Design Method of a Smart Rehabilitation Product Service System Based on Virtual Scenarios: A Case Study

Lei Zhao, Yufei Zhao, Lingguo Bu, Haoran Sun, Wanzhi Tang, Kun Li,
Wei Zhang, Weizhong Tang, and Yu Zhang

***Abstract*—The development of artificial intelligence and virtual reality technology has enabled rehabilitation service systems based on virtual scenarios to provide patients with a multi-sensory simulation experience. However, the design methods of most rehabilitation service systems rarely consider the physician–manufacturer synergy in the patient rehabilitation process, as well as the problem of inaccurate quantitative evaluation of rehabilitation efficacy. Thus, this study proposes a design method for a smart rehabilitation product service system based on virtual scenarios. This method is important for upgrading the rehabilitation service system. First, the efficacy of rehabilitation for patients is quantitatively assessed using multimodal data. Then, an optimization mechanism for virtual training scenarios based on rehabilitation efficacy and a rehabilitation plan based on a knowledge graph are established. Finally, a design framework for a full-stage service system that meets user needs and enables physician–manufacturer collaboration is developed by adopting a "cloud-end-human" architecture. This study uses virtual driving for autistic children as a case study to validate the proposed framework and method. Experimental results show that the service system based on the proposed methods can construct an optimal virtual driving system and its rehabilitation program based on the evaluation results of patients' rehabilitation efficacy at the current stage. It also provides guidance for improving rehabilitation efficacy in the subsequent stages of rehabilitation services.**

***Index Terms*—Rehabilitation service system, virtual scenarios, smart rehabilitation products, multimodal data-driven.**

I. INTRODUCTION

THE advent of the Industry 4.0 era has promoted intelligent products and innovative services [1]. Smart rehabilitation products (SRPs), as a category of intelligent products, have innovatively developed in intelligent manufacturing, product optimization, and information digitization [2]. SRP plays a crucial role in helping special groups (e.g., autism, stroke, and Parkinson's disease) to recover, compensate, or rebuild their maximum possible function for achieving the best functional state. It aims to utilize the interconnection of three core elements, namely, physical parts, intelligent parts, and connecting parts, for circulating information among product manufacturers, users, and other permitted data access parties to strengthen their rehabilitation service functions. SRP has the potential to break through the limitations of physical devices, meet additional external scene requirements, and make rehabilitation services more comprehensive [3], [4]. For example, using the rehabilitation method based on virtual scenes enhances the rehabilitation effect and shortens the rehabilitation process [5]. Meanwhile, adding virtual scenarios to replace real ones allows users to meet their rehabilitation needs in virtual scenarios [6]. Virtual scenarios are closely related to technology and the product of the mobile Internet era [7]. In the virtual scene, not only can the real world environment be simulated, but also processes and perspectives that may not be achievable in the real world can be provided. In addition, the data collected by SRP based on virtual scenes can be used to create innovative services that add important value to improving the rehabilitation effect [8].

At present, the service direction of rehabilitation products is developing toward innovative service modes based on digital transformation. Intelligent wearable devices [9], biosensors [10], and interactive service platforms [11] generate data to ensure reliable operation and implementation of extensibility for rehabilitation products. The integration of digital information and Internet technology drives the upgrading of

Manuscript received 15 May 2023; revised 30 August 2023 and 11 October 2023; accepted 11 November 2023. Date of publication 15 November 2023; date of current version 21 November 2023. This work was supported in part by the National Natural Science Foundation of China under Grant 52205275; in part by the Natural Science Foundations of Shandong Province, China, under Grant ZR2021QE115, Grant ZR2022QE297, Grant ZR2020ME115, and Grant ZR2020QE299; and in part by the Fundamental Research Funds for the Central Universities under Grant 2021JCG012. *(Corresponding authors: Lei Zhao; Lingguo Bu.)*

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Human Ethics Committee of Shandong University, and performed in line with the Declaration of Helsinki.

Lei Zhao, Yufei Zhao, Haoran Sun, Kun Li, and Wei Zhang are with the School of Mechanical and Electronic Engineering, Shandong Jianzhu University, Jinan 250101, China (e-mail: leizhao1219@sdjzu.edu.cn).

Lingguo Bu is with the Joint SDU-NTU Centre for Artificial Intelligence Research (C-FAIR), Shandong University, Jinan 250100, China (e-mail: bulingguo@sdu.edu.cn).

Wanzhi Tang is with the Faculty of Arts, University of Alberta, Edmonton, AB T6G 2R3, Canada.

Weizhong Tang and Yu Zhang are with the Department of Weizhong Children's Rehabilitation Center, Jinan 250000, China.

Digital Object Identifier 10.1109/TNSRE.2023.3333049

the rehabilitation service system. Service innovation in the Internet era provides the foundation for the reorganization and distribution of resources [12]. Information technology increases customer stickiness, enhances customer experience, and provides a platform for data collection. Eventually, new service designs are iterated through the application of big data [13]. As a result, intelligent innovative services are created, which provide better rehabilitation services for patients and a brand new, ultra personalized rehabilitation experience by harnessing the power of data and digital technology.

Although existing intelligent rehabilitation product innovative services have greatly progressed, the rehabilitation service model is not comprehensive, and some challenges still exist.

1) Virtual scenario-based services are widely used. However, existing services based on virtual scenarios are primarily applied in industrial products [14] and educational platforms [15], with rare application in the field of rehabilitation products. Therefore, the design of SRP service systems based on virtual scenarios is necessary.
2) In some novel research approaches at present, the service performance evaluation method incorporates user feedback information [16], [17]. However, the source of user data acquisition is limited, and the user data are relatively simple and susceptible to human factors, environment influences, and other variables. This limitation reduces the objectivity of the method. Consequently, the evaluation results may be prone to errors. Therefore, user scenario interaction data, user physiological data, and user behavior data need to be considered from multiple perspectives to improve the accuracy of quantitative rehabilitation efficacy evaluation.
3) Currently, the rehabilitation service usually follows a single-service model and lacks a service strategy that fosters physician–manufacturer synergy [3], [18]. At the same time, existing medical services are not comprehensive, with limited rehabilitation efficacy assessment services for special groups [19]. Therefore, improving the smart rehabilitation service model is necessary.

This study proposes a design method for the SRP service system based on virtual scenarios to address the abovementioned problems and challenges. The working logic of the proposed method can be described as follows. First, the efficacy of rehabilitation for patients is quantitatively assessed using multimodal data. Then, an optimization mechanism for virtual training scenarios based on rehabilitation efficacy and a rehabilitation plan based on a knowledge graph are established. Finally, a design framework for a full-stage service system that meets user needs and enables physician–manufacturer collaboration is developed by adopting a “cloud-end-human” architecture. This study utilizes a virtual driving rehabilitation system for autistic children as a case study to verify the effectiveness of the proposed framework and method through experiments. The experimental results of rehabilitation efficacy evaluation show that the virtual driving system can effectively improve the cognitive and behavioral functions of autistic children. Based on the evaluation results at the current stage, the service system designed using the proposed method can optimize the virtual driving scenarios and their rehabilitation program, guide the subsequent stages of rehabilitation services, and enhance rehabilitation efficacy. The contributions of this study are as follows: 1) an overall design framework for the SRP service system based on virtual scenarios, which advances the upgrading of rehabilitation services to better align with user needs; 2) a multisource data-driven quantitative evaluation method of rehabilitation efficacy to address issues of inaccurate evaluation; 3) a rehabilitation service method based on the synergistic collaboration between physicians and manufacturers, which promotes the optimization of medical services and products through synergy; and 4) a case study involving a virtual driving system for a special population, which helps in accelerating the rehabilitation process.

