	Communication	Enjoy	Common Participation	Social Intercourse	Competition	
Body Activity	Exercise	Supervision	Do it yourself	Health	Effort Saving	
Emotional Response	Avoid Danger	Sense of Accomplishment	Pleasant Amazement	Amusement	Privacy	Flaunting
Operational Function	Far End	Setup	Multipurpose	Simple	Time Saving	Advice

4. Employment of Quality Function Deployment

As mentioned above regarding the analysis of the survey of AIO lifestyle questionnaire, the research identified 5 factors associated with 12 preference requirement attributes.

Table 3. Factors and corresponding requirement attributes.

Type of Factor	Level	Preference Requirement Attribute
Function	1	Functional Display
	2	Simplified Function
	3	Complex Function
Safety	1	Stability
	2	Pressure Endurance
Adjustability	1	Repeated Operation
	2	Adjustable Structure
	3	Disassembly
Convenience	1	Easy Movement
	2	Easy Adjustment
Appearance	1	Simple Form
	2	Lightweight Construction

The 12 preference requirement attributes will be considered as customer requirements. As to the lower limb exercise product characteristic attributes, the research summarized 15 most frequent musculoskeletal motions and forwarded to 100 voluntary tested subjects to have multiple choices. Figure 2 illustrated an evaluation survey regarding the 15 musculoskeletal motions. The result showed that calf swings left and right when seated, leg swings left and right when seated, leg moves up and down when seating, leg moves up and down when lying down, leg moves up and down when flat seating, and calf moves up and down when seating are most preferable to taking exercise. This survey result helps the research identify suitable lower limb exercise product characteristic attributes. After customer requirement attributes and lower limb exercise product characteristic attributes having been determined, the research can then perform the process of employing quality function deployment. It is noted that the task needs to do in the employment of quality function deployment is the construction of the house of quality [10]. In constructing the house of quality, the research followed the general steps for the development of a house of quality [10-11].

Step 1. Identify customer requirements and place them on left side of the house.
In this research, 12 customer requirement attributes are considered based on the result of factor analysis. They are (1) functional display, (2) simplified function, (3) complex function, (4) stability, (5) pressure endurance, (6) repeated operation, (7) adjustable structure, (8) disassembly, (9) easy movement, (10) easy adjustment, (11) simple form, and (12) lightweight construction.

Step 2. Identify product characteristic attributes and place them on top of the house.
The research considered 10 product characteristic attributes based on the survey result of musculoskeletal motion analysis. They are (1) leg moves forward and backward, (2) foot slides up and down, (3) leg flexion and extension, (4) two legs swing, (5) two legs stamping on pedals, (6) calves swing left and right, (7) bicycle type of operation, (8) performing distance adjustment, (9) foot swings left and right, and (10) thigh flexion and extension.

Step 3. Determine relative values of importance for customer requirement attributes.
The research invited 15 voluntary tested subjects to make a paired comparison evaluation on these 12 user requirement attributes. The 15 voluntary tested subjects include 8 male and 7 female people whose ages range between 25 and 35 years. These young people usually work in the office and expect to have the chance to make lower limb exercise. A 10-point scale measurement is used and the result is averaged as absolute value of importance for each user requirement

