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Conceptual design of customized lower limb exoskeleton rehabilitation robot based on Axiomatic Design

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Abstract

In order to standardize the design process of complex products and improve customer satisfaction and intelligence of specific design scheme, a design case of Lower Limb Exoskeleton Rehabilitation Robot (LLERR) is presented in this paper. Under the precondition that walk assistance and rehabilitation training functions are achieved, higher demands for LLERR from psychological and physiological needs of users are proposed. Based on the research status and market demands of rehabilitation robots, a conceptual design of LLERR with the character of customized gait and customized exoskeleton is presented. The mapping process from functional requirement (FR) domain to design parameter (DP) domain of customized design scheme is analyzed according to Axiomatic Design (AD) theory. Then, an overall design matrix of 11×11, a triangular matrix, is obtained, revealing that the customized design scheme of LLERR is a decoupled design with great reliability. Lastly, the design scheme is optimized through constrains analysis. The correctness and practicality of this design scheme are verified. The paper's work can provide guidance for the design of the same type products.

Keywords: Axiomatic design; Lower limb exoskeleton rehabilitation robot; Customized design; Mapping analysis

1. Introduction

The LLERR worn on users' lower limb is a typical human-computer integrated system. It has combined the robotic technology of detection, control and information fusion and can provide power to assist users in rehabilitation training [1]. With the approach of the aging society and various accidents occurring frequently, the number of patients with lower limb dysfunction increases daily. By the end of 2014, the population over the age of 60 has reached 193 million in China, and the disabled is extremely huge with the number of 85 million. So the target people of LLERR are huge and the research is urgent.

One of the frequently used methodologies in the design process is AD theory. AD was developed by Suh at MIT and first published in his book in 1990 [2]. AD has been shown to greatly improve the design while shortening design time. The two axioms of AD, Independence Axiom and Information Axiom, maintain the independence of functions and minimize the information, or complexity of the design process. There are clear, simple rules which guide design process for the best solution for desired functions. AD, based on these two fundamental axioms, eliminates the possibility of making mistakes when products are developed. AD helps to overcome shortcomings in the product development process which is based on a recursive 'design/build/test' cycle requiring continuous modifications and changes as design flaws are discovered through testing [3]. AD can be applied to the design of products, processes, projects, and systems [4]. It has been called one of the most important engineering developments of the last hundred years.

AD is a design theory based on domains and design axiom. Its main purpose is to establish a scientific standard for the design process. AD provides theory basis for designers to conduct design and improve design. It makes system design process more clearly and can be able to overcome the problem in early design. Through design framework provided by AD, zig-zag mapping method is adopted to analyze design task

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layer by layer from the perspective of functional decomposition, so that the corresponding FRs and DPs can be obtained. AD has been applied to a number of theoretical and practical studies [5]. For example, Tan Zhang [6] develops a resilient robot based on AD theory. Coelho [7] shows that AD stimulates group collaboration in order to find out the most cost-effective solution for specified FRs. Mabrok [8] presents an extended design matrix, which includes the mapping relationships between a complete set of FRs and corresponding DPs. Kulak [9] develops a road map for design of cellular manufacturing systems using Independence Axiom. In addition, AD principles are also applied to design flexible manufacturing systems [10]. These studies have convincingly shown the applicability and benefits of AD in solving design problems.

Product features become more and more complex and sophisticated currently. The development of design methods for complex products is imperative. Therefore, based on the standardization and high efficiency of AD, LLERR is taken as a design case to standardize the design process and to improve customer satisfaction and intelligence of design scheme. Given the research status and market demands of rehabilitation robots, a conceptual design of LLERR with the character of customized gait and customized exoskeleton is presented. The mapping process from FR domain to DP domain of customized design scheme is analyzed according to AD theory. Then, an overall design matrix of 11×11 is obtained. Lastly, the design scheme is optimized through constrains analysis. The correctness and practicality of dual customized design scheme are verified, revealing that the design scheme is reliable and valuable. The paper's work can provide guidance for the design of the same type products.