The rest of the article is structured as follows. Section II provides a literature review. Section III introduces the overall architecture of the design method for the SRP service system based on virtual scenarios. Section IV presents a case study of a virtual driving system for autistic children. Sections V and VI provide the discussion and conclusion, respectively.

II. LITERATURE REVIEW

A. SRP Development

Most rehabilitation products at present focus on the development of intelligent rehabilitation robots. The two main categories of rehabilitation robots are end-effector and exoskeleton robots [20], [21]. The wearable exoskeleton robot, which is designed in accordance with ergonomics and bionic principles, is the current research hotspot in the field of intelligent rehabilitation robots. The exoskeleton robot is attached to the patient’s limbs, and its movement can be synchronized with those of the patient’s limbs to improve the effectiveness of rehabilitation training.

Current research is focused on developing wearable exoskeletons that can help individuals with lower limb paralysis in regaining the ability to walk. The ReWalk ReStore is a rehabilitation product that provides a new method for assisting patients with lower limb walking difficulties in clinical recovery, which allows them to walk more easily [22]. The Lokomat is a rehabilitation training robot that can adjust the gait of patients with neurological diseases, such as stroke, stroke, traumatic brain injury, and multiple sclerosis [23]. Recent developments in wearable exoskeletons have prompted researchers to investigate the use of exoskeleton robots with high flexibility to address issues related to inflexibility and discomfort [24]. Yang et al. studied soft wearable rehabilitation gloves and found that they can improve muscle function in patients’ hands while being lightweight [25]. Small and portable intelligent rehabilitation instruments are gaining popularity as mobile healthcare continues to evolve. Su et al. designed a rehabilitation training instrument that aids in the recovery of lower limb motor coordination [26]. This portable rehabilitation product not only improves patients’ enthusiasm for rehabilitation but also reduces the workload of rehabilitation therapists, which allows patients to actively participate in their treatment.

In the era of Industry 4.0, virtual reality technology is rapidly advancing; it is increasingly used in the field of rehabilitation, and its combination with rehabilitation robots has achieved enhanced rehabilitation outcomes [27]. Jahn et al. reviewed the potential of virtual reality in cognitive rehabilitation and found that it can assist patients in their cognitive rehabilitation journey [28]. Patsadu et al. found that autistic children expressed high satisfaction with virtual reality games [29]. Bartalucci et al. used a virtual reality-based exoskeleton design method and found that the equipment can provide an immersive experience of human interaction with virtual environment, which promotes patient rehabilitation [30]. These SRPs have rapidly developed and have been applied in rehabilitation training. However, rehabilitation products based on virtual technology are relatively few. Therefore, the untapped potential of rehabilitation products based on virtual scenarios must be further explored.

B. Development of Rehabilitation Product Service System

The continuous integration of science and technology and rehabilitation medicine in today's world has empowered SRP and services with enduring innovation potential [31]. The big data generated by the Internet of Things, artificial intelligence, and mobile rehabilitation contribute to the iterative refinement of the design of rehabilitation products and services, particularly within hospital, community, and family settings [32], [33], [34]. The user is the key element of the service system, with the design centered on meeting the service expectations of users; the existence of the rehabilitation needs of users drives the emergence of other factors [35], [36].

User-centric services driven by multimodal data fusion are a research hotspot at present. The core challenge in developing data-driven intelligent medical product service systems lies in efficiently utilizing the multitype data generated by various factors to play an important role in the medical domain [37]. Bu et al. proposed a data-based service innovation method that collects user-related multimodal data to inform services, which generated effective results [3]. Shihundla et al. developed an integrated product service system that incorporates data-driven services, including product self-maintenance, product information collection, and product health evaluation [38]. Negash et al. explored the application of digital health services in SRP and proposed a solution involving continuous digitization of products and services to improve resource utilization efficiency through data management between physicians and patients [39]. Izonin et al. introduced a data-driven approach that solves the challenge of medical professionals accurately and quickly diagnosing patients [18]. The intelligent rehabilitation service system is designed to provide flexible and efficient rehabilitation treatment. Chang et al. examined the role of rehabilitation service systems in medication management and reported that they serve as valuable aids [17]. Chae et al. investigated the upper limb rehabilitation system and discovered that the system effectively promotes patient rehabilitation while reducing rehabilitation costs [40].

The development of science and technology has facilitated the extensive study and application of virtual reality technology in rehabilitation services. Beani et al. used virtual reality technology to evaluate postural control in children and conducted tests through a postural control platform. The results showed that the virtual reality rehabilitation system is effective [41]. ?uk et al. estimated lower limb kinematic parameters through virtual reality technology, and the research results showed that this technology can realize low-cost evaluation [42]. Maggio et al. reviewed the application of virtual scenes in rehabilitation and found that they positively affect the rehabilitation treatment of patients [43]. Maggio et al. studied the effects of virtual scene-based rehabilitation, and their results showed that virtual technology is a valuable rehabilitation method [44]. However, the current rehabilitation service model lacks comprehensiveness. Therefore, the rehabilitation service system based on virtual scenarios should be improved to provide better services for patients.

C. Knowledge Gaps

As mentioned in Sections II-A and II-B, SRPs have rapidly developed through innovation with modern technology. However, the service innovation aspect of SRP is not fully developed, and intelligent rehabilitation services based on virtual scenarios, as well as services for special groups, are less common. Moreover, the upgrading of rehabilitation service systems rarely considers the synergistic collaboration between physicians and manufacturers in the rehabilitation process of patients and results in inaccurate evaluations of rehabilitation efficacy.

Therefore, this study proposes a design method for the SRP service system based on virtual scenarios. This method is crucial for upgrading the rehabilitation service system. First, the efficacy of rehabilitation for patients is quantitatively assessed using multimodal data. Then, an optimization mechanism for virtual training scenarios based on rehabilitation efficacy and a rehabilitation plan based on a knowledge graph are established. Finally, on the basis of the abovementioned components, a design framework for a full-stage service system that meets user needs and enables physician–manufacturer collaboration is developed by adopting a "cloud-end-human" architecture.

III. OVERALL ARCHITECTURE FOR SRP SERVICE SYSTEM

This study proposes an overall framework for the SRP service system design method based on virtual scenarios, as shown in Fig. 1. The design method and the process of the service system are introduced in detail, including virtual scene construction, interactive data collection based on virtual scenarios, cloud data analysis, and collaborative rehabilitation services between physicians and manufacturers.