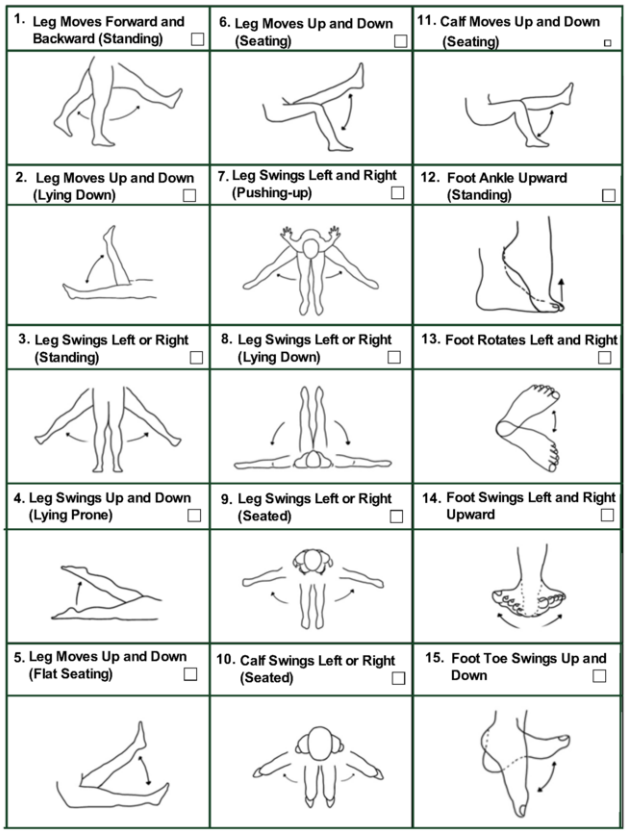


Figure 2. Example sowing a musculoskeletal motion survey.

attribute. The absolute values for the 12 user requirement attributes are normalized to be relative values. Each relative value of importance is expressed as a percentage and will form the chimney of the house of quality.

Step 4. Evaluate relations between product characteristic attributes.

The relation between characteristic attributes are cross-evaluated and will form the roof of the house. The research used symbols of "◎", "○", and "△" to represent very strong, strong, and medium relations, respectively. Instead, the symbols of "-◎", "-○", and "-△" represent negative relations, respectively.

Step 5. Construct the relationship matrix.

In the relationship matrix, the strong close relationships between customer requirement attributes and product characteristic attributes are evaluated with a 5-point scale measurement. Note that each matrix cell denotes a relationship on how much impact of a customer requirement attribute to the corresponding product characteristic attribute. The rating scales of 0, 1, 2, 3, 4, and 5 denote none, very weak, weak, medium, strong, and very strong relationship, respectively. The survey data from all tested subjects will be averaged.

Step 6. Determine absolute values of importance for product characteristic attributes.

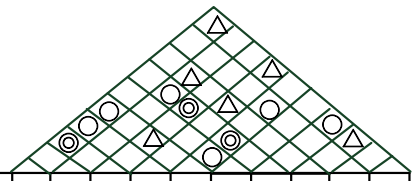
The determination of the absolute value of importance for each product characteristic attribute is to do a summation of the values by multiplying the relative value of each customer requirement attribute and the corresponding

relationship matrix cell value of a product characteristic attribute. Note that the value of summation denotes the contribution of a product characteristic attribute to the overall customer satisfaction.

Step 7. Normalize product characteristic attribute absolute values to be relative values. The relative value of importance for each product characteristic attribute can be obtained by calculating the absolute value of each product characteristic attribute divided by the summation of all absolute values of product characteristic attributes. As usual, the relative values of the product characteristic attributes are expressed as percentages.

Step 8. Identify critical product characteristic attributes for further development. The relative values of importance for product characteristic attributes are ranked. In general, a higher relative value will have a smaller rank number representing its significant importance to product design and need to pay more attention.

The construction of a partial house of quality for this research is illustrated in Figure 3. In Figure 3, certain smaller ranks of product characteristic attributes such as "leg moves forward and backward", "bicycle type of operation", and "Foot slides up and down" will be considered as critical product characteristic attributes.



