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A data-driven innovative design method for smart product-service systems to achieve mass personalization in rehabilitation

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A data-driven innovative design method for smart product-service systems to achieve mass personalization in rehabilitation

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Abstract. Smart product-service system (Smart PSS), as an emerging digital paradigm, offers users solution bundles to enhance the digitalization capability of the system by utilizing user-generated data. Massive information can be collected to investigate the dynamic changes of user requirements and assists the developers in designing personalized products and services. Meanwhile, key technologies (i.e. big data analysis and cloud computing) have enabled upgrading the rehabilitation equipment from the traditional physical training device to the personalized smart rehabilitation product-service system. However, few studies focus on gathering and utilizing user-generated physiological data to guide the innovative design of rehabilitation solutions in the Smart PSS environment. To fill this gap, an innovative design method is proposed to guide the Smart PSS development in the personalized rehabilitation field. The presented approach can be divided into three phases: the research phase, the development phase, and the usage phase. A personalized lower limb rehabilitation smart product-service system was described to explain the proposed approach.

1. Introduction

With the rapidly increasing development of information and communication technology (ICT), digital service gradually affects the sector of health care and manufacturing enterprises in all professions [1]. A new IT-driven business paradigm has appeared, named as "Smart-product service system (Smart PSS)" [2]. Various types of data (i.e. product-generated data and user-generated data) will be analyzed to promote innovation in service and satisfy personalized user requirements by utilizing the ICT (i.e. smart sensing, cloud computing, Internet of Things, and digital twin) [3]. In addition, rehabilitation plans are different and personalized to patients. Though the above situation exists and Smart PSS can be utilized in resolving this problem, Smart PSS in the personalized field of rehabilitation has rarely been studied and gotten attention from academics and manufacturing enterprises. To fill the gap, this paper proposes a new design method for the personalized rehabilitation field and explains the approach with the personalized lower limb rehabilitation Smart PSS.

2. Related works

Mass personalization takes users as individuals and offers appropriate products according to their internal needs to obtain a positive user experience and satisfy users effectively and efficiently [4].

Moreover, product-service system (PSS) in a mass personalization environment can combine product and service modules to satisfy user requirement personalization and quickly provide [5]. Chiu et al. (2021) developed a personalized recommendation system for Smart PSS based on an unsupervised learning model [6]. Li et al. (2021) presented a data-driven reversible framework for sustainable Smart PSS [7]. Meanwhile, Bu et al.(2021) proposed a user-centered design method for Smart PSS by using virtual reality technology [8].

Since Smart PSS was first proposed by [9], it has been used in many fields below [10]. Zheng et al. (2018) provided a systematical design framework and applied it in the smart medical field [2]. Lee et al. (2019) proposed an innovative design method for Smart PSS and illustrated a smart beauty service system to explain this approach [11]. Yang et al. (2021) presented a systematic development method of Smart PSS, which is applied in the field of smart home to add the emotional factors of smart beds [12]. Jia et al. (2021) introduced a method of rehabilitation assistive smart product-service system based on digital transformation [13]. As views as above, though Smart PSS added value is gaining attention, and mass personalization can meet personalized user needs, little research has applied mass personalization in the field of personalized rehabilitation Smart PSS.

3. Methodology

The innovative design method proposed to guide the Smart PSS development in the personalized rehabilitation field can be divided into three phases: the research phase, the development phase, and the usage phase. The proposed method details are shown in Fig.1.