A. Virtual Scenes Construction

Virtual scene construction involves configuring hardware and virtual technology, which is the foundation for creating service value. This study focuses on virtual scene modeling, with an emphasis on improving the user experience. Key areas of focus include technologies such as haptic feedback, voice prompts, motion capture, and direction tracking, all of which contribute to providing an authentic and immersive user experience. Meanwhile, by aligning the design requirements of rehabilitation games with the context of rehabilitation applications, the scenes are constructed to meet the training needs while ensuring compatibility with the rehabilitation goals and environment [45]. In addition, the design incorporates attractive and enjoyable elements to stimulate user interest and engagement. Sensing devices, such as the steering wheel, display, and handle of the virtual driving system, are the medium for users to interact with the virtual scene and

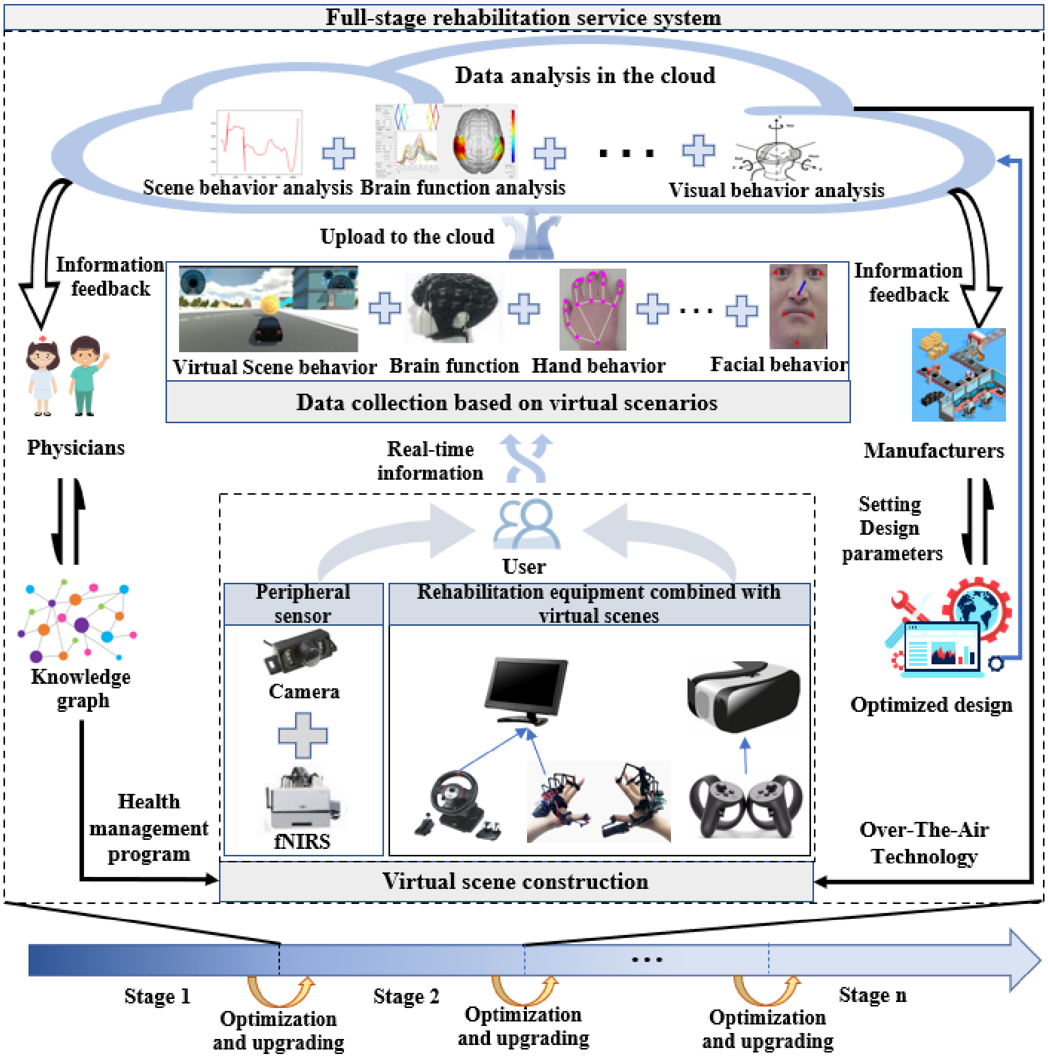

Fig. 1. Overall structure of the SRP service system based on virtual scenarios.

are configured within the physical environment. Peripheral sensors, such as fNIRS and behavior capture devices, are important tools for increasing data sources and effectively assisting users in the implementation of rehabilitation services.

B. Data Collection and Analysis Based on Virtual Scenarios

Data collection and analysis based on virtual scenarios are critical to the success of ultimate rehabilitation service. The collected virtual scene interaction data include user scenario interaction data, user physiological data, and user behavior data. User scenario interaction data, such as social guidance data, direction guidance data, and car speed in the scene, are read and saved by the built-in program of the virtual scene platform. User physiological data, such as cerebral oxygen signal and EEG signal, as well as user behavioral data, including facial expression, head posture, and body posture, can be collected through neuroimaging and visual sensors integrated into the virtual scene platform. The collected data are uploaded to the cloud for comprehensive data analysis, which includes brain science analysis technology and behavioral analysis methods. These techniques enhance the quality of virtual scene data. For example, brain science analysis uses methods such as high- and low-pass filtering, as well as first-order linear correction, to improve signal quality. Data analysis also employs the feature fusion method to study the internal rules between different types of features. For example, it integrates and analyzes brain science data and behavioral data to uncover the internal connections.

C. Rehabilitation Service Based on Virtual Scenarios

Full-stage rehabilitation service is a long-term, continuous, cyclical, and spiraling process of a comprehensive range of services. Evaluation of the effects and adjustments to intervention measures are necessary after their implementation. Data-enabled services can reflect the service of SRP throughout its entire life cycle [46]. Scenario-based interactive data services can better reflect users' needs in real-time dynamic interaction, which improves the rehabilitation effect. In this study, the full-stage rehabilitation service based on virtual scenarios comprises four key stages: 1) The rehabilitation effects of patients at the current stage are evaluated, which yields objective evaluation results based on multidimensional virtual scenario interactive data. Feedback is provided to physicians and manufacturers. 2) Physicians use the knowledge graph method for scientific management and formulate the subsequent steps of a health management program. 3) Manufacturers formulate the next steps of product optimization parameters, optimize the design, upload the upgrade package to the cloud, and use Over-The-Air (OTA) technology to update the scenario scheme. 4) Collaborative optimization between physicians and manufacturers forms the basis for continuous optimization and upgrades from the current stage to the next stage, which achieves a comprehensive rehabilitation service throughout the entire stage.

IV. CASE STUDY

In this section, a virtual driving system is developed to better illustrate the proposed architecture and method. The virtual driving environment is used as a complex multitask motivation source to organically combine the brain system and human movement control. The system effectively maintains the sustained attention of children by incorporating engaging cartoon-like virtual scenes. Simultaneously, the scene is designed to include social guidance, sound stimulation, and cognitive tasks to support the rehabilitation of children. The system collects user scene interaction data, user physiological data, and user behavior data. The high-quality information obtained through in-depth analysis of data is then used to guide subsequent rehabilitation services.