	Relative Value of User Requirement Attribute (100%)	Leg Moves forward and backward	Foot Slides up and down	Leg flexion and Extension	Two Legs awing	Two legs stamping on pedals	Calves Swing Left and Right	Foot Swing left and Right	Performing Distance Adjustment	Bicycle Type Operation	Thigh Flexion and Extension
Functional Display	8.6	4.5	3.8	2.6	4.0	2.2	2.8	4.2	2.4	3.5	4.1
Simplified Function	9.1	2.4	3.1	3.0	2.7	3.0	2.7	2.6	3.5	3.9	2.5
Complex Function	7.0	3.6	3.7	3.6	2.4	2.9	3.6	3.2	2.9	3.7	3.0
Stability	8.7	3.7	3.4	2.5	3.8	3.0	2.7	3.6	2.9	3.7	3.4
Pressure Endurance	7.2	3.3	3.5	2.8	3.2	2.0	3.8	2.8	3.3	3.2	3.0
Repeated Operation	6.4	3.6	3.0	2.7	2.8	2.3	3.3	3.8	2.6	2.8	2.2
Adjustable Structure	8.2	3.8	2.6	2.3	1.9	3.8	2.8	3.8	3.8	3.9	3.2
Disassembly	7.1	3.1	3.1	3.3	4.2	3.2	2.8	3.2	3.9	3.4	2.2
Easy Movement	9.7	3.2	4.4	3.9	3.7	3.9	3.9	3.9	4.1	3.9	3.6
Easy Adjustment	9.3	3.5	4.2	4.0	3.4	2.9	2.7	2.5	3.7	3.5	3.4
Simple Form	8.4	3.9	3.3	3.2	3.1	3.2	2.9	3.1	2.8	2.7	2.5
Lightweight Construction	10.3	4.3	4.1	4.4	4.4	4.0	4.0	4.1	4.2	4.2	4.3
Absolute Value of Design Characteristic Attributes		359	348	324	334	309	317	310	338	357	318
Relative Value of Design Characteristic Attributes (100%)		10.8	10.5	9.8	10.1	9.3	9. 6	9.4	10.2	10.8	9.6
Rank Order of Design Characteristic Attribute		1	3	6	5	10	8	9	4	2	7

Figure 3. A house of quality for lower limb leisure exercise product design.

5. Development of Conceptual Lower Limb Leisure Exercise Product Alternatives

The result of quality function deployment analysis provided the research for a guidance in developing conceptual design alternatives. Two conceptual design alternatives will be introduced in this manuscript. They are (1) intelligent treadmill, and (2) hand and foot exercise type of apparatus. The intelligent treadmill is equipped with related components of the internet of things (IoT) that can help adjust the user exercise condition for a more suitable performance. Two air pressure pipes will adjust the tread resistance for the user based on recording the previous data. On top of the seat, a build-in speaker will use voices to remind the user to follow the instruction when taking exercise. An optimum exercise ratio gives 20 cm of tread exercise distance and 30 degrees of activity space that will provide the user with an efficient exercise. Figure 4 illustrated the conceptual design alternative of the intelligent treadmill. As to the hand and foot exercise type of apparatus, it is designed with a seat, two cylinder types of hand drag, and two big pedals as illustrated in Figure 5. In Figure 5, the proposed design is also equipped with an IOT modular under the apparatus base. The designed apparatus allow the user to be seated and use both hands and feet to operate hand drags and foot pedals just like rowing a boat when taking the exercise. The IoT modular will record previous data and automatically adjust the tread resistance so that the exercise training can help the user achieve the most suitable exercise mode.

(a) a perspective representation (b) partial details of components

Figure 4. A conceptual treadmill design alternative.

Figure 5. A hand and foot exercise design alternative.

6. Conclusion

The manufacturing technology has long been in advance of product design, but product design is always considered as the first step in developing manufacturing systems. Since current product design decisions in most industries are still based on the experience of designers and managers, it is important for designers to explore theoretical strategies associated with user requirements to identify relevant product characteristics for improving the design solution. In this research, the lower limb exercise product design is chosen as an example to demonstrate the applicability of the procedure. It is noted that muscle and joint activities are important to the human health. The range of specific muscle-joint performance might be a critical factor in designing an innovative leisure exercise product. Current investigation showed that various kinds of leisure exercise products exist in the market, but about 50% of which are lower limb leisure exercise products. Therefore, the purpose of the research effort is to propose an integrated design process incorporating the musculoskeletal motion analysis in the engineering design to help determine design criteria and generate innovative design alternatives. The analysis of musculoskeletal motion is incorporating in the statistical factor analysis and quality function deployment for determining lower leisure exercise product design criteria. The results indicate that the proposed design procedure will provide designers with a useful way in generating innovative design alternatives.

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