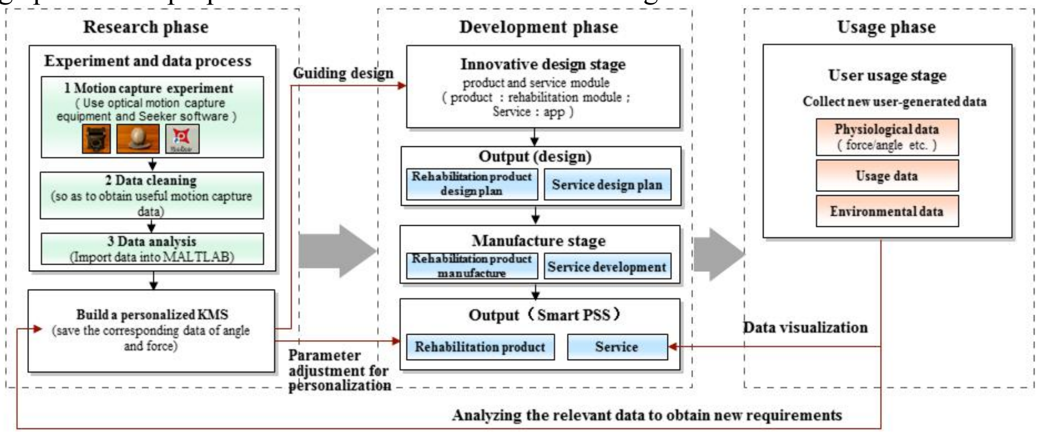

Figure. 1 Design method framework of the smart PSS development in the personalized rehabilitation field.

In the first phase, personalized parameters can be measured and calculated from the motion capture experiment and Matlab, and data analysis can be conducted to build the KMS. In the experiment, personalized kinematics data will be obtained through Nokov optical 3D motion capture equipment. The software part of the Nokov motion capture system is Seeker, which is used for motion capturing and raw data processing. The Seeker includes two modules: Live Mode and Post Process. It can export 3D Euler Angle data of the rigid extremity body which the rotation order of the primitive is ZYX. Furthermore, the rigid body method is not limited by the mark position and does not affect the accuracy of data calculation [14]. The Euler Angle data sequence output by Seeker can be used to calculate the coordinate transformation matrix from the ground coordinate system g to the limb fixed connected coordinate system b at each moment [15], which is applied to convert the angular velocity in the body coordinate system to the ground coordinate system at each moment. The coordinate transformation matrix is calculated as follows:

$$\boldsymbol{C}_{bg}=\begin{bmatrix}1 & 0 & 0\\ 0 & \cos(\varphi) & \sin(\varphi)\\ 0 & -\sin(\varphi) & \cos(\varphi)\end{bmatrix}\begin{bmatrix}\cos(\theta) & 0 & -\sin(\theta)\\ 0 & 1 & 0\\ \sin(\theta) & 0 & \cos(\theta)\end{bmatrix}\begin{bmatrix}\cos(\psi) & \sin(\psi) & 0\\ -\sin(\psi) & \cos(\psi) & 0\\ 0 & 0 & 1\end{bmatrix} \quad (1)$$

, where ψ , θ and φ respectively are Euler Angle in ZYX rotation sequence. The Euler Angle gradient $\begin{bmatrix} \dot{\varphi} & \dot{\theta} & \dot{\psi} \end{bmatrix}^{\mathrm{T}}$ can be approximated by making a difference and dividing the Euler Angle data sequence output by the motion capture software by the sampling interval:

$$\begin{bmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \approx \begin{bmatrix} \varphi_k - \varphi_{k-1} \\ \theta_k - \theta_{k-1} \\ \psi_k - \psi_{k-1} \end{bmatrix} / \Delta t \tag{2}$$

, where $\begin{bmatrix} \varphi_k & \theta_k & \psi_k \end{bmatrix}^{\mathrm{T}}$ and $\begin{bmatrix} \varphi_{k-1} & \theta_{k-1} & \psi_{k-1} \end{bmatrix}^{\mathrm{T}}$ respectively are Euler Angle at k and $k-1$ moment, and Δt is sampling interval. After Euler Angle gradient is obtained, the following formula is used to calculate the angular velocity in the body coordinate system:

$$\begin{aligned} \begin{bmatrix} \omega_x^b \\ \omega_y^b \\ \omega_z^b \end{bmatrix} &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\varphi) & \sin(\varphi) \\ 0 & -\sin(\varphi) & \cos(\varphi) \end{bmatrix} \begin{bmatrix} \cos(\theta) & 0 & -\sin(\theta) \\ 0 & 1 & 0 \\ \sin(\theta) & 0 & \cos(\theta) \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \dot{\psi} \end{bmatrix} \\ &+ \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\varphi) & \sin(\varphi) \\ 0 & -\sin(\varphi) & \cos(\varphi) \end{bmatrix} \begin{bmatrix} 0 \\ \dot{\theta} \\ 0 \end{bmatrix} + \begin{bmatrix} \dot{\varphi} \\ 0 \\ 0 \end{bmatrix} \\ &= \begin{bmatrix} 1 & 0 & -\sin(\theta) \\ 0 & \cos(\varphi) & \cos(\theta)\sin(\varphi) \\ 0 & -\sin(\varphi) & \cos(\theta)\cos(\varphi) \end{bmatrix} \begin{bmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} \end{aligned} \tag{3}$$