A. Construction of a Virtual Driving System

The advantages of modern virtual reality technology should be leveraged in constructing virtual scenes to ensure the relative authenticity of scene production, which enhances the user experience [7]. The virtual scene system needs to meet several requirements, such as realistic modeling and environment, the incorporation of manipulation modes that conform to reality, and the display of real effects within the scene. As shown in Fig. 2, the virtual driving system in this study is developed with these essential requirements in mind. The environment necessary for building the virtual driving system is completed through the environment plug-in in Unity3d. The primary environment components include terrain, vegetation, roads, cartoon-like buildings, decorations, and vehicles. For the driving scenarios, terrain is the foundation upon which various environments are constructed. The initial focus is on terrain design, following the design idea of an intuitive, concise, and cartoon-like terrain, which aligns with the characteristics and style of the driving scene while meeting the needs of young users. Surrounding buildings, car models, road signs, and other elements are then constructed. These models are arranged successively based on the scene use wizard to ensure the reliability and appeal of the scene.

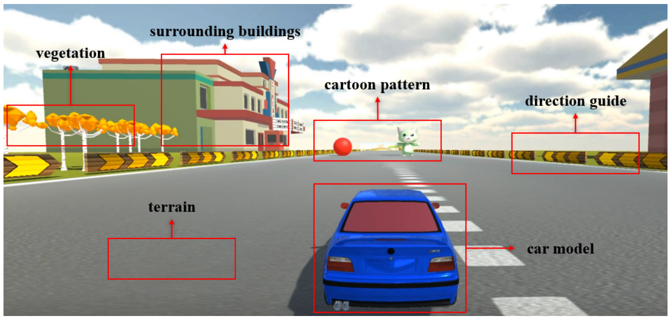

Fig. 2. Virtual scene construction to meet the needs of autistic children.

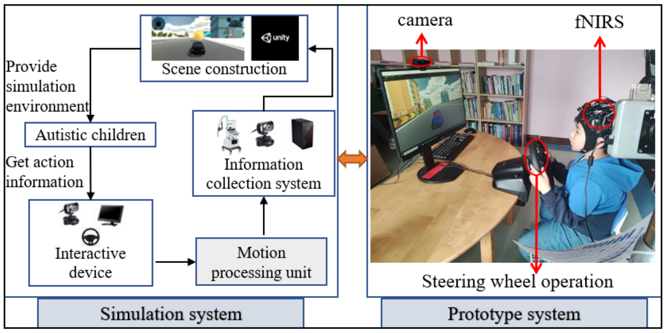

Fig. 3. System architecture of virtual driving system.

TABLE I
THE RELEVANT ASSESSMENT DATA OF PARTICIPANTS

Parameter	Low score group
Age* (years old)	6.5 ±1.5
Weight* (kg)	24.0±2.0
Sex (girl: boy)	1:11
Height* (cm)	122±5.0
Score of ABC	46±24.8

This virtual driving system integrates rehabilitation training functionality and data acquisition capabilities. As shown in Fig. 3, the system simulates a real driving scene, which enables users to complete rehabilitation training in an engaging manner. The system then uses a built-in program capable of reading and storing user scene interaction data, such as the angle of the steering wheel. Visual sensors and brain signal collectors are integrated into the system. The collected data, including scene interaction data, visual information, and brain signals, are processed, analyzed, and used as a basis for delivering innovative services.

B. Data Processing and Analysis

Data from 12 autistic children were collected in this experiment, and the details are provided in TABLE I. The experiment was conducted at the Weizhong Children's Rehabilitation Center in Jinan, Shandong Province. Participants were required to undergo the Autism Behavior Checklist, and their diagnosis was determined based on a score called ASD (or ASD tendency). All participants satisfied the following criteria: (a) no history of seizures, (b) normal limb motor function, (c). no abnormalities in brain function attributable to external factors, and (d) no mental retardation or other neurological disorders. Prior to the experiment, a therapist guided each child for 5 min according to the rules of virtual driving operations. All guardians granted their consent for participation and signed informed consent forms.

In this study, the virtual scene interactive data were collected and output through a combination of fNIRS, vision sensors, and Logitech G29 devices integrated with the virtual driving scene platform. The visual sensor collected head pose data,

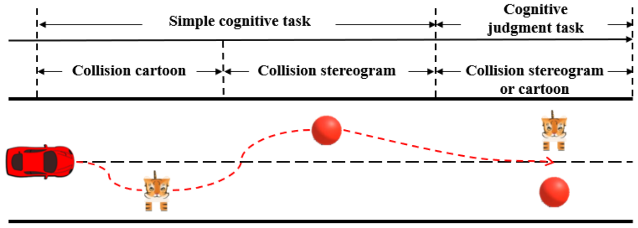

Fig. 4. Virtual driving system operation scene display.

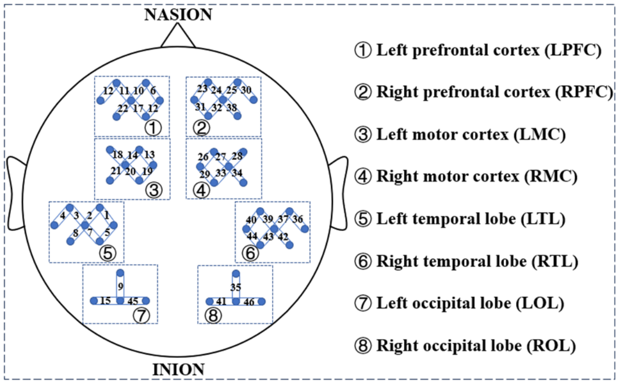

Fig. 5. Configuration of the measurement channels.

fNIRS collects brain oxygen data, and G29 recorded steering wheel operation information and target position during driving.

The experiment was divided into two states: the resting state (10 min) and the task state (5 min). During the experiment, the participants wore portable 46-channel near-infrared devices provided by Danyang Huichuang Medical Equipment Co., Ltd. The layout of the channels is shown in Fig. 5. Previous studies have demonstrated the reliability of this device [47], [48]. In the resting state, the participants remained stationary, and only brain oxygen data were collected. The task state was realized using a self-developed virtual driving training feedback system, with data collection including brain and behavioral data were collected. Participants controlled the target within the scene by controlling the steering wheel and completed cognitive tasks guided by spoken instructions. The task state consisted of two phases: the first phase, which lasted approximately 3 min, involved a simple cognitive task; the second phase, which lasted approximately 3 min, was a cognitive judgment task.

Voice prompts were provided to the participants throughout the task. In the first phase, participants encountered two different situations: car collisions with a cartoon image and car collisions with a 3D graphic. The second phase involved both images appearing simultaneously. Fig. 4 shows scene diagrams depicting the cognitive tasks in the first stage and the cognitive judgment tasks in the second stage.