2. Demand analysis

Considering the customer-oriented market environment, traditional functional design is far from the mere goal of an ideal product design. Maslow's hierarchy of needs theory declares that users' needs will climb to a higher level when a certain level of needs is relatively satisfied [11]. Meanwhile, the desire for higher level of needs drives people's behaviors in turn. In daily life, walking is very important for persons to achieve desired tasks. Over the last decade, several lower limb rehabilitation robots have been developed to restore the affected limbs, such as Lokomat [12], LokoHelp [13], ALEX [14], Sting-Man [15], Rewalk [16] and HAL [17]. Understanding users' demands and distinguishing their differences are of critical importance for managing these needs. Users should be focused on not only to meet their needs but also to increase their customer satisfaction [18]. Kano model [19, 20], which is a good way to investigate the characteristics of customer demands, is used to classify users' demands into three levels, i.e. demands for basic quality, demands for desired quality and demands for attractive quality.

Customer satisfaction determines whether customers will buy this product or service again. It even affects opinions of other consumers. Based on Kano Customer Satisfaction model, the customer satisfaction of LLERR is analyzed. Firstly, if the basic functions of assisting walk can't be acquired, the customer dissatisfaction will increase dramatically, but the dissatisfied mood can be eliminated when walking assistance is realized without improving customer satisfaction. Demands for basic quality are regarded as merited by customers. Secondly, when the desire of self-walking is achieved by LLERR through rehabilitation training, the customer satisfaction will increase. Demands for desired quality are expectations of customers. Lastly, if a LLERR is designed with the additional functions, such as user-friendly control interface, comfortable support structures, the customer satisfaction will increase significantly. Demands for attractive quality are functions beyond customers' original expectations. As a result, higher demands for LLERR from psychological and physiological needs should be analyzed to increase customer satisfaction, so that a better design scheme for LLERR can be obtained.

In terms of lower limb dysfunction patients, under the precondition that walk assistance and rehabilitation training functions are achieved, the trend of users' needs will evolve to more specific and personalization. In order to meet the high-level psychological and physiological needs, the task solving mode, driven by problem, scheme, information and knowledge, in cognitive-developmental theory is adopted to conduct design analysis. Finally, a better design scheme of LLERR with customized gait and customized exoskeleton is proposed. The 3D model of LLERR design based on the demand analysis is as shown in Fig.1 and Fig.2.

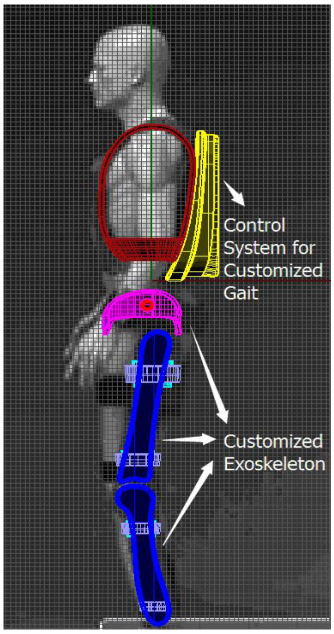

Fig. 1 The wireframe model of LLERR

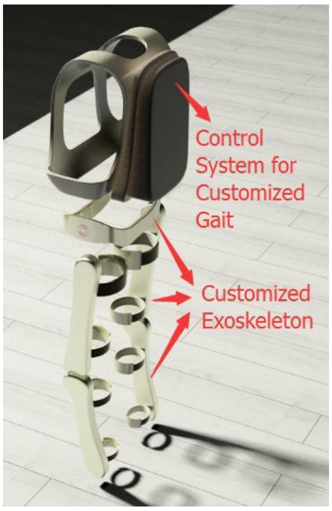

Fig.2 The rendering model of LLERR

3. Analysis of Mapping Process

Design is broadly defined to deal with mapping from societal wants or needs to the means for satisfying these needs. AD is composed of five concepts. These concepts are domains, hierarchies, zigzagging, and the two design axioms. The coupling relationship and mapping process between FR and DP are the most important part [2, 21]. And they are also the main research works about conceptual design of LLERR in this paper.