, where $\begin{bmatrix} \omega_x^b & \omega_y^b & \omega_z^b \end{bmatrix}^{\mathrm{T}}$ is component of angular velocity in limb fixed coordinate system. So, the angular velocity component $\begin{bmatrix} \omega_x^g & \omega_y^g & \omega_z^g \end{bmatrix}^{\mathrm{T}}$ in ground coordinate system can be calculated using inverse coordinate transformation matrix $\boldsymbol{C}_{bg}^{-1}$ as follow:

$$\begin{bmatrix} \omega_x^g \\ \omega_y^g \\ \omega_z^g \end{bmatrix} = \boldsymbol{C}_{bg} \begin{bmatrix} \omega_x^b \\ \omega_y^b \\ \omega_z^b \end{bmatrix} \tag{4}$$

We can calculate the included angle between the axis of limb movement of the subject and the horizontal plane $\left(x_g O y_g\right)$ as α by the following formula (5).

$$\alpha = \arcsin\left(\frac{\omega_z^g}{\sqrt{\left(\omega_x^g\right)^2 + \left(\omega_y^g\right)^2 + \left(\omega_z^g\right)^2}} \right) \tag{5}$$

The angular velocity direction of the limb in the ground coordinate system is the spatial direction of the rotation axis, so the included angle, which between the joint (e.g., knee joint and ankle joint) and the plane of each coordinate system, can be obtained according to the angular velocity component in the ground coordinate system. Moreover, the included angle is discrepant for different people in most cases. The data can be collected and analyzed to build the KMS.

In the second phase, the system development can be divided into four stages. Personalized parameters and KMS can be used to guide the personalized design, including ensuring the scope of angle in the experiment and forming the product and service design plans. It is conducive to obtain a positive rehabilitation effect and an active user experience.

In the last phase, the patient-generated physiological data and usage data can be collected to guide the adjustment of the angle or modules and analyze new user needs. Specifically, we can collect the force signal data from the force sensor to quantify the user performance [16] and obtain the usage data from the smartphone APP. The collected data was visualized to adjust the angle α and display in the interactive interface for users. Meanwhile, analyzing the feedback results also can be used in the design improvement and the KMS enrichment.

4. Case study

A personalized lower limb rehabilitation Smart PSS was described to explain the proposed approach below.

Phase 1: Research phase. Different patients would get individual lower limb movement trajectories and motion axis. Nokov 3D optical motion capture experiment equipment, environment, marker position of the participant, and the seeker interface are shown in Fig 2. Kinematics data will be obtained through Nokov 3D optical motion capture experiment to analyze the personalized lower limb motion axis of users. In other words, the experiment is to analyze the included angle between the rotation axis of the knee joint and the horizontal plane. The experiment task is to sit in a high seat, ensure that the leg is suspended. Meanwhile, the thigh is close to the seat, and the lower limb is regular to swing respectively and lift the right leg first.

Figure. 2 Experiment equipment, environment, participant, marker position, and the seeker interface.

After having trimmed incomplete motion capture data, we exported the kinematics data from the motion capture experiment and calculated the included angle between the axis of knee movement and the horizontal plane $\left(x_g O y_g\right)$ as α by the formula mentioned in the methodology of section 3 (5). The definition and 3D schematic diagram of angular velocity computing process, and the diagrammatic drawing of the α angle is illustrated in Fig.3. Two complete motion cycles are obtained, and the calculated results are shown in Fig. 4. The mean of α in these two cycles is about 4.6°. Different participants can be invited to conduct the abundant experiments in order to obtain the scope of α and build the KMS.