The processing fNIRS data involved several steps. 1) Meaningless signals were removed using the Exclude function, which is a method for removing apparently abnormal fNIRS signals. 2) Gaussian noise was removed using the Motion function, which is a method based on moving standard deviation and spline interpolation [47]. 3) Machine noise and human breathing were filtered out using a high-pass signal of 0.01 Hz and a low-pass signal of 0.2 Hz. 4) Optical density values were converted to hemoglobin values. According to the modified Beer–Lambert law, the converted HbO (oxygenated hemoglobin) and HbR (deoxygenated hemoglobin) signals are as follows:

$$OD^{\lambda_i} = \ln \frac{I_{Oi}}{I_I} = \left(\varepsilon^{\lambda_i}_{Hbo} C_{HbO} + \varepsilon^{\lambda_i}_{HbR} C_{HbR}\right) \times r \times DPF^{\lambda_i} i = 1, 2, 3 \tag{1}$$

$$\Delta OD^{\lambda_i} = \left(\varepsilon^{\lambda_i}_{HbO} \Delta C_{HbO} + \varepsilon^{\lambda_i}_{HbR} \Delta C_{HbR}\right) \times r \times DPF^{\lambda_i} i = 1, 2, 3 \tag{2}$$

$$\begin{pmatrix} \Delta C_{HbO} \\ \Delta C_{HbR} \end{pmatrix} = \begin{pmatrix} \varepsilon^{\lambda_1}_{HbO} \varepsilon^{\lambda_1}_{HbR} \\ \varepsilon^{\lambda_2}_{HbO} \varepsilon^{\lambda_2}_{HbR} \\ \varepsilon^{\lambda_3}_{HbO} \varepsilon^{\lambda_3}_{HbR} \end{pmatrix}^{-1} \begin{pmatrix} \frac{\Delta OD^{\lambda_1} / (r \times DPF^{\lambda_1})}{\Delta OD^{\lambda_2} / (r \times DPF^{\lambda_2})} \\ \Delta OD^{\lambda_3} / (r \times DPF^{\lambda_3}) \end{pmatrix} \tag{3}$$

In the formula, ΔOD, r, ε, and DPF are the amount of change in light absorption, the linear distance between probes, the wavelength dependent extinction coefficient, and the effective length from the light source to the detector, respectively. ΔC_{HbO} is the relative concentration change of HbO. ΔC_{HbR} is the relative concentration change of HbR.

IBM SPSS was used for the feature fusion method. Through a correlation analysis of different movement characteristics and different brain regions, we could express the functional characteristics of brain-related regions when the human body is moving. The Pearson correlation coefficient was selected to analyze the correlation between brain science and behavioral data. The two variables are correlated if $p < 0.05$.

The visual sensor is used to collect head pose data, which are read by running the program and positioning the sensor above the display. In this study, the screen area is considered the key content of visual interaction data processing because children can be susceptible to interferences from other non-rehabilitation training systems during operation. The display device has a size of 23.6 inches, with a transverse dimension x of 52.3 cm and a longitudinal dimension y of 29.4 cm. Given that children maintain a level line of sight with the display plane during operation, the head posture in the direction of yaw is extracted as the focus of this visual interaction processing. In the Unity3d system, the addition of a camera to the vehicle ensures that the center point of the vehicle consistently aligns with the center of the screen, regardless of the game target's position during gameplay. During forward driving, the steering angle of the vehicle is within the range of $(0°, 90°)$. Consequently, a 45° angle is taken to represent the average position of the vehicle. In this 45° posture, the lateral length x_c of the vehicle is approximately 20 cm. Children with autism were positioned horizontally in front of the screen while operating the virtual driving rehabilitation training system, with a vertical distance d of 50 cm. Considering the back-and-forth movement of the head during the child's operation, the line of sight of the screen area (los) was estimated using the right triangle arctangent formula and the radian angle transformation formula.

$$los = \pm arctan(\frac{180x}{2\pi d}) \tag{4}$$

Children's visual range in the screen area was calculated as $(-28°, 28°)$. Similarly, the line of sight directed toward the car $(losc)$ was estimated, which resulted in a focus area of $(-12°, 12°)$ for children when steering the vehicle.

$$losc = \pm arctan(\frac{180x_c}{2\pi d}) \tag{5}$$

The SDK provided by the Logitech G29 device was programmed to obtain real-time steering wheel angle and coordinate position information while the vehicle is in motion. The steering wheel can rotate in clockwise and counterclockwise directions, with a maximum angle of 450° in each direction. When converting these angles into standard units, the angle conversion rate defined by the built-in SDK is 32,768. The unit of output time is minutes. The rotation angle of the entire steering wheel is $[\theta_1, \theta_1, \theta_3 \ldots\ldots \theta_n]$, with corresponding times denoted as $[t_1, t_1, t_3 \ldots\ldots t_n]$. The formula for calculating the steering wheel speed $\omega_i (i = 1, 2, 3 \ldots n)$ is as follows:

$$\omega_i = \frac{\theta_i - \theta_{i-1}}{60t_i} \times \frac{32768}{450} \tag{6}$$

Therefore, the speed of the steering wheel throughout the entire process is $[\omega_1, \omega_2, \omega_3 \ldots\ldots \omega_n]$, and the average velocity ω_m of the entire process is determined using the following formula.

$$\omega_m = \frac{\sum_1^n \omega_i}{n} \tag{7}$$

The speed standard deviation ω_{std} is computed using the following formula.

$$\omega_{std} = \sqrt{\frac{\sum_1^n (\omega_i - \omega_m)^2}{n-1}} \tag{8}$$

C. Rehabilitation Service Based on Virtual Driving Scenarios

1) Results of Rehabilitation Evaluation at the Current Phase:

The PERCLOS algorithm is extended to count the number of frames in different lines of sight areas during virtual driving. Children's attention status can be obtained by setting thresholds. The ratio of the total number of frames in the target area of the car over a specific period to the total number of frames within the screen area over the same period was used to indicate a child's level of concentration. Data from 12 children were analyzed, as shown in Fig. 6. The results show that the ratio is greater than 0.7 for 8 children. Meanwhile, conversations with rehabilitation therapists reveal that children with autism perform well when they spend more than half their time on screens. Consequently, virtual driving appears to capture the attention of children with autism.

The t-test was used to analyze the activation of brain channels in the task and rest states. Under the condition of colliding cartoon images in the first stage, channels 18 $(t = 2.576, p = 0.026)$, 19 $(t = -3.426, p = 0.006)$, 22 $(t = -3.095, p = 0.010)$, 28 $(t = -2.777, p = 0.018)$, 34 $(t = -6.297, p = 0.000)$, and 44 $(t = 2.702, p = 0.021)$ are significantly activated. Under the condition of collision with stereogram in the first stage, channels 17 $(t = 2.383, p = 0.036)$, 18 $(t = 2.433, p = 0.033)$, 19 $(t = -4.195, p = 0.001)$, 20 $(t = 2.861, p = 0.015)$, 28 $(t = -2.486, p = 0.030)$, 34 $(t = -9.371, p = 0.000)$, and 38 $(t = 3.025, p = 0.012)$ are significantly activated. In the second stage judgment task, channels 18 $(t = 4.643, p = 0.001)$, 19 $(t = -2.512, p = 0.029)$, 28 $(t = -2.469, p = 0.031)$, 34 $(t = -5.397, p = 0.000)$, and 38 $(t = 2.967, p = 0.013)$ are significantly activated. Throughout the entire duration of the task, channels 11 $(t = 2.390, p = 0.036)$, 18 $(t = 3.481, p = 0.005)$, 19 $(t = -3.273, p = 0.007)$, 20 $(t = 2.602, p = 0.025)$, 22 $(t = -2.349, p = 0.039)$, and 34 $(t = -5.726, p = 0.000)$ are significantly activated. The visualization results are presented in Fig. 7. Panel A compares the activation of brain regions during task and resting states when colliding with cartoon images in the first stage. Panel B compares the activation of brain regions during the task and resting states when colliding with stereograms in the first stage. Panel C shows the comparison of brain region activation during the task and resting states in the second stage of the judgment task. Panel D presents the comparison between the activation in the task and resting states in the entire task process. The results show that the activated channels are primarily distributed in (LPFC/RPFC) and (LMC/RMC). Among them, the highest number of channels are activated under the condition of colliding with stereograms in the first stage, which suggests that stereograms are more effective in activating children's brain. In the second stage judgment task, channel activation is lower, which implies that task difficulty affects children's brain activation.