3.1. Mapping process between FRs and DPs on the first layer

Based on AD theory, through performing control system analysis, dynamics computation and so on of LLERR, the main FR is obtained. The high-level mapping relationships between FRs and DPs are established as shown in Fig.3.

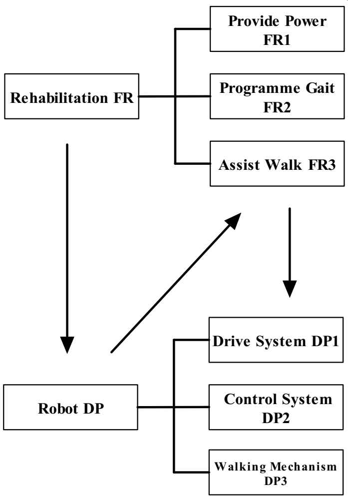

Fig.3 The mapping process between main FRs and DPs

Based on the mapping relationships shown in Fig. 3, the design equation is obtained.

$$\begin{pmatrix} FR_1 \\ FR_2 \\ FR_3 \end{pmatrix} = \begin{pmatrix} X & 0 & 0 \\ 0 & X & 0 \\ X & X & X \end{pmatrix} \begin{pmatrix} DP_1 \\ DP_2 \\ DP_3 \end{pmatrix} \quad (1)$$

Design matrix shows coupling relationships between FRs and DPs at one level of design hierarchy [22]. In a design matrix [23], 0 indicates a weak effect between an FR and a DP, while X represents a strong effect by a DP on an FR. When the design matrix is a diagonal matrix, it means a non-coupled design. When the design matrix is a triangular matrix, it means a decoupled design. The design matrix generally only involves physical things, and disobeys coordinate transformation. Therefore, it only represents the coupling relationships.

3.2. Mapping process between FRs and DPs on the second layer

Decisions made at higher levels of design hierarchies affect the statement of design tasks at lower levels. At a given level of the design hierarchy, a set of FRs exists. Before these FRs can be decomposed, corresponding DPs must be selected. Once an FR can be satisfied by a corresponding DP, so that the FRs can be decomposed into a set of sub-requirements, and the process is repeated.

According to the DPs obtained on the first layer, the FRs on the second layer satisfied the DPs on the first layer is determined. Then, the corresponding DPs on the second layer also can be obtained. Firstly, design of the drive system is required to select an appropriate power source, and to convert electric energy to mechanical energy, i.e. energy conversion function. Secondly, as the important and difficult part of LLERR design, the functions of users' motion information detection, processing of motion information, providing assistance force and customized gait design need to be achieved through the control system design. Thirdly, as the key part to realize exoskeleton customized, the customized exoskeleton is analyzed by exoskeleton design system. The main functions of walking mechanism are to maintain standing posture and to transfer motion. Finally, the corresponding design parameters are analyzed according to the FRs described above.

The mapping process between FRs and DPs is as shown in Tab.1.

Table 1. The mapping processes between FRs and DPs on the second layer

FRs	Function Description	DPs	Parameter Description
FR11	Store Energy	DP11	Power Source
FR12	Convert Energy	DP12	Electrical Motor
FR21	Detect Gait	DP21	Motion Capture Device
FR22	Process Information	DP22	High Performance CPU
FR23	Provide Force as Demand	DP23	Force Sensors

FR24	Customize Gait	DP24	Gait Decision System
FR31	Support Body	DP31	Support Structure
FR32	Transfer Motion	DP32	Transmission Mechanism
FR33	Customize Exoskeleton	DP33	Exoskeleton Design System

The design equations for this layer are:

$$\begin{cases} \begin{pmatrix} FR_{11} \\ FR_{12} \end{pmatrix} = \begin{pmatrix} X & 0 \\ X & X \end{pmatrix} \begin{pmatrix} DP_{11} \\ DP_{12} \end{pmatrix} \\ \begin{pmatrix} FR_{21} \\ FR_{22} \\ FR_{23} \\ FR_{24} \end{pmatrix} = \begin{pmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ 0 & X & X & 0 \\ X & X & X & X \end{pmatrix} \begin{pmatrix} DP_{21} \\ DP_{22} \\ DP_{23} \\ DP_{24} \end{pmatrix} \\ \begin{pmatrix} FR_{31} \\ FR_{32} \\ FR_{33} \end{pmatrix} = \begin{pmatrix} X & 0 & 0 \\ 0 & X & 0 \\ X & X & X \end{pmatrix} \begin{pmatrix} DP_{31} \\ DP_{32} \\ DP_{33} \end{pmatrix} \end{cases} \quad (2)$$

All design matrixes of the second layer are triangular matrix, showing that the design scheme of this layer satisfied Independence Axiom well as a decoupled design.