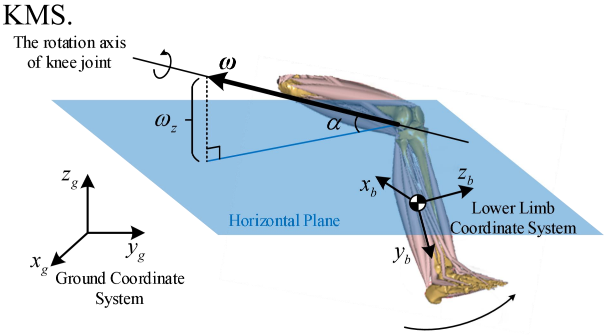

Figure. 3 Definition and 3D schematic diagram of angular velocity computing process, the diagrammatic drawing of the α angle.

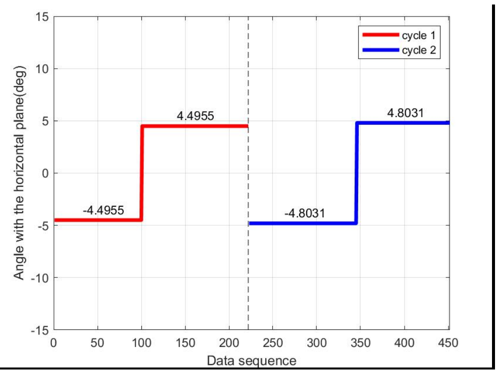

Figure. 4 The included angle between the axis of knee movement of the subject and the horizontal plane.

Phase 2: Development phase. Based on the combination of the KMS in the research stage and the rehabilitation requirements of users, we developed the design plan of a preliminary personalized lower limb rehabilitation product (Fig.5) and its e-service(Fig.6). The sensors mainly include a two-dimensional force sensor mounted on the knee joint to measure the contact force between the leg and the rehabilitation equipment, and a force sensor to measure the force between the soles of the feet and the rehabilitation equipment. The change of the user physiological data can be utilized to guide the personalized adjustment of the rehabilitation equipment [17]. Service design was developed to assist the lower limb rehabilitation instruments. According to the guidance in the smartphone interface, users could obtain the functional force data of their lower limb and learn how to adjust the included angle of the rehabilitation instruments.

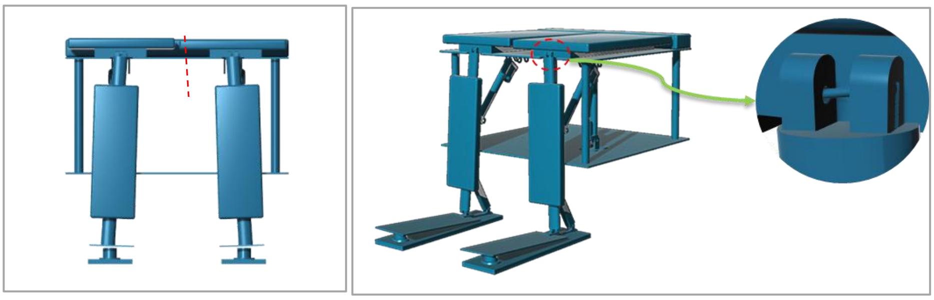

Figure. 5 Rehabilitation product plan.

Figure. 6 Smart service design interface.

Phase 3: Usage phase. The force sensors of rehabilitation devices will imultaneously update lower limb force signal synchronization by the Bluetooth module. The form of a line chart can show the force signal to the users in the heart of the service design for the fluctuation of the observation signal. When the force signal gradually stabilizes to a certain range and a little gap, the user can reduce the angle α of the rehabilitation equipment by 1° and continue the rehabilitation exercise. Moreover, the user can observe the changing trend of the mechanical signal after adjusting the angle synchronously. The usage data (e.g., click frequency and error operation rate) collected from the APP also can be utilized to explore the potential user requirements.

5. Conclusion

Smart PSS, an IT-driven business paradigm, is gradually affecting the sector of health care and medical manufacturing enterprises. This paper proposes an innovative design method to guide the Smart PSS development in the rehabilitation field and further satisfy user needs. The main contribution of this paper can be summarized below. (1) An innovative design method is proposed to guide the Smart PSS development in the rehabilitation field. (2) A personalized lower-extremity rehabilitation instrument service system was described to explain the proposed approach. However, some limitations still exist in this work. The establishment of the knowledge management system in the later stage also contributes to the further refinement and improvement of the product design. Further research on the data supporting Smart PSS upgrade needs to be conducted after subsequent development.

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