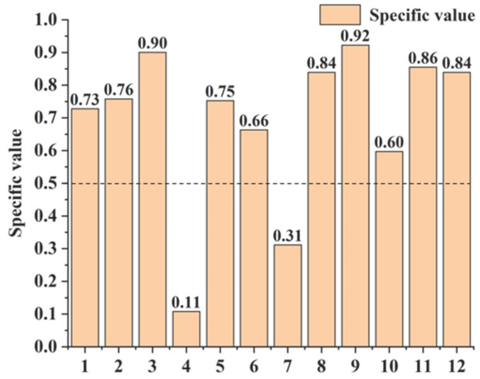

Fig. 6. Concentration statistics of autism children.

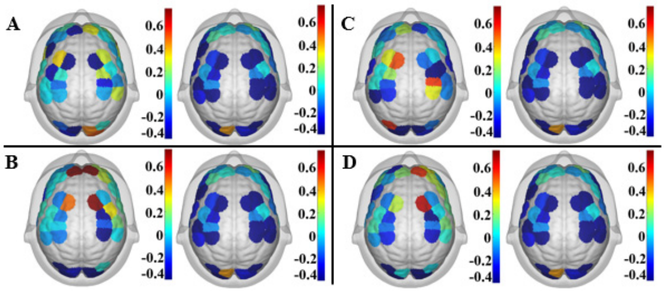

Fig. 7. Activation diagram of brain channels.

The Pearson correlation analysis was used to examine the relationship between the interactive data of the task scenario

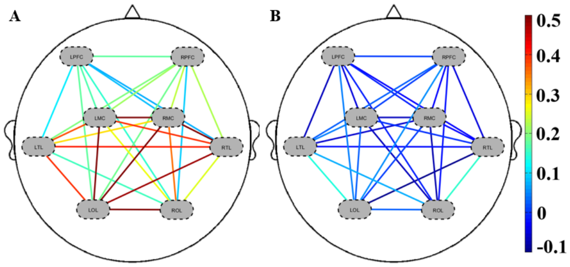

Fig. 8. Functional connectivity of brain regions.

(steering wheel speed ω and standard deviation ω_{std}) and the activation of brain regions. The correlation results are as follows: LMC-ω ($r = -0.585$, $p = 0.046$) and LMC-ω_{std} ($r = -0.660$, $p = 0.020$). Brain activation is negatively correlated with the steering wheel speed and speed standard deviation, which suggests that a smaller steering wheel speed and standard deviation result in a higher degree of brain region activation. In simpler terms, smoother vehicle handling during virtual driving corresponds to better brain region activation. These findings show that interaction behavior in virtual scenes has a strong correlation with brain activation, which indicates that virtual scenes are conducive to brain activation.

Pearson correlation was utilized to analyze the relationship between brain regions throughout the entire task. The brain regions with strong correlations from the analysis are listed as follows: RMC-LMC ($r = 0.740$, $p = 0.006$), RMC-RTL ($r = 0.806$, $p = 0.002$), RMC-ROL ($r = 0.794$, $p = 0.002$), and RTL-ROL ($r = 0.633$, $p = 0.027$). The visualization results are shown in Fig. 8, where A represents the task state and B represents the resting state. The results show that speech cues systematically applied throughout the task enhance the connections between the occipital and temporal lobes of the brain and the motor cortex.

2) Optimization and Upgrading of Scenario Schemes: The design variables of intelligent rehabilitation products directly affect the efficacy of rehabilitation products. The mapping relationship between the design variables of rehabilitation products and their efficacy remains unclear. On the basis of the evaluation results of rehabilitation efficacy, this study provides scenario-related optimization schemes for key design variables. These strategies bridge the information gap between manufacturers and rehabilitation efficacy. Manufacturers then optimize, enrich, and improve the scenario scheme based on the evaluation results presented in Section C.1). Fig. 9 shows an example of the optimization design for rehabilitation products intended for autistic children using the virtual driving system. The refined rehabilitation needs of children with autism, as per the evaluation results, provide manufacturers with ideas for product design improvements. An upgrade package for the scenario plan is designed and produced by the manufacturer, which can be remotely upgraded through OTA technology to better meet the comprehensive rehabilitation needs of autistic children. Drawing from the evaluation results presented in Section C.1), the following observations are made. (1) In the first stage, a greater number of channels are activated during collisions with stereograms, which indicates that stereograms are more favorable to activating children's brain. (2) In the second stage judgment task, channel activation is less, which implies that task difficulty affects children's brain activation. (3) Systematic voice cues applied throughout the task enhance the connections between the occipital and temporal lobes of the brain and the motor cortex. Based on the abovementioned experimental results, the system design requirements are mapped as follows: (1) In the virtual driving scenario, more 3D graphics should be applied on the roads when children with autism drive the car to find the target. (2) When setting the task difficulty levels in the scene, children's ability should be considered and the difficulty levels should be reasonably divided. (3) When autistic children are driving, constant voice prompts should be provided and directions on the road should be more intuitive.

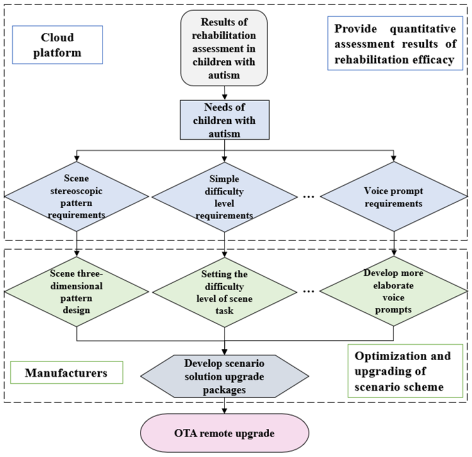

Fig. 9. The process of optimizing and upgrading scenario scheme.

3) Rehabilitation Program Based on Knowledge Graph: The knowledge graph method is used to develop rehabilitation programs that utilize an abundant knowledge and data pool, which provide a robust foundation for their development. The virtual driving system for autistic children, an shown in Fig. 10, serves as an example. A health management plan for autistic children is developed based on the evaluation results and rehabilitation knowledge. The evaluation results in Section C.1) highlight brain functional connections mainly distributed in RMC-LMC, RMC-RTL, RMC-ROL, and RTL-ROL, the prevalence of brain activation channels in areas like (LPFC/RPFC) and (LMC/RMC), and the capacity of virtual driving to capture children's attention. On the basis of these findings, a health management graph is developed. This graph centers around children and interconnects physicians and autistic children. Physicians link diagnosis results, including brain functional connections and brain region activation, with virtual driving rehabilitation knowledge, guidance, consultation, learning, and sharing. Children with autism are linked to virtual driving rehabilitation training and healthy consciousness. This scheme meets the needs of rehabilitation programs for children with autism by utilizing evaluation results and health knowledge. Knowledge graph-based rehabilitation programs can provide health management and knowledge dissemination for autistic children. For example, these programs can be developed to increase training frequency based on brain functional connections and brain region activation. Simultaneously, they can guide subsequent phases of rehabilitative services to enhance the efficacy of rehabilitation.