3.3. Mapping process between FRs and DPs on the third layer

The dual customized design concept has already been proposed on the second layer. It is the core part of LLERR design. So we will pay more attention to the analysis of customized gait and customized exoskeleton on this layer.

Considering the FRs depending on the DPs of gait decision system, there is something we can find as follows. On one hand, for users who lose motion consciousness completely, biological dynamics model for each person is established and analyzed. Under the era of big data, according to gait analysis results of normal people, the conventional gait is preset. Optimization gait is selected according to simulation of dynamics model for specific user. Consequently, the customized gait under unconsciousness is achieved. On the other hand, for users who have restored consciousness to a certain degree by rehabilitation training, or patients retain a weak motion consciousness, the active and passive control strategy is taken to implement customized gait. Based on 9-axis gyroscope array technology and the DPs on the second layer, high performance microprocessor and advanced solution for dynamics calculation and Kalman filter algorithm are adopted to acquire real-time motion information of lower limb, such as angle, angular velocity and angular acceleration. The multi-source information fusion technology is used to manage the motion information. Combining force feedback technology and impedance control technology and optimization strategy, the intelligent gait predication system is realized, i.e. intelligent gait adaptive system under weak consciousness.

Considering the FRs depending on the DPs of exoskeleton design system, it's easy for us to find some truth as follows. For one thing, in order to guarantee a favourable biocompatibility for wearable exoskeleton equipment and ensure that exoskeleton equipment is easy and comfortable to wear, the ergonomics is taken into consideration. And it is necessary to analyze the biodynamic model of each user so that the customized exoskeleton design is achieved. For another, given the conditions that different users have different demands for exoskeleton device and the differences in different users' hip size, the exoskeleton design based on demands of specific customer is adopted to achieve the design goal for individualized and detailed design according to each user's characteristics, and to make exclusive exoskeleton device for each user. Through the design scheme analyzed above, the customized exoskeleton is realized.

According to functional decomposition and corresponding design parameters of customized gait and customized exoskeleton, the mapping processes between FRs and DPs on the third layer are as shown in Tab.2.

Table 2. The mapping processes between FRs and DPs on the third layer

FRs	Function Description	DPs	Parameter Description
FR241	Customize Gait under Unconsciousness	DP241	Conventional Gait Preset System
FR242	Customize Gait under Weak Consciousness	DP242	Intelligent Gait Adaptive System
FR331	Guarantee Favorable Biocompatibility	DP331	Exoskeleton Design Based on Biodynamic Model
FR332	Guarantee Suitable Exoskeleton style	DP332	Exoskeleton Design Based on Specific Customer

The design equations for this layer are:

$$\begin{cases} \begin{pmatrix} FR_{241} \\ FR_{242} \end{pmatrix} = \begin{pmatrix} X & 0 \\ 0 & X \end{pmatrix} \begin{pmatrix} DP_{241} \\ DP_{242} \end{pmatrix} \\ \begin{pmatrix} FR_{331} \\ FR_{332} \end{pmatrix} = \begin{pmatrix} X & 0 \\ X & X \end{pmatrix} \begin{pmatrix} DP_{331} \\ DP_{332} \end{pmatrix} \end{cases} \quad (3)$$

The design matrixes of the third layer are diagonal matrix and triangular matrix, revealing that the design scheme of customized exoskeleton also can be decoupled.