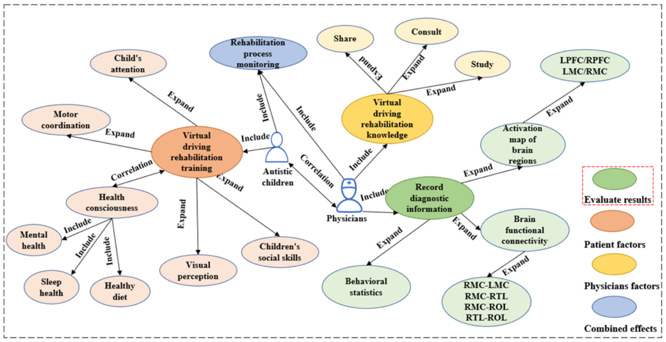

Fig. 10. Rehabilitation program based on knowledge graph.

V. DISCUSSION

The SRP service system based on virtual scenarios prioritizes users and collects user scenario interaction data, user physiological data, and user behavior data. These data sources contribute to the establishment of comprehensive and reliable evaluation standards for innovative services. The synergistic collaboration between physicians and manufacturers in the entire patient rehabilitation process jointly promotes the rehabilitation journey of users and continuously improves the quality of service. In the case study of the virtual driving system, the results indicate that the designed service system can construct the optimal virtual driving system and its rehabilitation program based on the evaluation of rehabilitation efficacy at the current stage. Furthermore, it provides guidance for the subsequent stages of rehabilitation services to improve rehabilitation efficacy.

Compared with traditional methods, this method enables physicians and manufacturers to create knowledge graph-based rehabilitation plans and optimization schemes for virtual scenario-based product designs based on the evaluation results of patients' rehabilitation efficacy. In addition, it offers guidance for the subsequent stages of rehabilitation services. The method promotes cooperation between medical institutions and manufacturers, realizes the collaborative optimization of medical services and products, and improves the effectiveness of rehabilitation.

This study uses a data-driven approach to enhance rehabilitation services, but some limitations in the data collection and analysis process remain. For example, obtaining a sufficient quantity of data is difficult due to experimental constraints. With a small sample size, the research method may lack the extensive support of large datasets. In the fusion analysis of brain and behavioral data, establishing effective correlations between brain science and behavioral data is also a potential challenge.

The following issues should be considered to continuously improve the quality of rehabilitation services. The service scope should be expanded to special user groups and be integrated into their daily lives. The daily behavior monitoring system should be improved also needs to be enhanced to expand the range of data collection. In addition, advanced multimodal data analysis methods could be explored to provide high-quality health services and design more suitable rehabilitation products through in-depth data mining of user data and a thorough understanding of user needs.

VI. CONCLUSION

The advent of Industry 4.0 has facilitated the widespread deployment and utilization of intelligent terminals, sensors, and other equipment for effectively collecting a large amount of data resources. Compared with traditional rehabilitation services, smart rehabilitation services offer objective, quantitative, and efficient advantages. This study presents a design method for an SRP service system based on virtual scenarios. This method realizes the design of a data-driven service system for SRP by collecting, processing, and analyzing multimodal data to cater to the diverse health needs of users and promote all-round healthy development. In this study, the SRP service system based on virtual scenarios serves as the research framework, and virtual driving for autistic children is chosen as the research object. The main contributions of this study are as follows:

1) This study proposes an overall design architecture for the SRP service system based on virtual scenarios. It integrates scene building, data collection, data analysis, and innovative services. This way enhances the service mode of SRP and promotes the intelligent development of SRP services.
2) A multisource data-driven quantitative evaluation method for rehabilitation efficacy is proposed. This method improves the accuracy of quantitative rehabilitation efficacy evaluation through comprehensive multimodal data analysis.
3) A method of rehabilitation services based on the synergistic collaboration between physicians and manufacturers is proposed. This method helps physicians and manufacturers create knowledge graph-based rehabilitation plans and optimization schemes for virtual scenario-based product designs based on the evaluation results of patients' rehabilitation efficacy. It also provides guidance for the subsequent stages of rehabilitation services.
4) A case study is conducted on a virtual driving system for autistic children. Scene interaction data, physiological data, and behavioral data of autistic children are analyzed from multiple perspectives. The rehabilitation effect of autistic children is evaluated, and the proposed service system framework is verified.

REFERENCES

[1] S. Aheleroff, N. Mostashiri, X. Xu, and R. Y. Zhong, "Mass personalisation as a service in industry 4.0: A resilient response case study," *Adv. Eng. Informat.*, vol. 50, Oct. 2021, Art. no. 101438.

[2] F. F. Rad et al., "Industry 4.0 and supply chain performance: A systematic literature review of the benefits, challenges, and critical success factors of 11 core technologies," *Ind. Marketing Manage.*, vol. 105, pp. 268–293, Aug. 2022.

[3] L. Bu, C.-H. Chen, G. Zhang, B. Liu, G. Dong, and X. Yuan, "A hybrid intelligence approach for sustainable service innovation of smart and connected product: A case study," *Adv. Eng. Informat.*, vol. 46, Oct. 2020, Art. no. 101163.

[4] O. Postolache, D. J. Hemanth, R. Alexandre, D. Gupta, O. Geman, and A. Khanna, "Remote monitoring of physical rehabilitation of stroke patients using IoT and virtual reality," *IEEE J. Sel. Areas Commun.*, vol. 39, no. 2, pp. 562–573, Feb. 2021.

[5] M. G. Maggio et al., "The growing use of virtual reality in cognitive rehabilitation: Fact, fake or vision? A scoping review," *J. Nat. Med. Assoc.*, vol. 111, no. 4, pp. 457–463, Aug. 2019.

[6] H.-W. Liang, S.-Y. Chi, B.-Y. Chen, and Y.-H. Hwang, "Reliability and validity of a virtual reality-based system for evaluating postural stability," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 29, pp. 85–91, 2021.

[7] C. Huang, W. Zhang, and L. Xue, "Virtual reality scene modeling in the context of Internet of Things," *Alexandria Eng. J.*, vol. 61, no. 8, pp. 5949–5958, Aug. 2022.

[8] L. Bu, C.-H. Chen, K. K. H. Ng, P. Zheng, G. Dong, and H. Liu, "A user-centric design approach for smart product-service systems using virtual reality: A case study," *J. Cleaner Prod.*, vol. 280, Jan. 2021, Art. no. 124413.

[9] B. Noronha et al., "Soft, lightweight wearable robots to support the upper limb in activities of daily living: A feasibility study on chronic stroke patients," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 30, pp. 1401–1411, 2022.

[10] E. R. Kim, C. Joe, R. J. Mitchell, and M. B. Gu, "Biosensors for healthcare: Current and future perspectives," *Trends Biotechnol.*, vol. 41, no. 3, pp. 374–395, Mar. 2023.

[11] B. Lu, L. Yan, and Z. Chen, "Perceived values, platform attachment and repurchase intention in on-demand service platforms: A cognition-affection-conation perspective," *J. Retailing Consum. Services*, vol. 67, Jul. 2022, Art. no. 103024.