3.4. Analysis of overall design matrix

One major advantage of AD is that decisions are formalized using a well-understood pattern. Through adopting the zigzag approach, and checking the correctness of the design scheme at each level, the solutions to the sub-problems are known. As a result, the original problem can be decomposed. Then, the whole design scheme is achieved. The final result of design is to obtain every components of design, i.e. DPs of each leaf, so that FRs can be satisfied. According to the coupling relationships between FRs and DPs in each design matrix, a final overall design matrix describing relationships between FRs and DPs of the whole leaves are established. The customized design scheme of LLERR is detailed in DPs of eleven leaves, corresponding to eleven detailed FRs. From the coupling relationships described in the design matrix above, an overall design matrix of 11×11 is obtained, which is shown in Tab. 3.

Table 3. The overall design matrix of LLERR

Functional Requirements	Design Parameters										
	DP11	DP12	DP21	DP22	DP23	DP241	DP242	DP31	DP32	DP331	DP332
FR11	X	0	0	0	0	0	0	0	0	0	0
FR12	X	X	0	0	0	0	0	0	0	0	0
FR21	0	0	X	0	0	0	0	0	0	0	0
FR22	0	0	X	X	0	0	0	0	0	0	0
FR23	0	0	0	X	X	0	0	0	0	0	0
FR241	0	0	X	X	0	X	0	0	0	0	0
FR242	0	0	X	X	X	0	X	0	0	0	0
FR31	X	X	0	0	0	X	X	X	0	0	0
FR32	0	X	0	0	0	X	X	0	X	0	0
FR331	X	X	0	0	0	X	X	X	X	X	0
FR332	0	0	0	0	0	0	0	0	0	X	X

Independence Axiom is an important design axiom in AD [2, 24]. It states that the independence of FR must always be maintained. And FR is defined as the minimum set of independent requirements to characterize the design goals. DP, which is the key variable, ia chosen to satisfy the specified FR throughout the design process [25]. In this paper, the mapping processes from FRs domain to DPs domain are analyzed, and the dual customized design scheme with customized gait and customized exoskeleton is presented. The motion capture technology is used to conduct gait control. And psychological and physiological needs are focused for exoskeleton design. Then, a triangular design matrix of 11×11 is obtained, revealing that the design scheme meets the Independence Axiom well and is a decoupled design. Overall, the dual customized design scheme of LLERR is reliable and valuable.

As we all know, uncoupled designs are the best design scheme from the view of ergonomics, since they do not have imaginary complexity. Decoupled designs can create imaginary complexity, so they are less desirable than uncoupled designs. To reduce design complexity, real complexity and imaginary complexity must be eliminated. Nonlinear optimization methods are used to find the optimum settings of DP tolerances. The constraints, such as safety, cost and ergonomics factors, are taken into consideration. In terms of constraint of cost, the cost model is served as objective functions. The tolerance control cost and the variation reduction cost are addressed to satisfy the FRs [26]. The constraints in the optimization formulation address the requirements for independence, variation control, and design simplicity. As a result, through constrains analysis process of LLERR, the better design result can be obtained.

4. Conclusions

Product design is a complex process of analysis, synthesis and decision-making. In order to standardize the design process of complex products and improve customer satisfaction and intelligence of specific design scheme, a design case of LLERR is presented in this paper. Under the precondition that walk assistance and rehabilitation training functions are achieved, higher demands for LLERR from psychological and physiological needs of users are proposed. Based on the research status and market demands of rehabilitation robots, a conceptual design scheme of LLERR with the character of customized gait and customized exoskeleton is presented. The mapping process from FR domain to DP domain of customized design scheme is analyzed according to AD theory. Then, an overall design matrix of 11×11, a triangular matrix, is obtained, revealing that the dual customized design scheme of LLERR is reliable and valuable. Lastly, the design scheme is optimized through constrains analysis. The correctness and practicality of this design scheme are verified. The paper's work can provide guidance for the design of the same type products.

With the development of modern design theory, much more and better design theories have been presented, such as TRIZ, FBS (Function Behavior Structure), FEMA (Failure Modes and Effects Analysis) and so on. The future research will pay more attention to integrate these theories into design process, so that the customer satisfaction will increase significantly with a standardization design process and an intelligent design scheme.

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