[12] X. Zhang and X. Ming, "Comprehensive understanding of smart product service system from multi-dimension and multi-perspective: An innovative service model for customer-product interaction life cycle (CILC)," *Adv. Eng. Informat.*, vol. 52, Apr. 2022, Art. no. 101619.

[13] S. Lokesh, S. Chakraborty, R. Pulugu, S. Mittal, D. Pulugu, and R. Muruganantham, "AI-based big data analytics model for medical applications," *Meas., Sensors*, vol. 24, Dec. 2022, Art. no. 100534.

[14] Z. Guo et al., "Applications of virtual reality in maintenance during the industrial product lifecycle: A systematic review," *J. Manuf. Syst.*, vol. 56, pp. 525–538, Jul. 2020.

[15] J. L. Yao and W. H. Hu, "Research on educational content service platform based on virtual reality technology," in *Proc. Int. Conf. Big Data Artif. Intell.*, 2019, pp. 35–39.

[16] H. L. Nguyen, K. Tran, P. L. N. Doan, and T. Nguyen, "Demand for mobile health in developing countries during COVID-19: Vietnamese's perspectives from different age groups and health conditions," *Patient Preference Adherence*, vol. 16, pp. 265–284, Feb. 2022.

[17] D. Chang, Z. Gu, F. Li, and R. Jiang, "A user-centric smart product-service system development approach: A case study on medication management for the elderly," *Adv. Eng. Informat.*, vol. 42, Oct. 2019, Art. no. 100979.

[18] I. Izonin, H. Kutucu, and K. K. Singh, "Smart systems and data-driven services in healthcare," *Comput. Biol. Med.*, vol. 158, May 2023, Art. no. 106074.

[19] S. An, C. K. Chan, and B. Kaukenova, "Families in transition: Parental perspectives of support and services for children with autism in Kazakhstan," *Int. J. Disability, Develop. Educ.*, vol. 67, no. 1, pp. 28–44, Jan. 2020.

[20] H. M. Qassim and W. Z. Wan Hasan, "A review on upper limb rehabilitation robots," *Appl. Sci.*, vol. 10, no. 19, p. 6976, Oct. 2020.

[21] J. Zhou, S. Yang, and Q. Xue, "Lower limb rehabilitation exoskeleton robot: A review," *Adv. Mech. Eng.*, vol. 13, no. 4, Apr. 2021, Art. no. 168781402110118.

[22] L. N. Awad, A. Esquenazi, G. E. Francisco, K. J. Nolan, and A. Jayaraman, "The ReWalk ReStore$^{\text{TM}}$ soft robotic exosuit: A multi-site clinical trial of the safety, reliability, and feasibility of exosuit-augmented post-stroke gait rehabilitation," *J. NeuroEng. Rehabil.*, vol. 17, no. 1, pp. 1–11, Dec. 18, 2020.

[23] F. Baronchelli, C. Zucchella, M. Serrao, D. Intiso, and M. Bartolo, "The effect of robotic assisted gait training with Lokomat® on balance control after stroke: Systematic review and meta-analysis," *Frontiers Neurol.*, vol. 12, Jul. 2021, Art. no. 661815.

[24] L. Xing, M. Wang, J. Zhang, X. Chen, and X. Ye, "A survey on flexible exoskeleton robot," in *Proc. IEEE 4th Inf. Technol., Netw., Electron. Autom. Control Conf. (ITNEC)*, vol. 1, Jun. 2020, pp. 170–174.

[25] J. Yang, D. Kim, J. Yoon, J. Kim, and D. Yun, "Ring-pull type soft wearable robotic glove for hand strength assistance," *IEEE Robot. Autom. Lett.*, vol. 7, no. 4, pp. 11378–11385, Oct. 2022.

[26] Y. Su and L. Su, "Intelligent medical rehabilitation training instrument based on movement coordination," *IEEE Access*, vol. 8, pp. 73373–73387, 2020.

[27] L. Lhotska, "Application of industry 4.0 concept to health care," in *Proc. 17th Int. Conf. Wearable Micro Nano Technol. Personalized Health*, in Studies in Health Technology and Informatics, 2020, pp. 23–37.

[28] F. S. Jahn, M. Skovbye, K. Obenhausen, A. E. Jespersen, and K. W. Miskowiak, "Cognitive training with fully immersive virtual reality in patients with neurological and psychiatric disorders: A systematic review of randomized controlled trials," *Psychiatry Res.*, vol. 300, Jun. 2021, Art. no. 113928.

[29] O. Patsadu, Y. Muchchimwong, and N. J. I. T. J. Narudkun, "The development of game to develop the cognitive skill for autistic children via virtual reality," *Inf. Technol. J.*, vol. 15, no. 2, pp. 12–22, 2019.

[30] L. Bartalucci et al., "An original mechatronic design of a kinaesthetic hand exoskeleton for virtual reality-based applications," *Mechatronics*, vol. 90, Apr. 2023, Art. no. 102947.

[31] A. Kumar, V. Mani, V. Jain, H. Gupta, and V. G. Venkatesh, "Managing healthcare supply chain through artificial intelligence (AI): A study of critical success factors," *Comput. Ind. Eng.*, vol. 175, Jan. 2023, Art. no. 108815.

[32] X. Zhao et al., "Intelligent city intelligent medical sharing technology based on Internet of Things technology," *Future Gener. Comput. Syst.*, vol. 111, pp. 226–233, Oct. 2020.

[33] T. L. Dai and S. Tayur, "Designing AI-augmented healthcare delivery systems for physician buy-in and patient acceptance," *Prod. Oper. Manage.*, vol. 31, no. 12, pp. 4443–4451, Dec. 2022.

[34] R. Nussbaum, C. Kelly, E. Quinby, A. Mac, B. Parmanto, and B. E. Dicianno, "Systematic review of mobile health applications in rehabilitation," *Arch. Phys. Med. Rehabil.*, vol. 100, no. 1, pp. 115–127, Jan. 2019.

[35] I. Krzeminska, "Personalizing smart services based on data-driven personality of user," in *Proc. OTM*, 2020, pp. 199–203.

[36] J. Cong, C.-H. Chen, X. Meng, Z. Xiang, and L. Dong, "Conceptual design of a user-centric smart product-service system using self-organizing map," *Adv. Eng. Informat.*, vol. 55, Jan. 2023, Art. no. 101857.

[37] A. Carrera-Rivera, F. Larrinaga, and G. Lasa, "Context-awareness for the design of smart-product service systems: Literature review," *Comput. Ind.*, vol. 142, Nov. 2022, Art. no. 103730.

[38] T. B. Shihundla, K. Mpofu, and O. T. Adenuga, "Integrating product-service systems into the manufacturing industry: Industry 4.0 perspectives," in *Proc. 11th CIRP Conf. Ind. Product-Service Syst.*, 2019, pp. 8–13.

[39] Y. T. Negash and L. S. C. Sarmiento, "Smart product-service systems in the healthcare industry: Intelligent connected products and stakeholder communication drive digital health service adoption," *Heliyon*, vol. 9, no. 2, Feb. 2023, Art. no. e13137.

[40] S. H. Chae, Y. Kim, K.-S. Lee, and H.-S. Park, "Development and clinical evaluation of a web-based upper limb home rehabilitation system using a smartwatch and machine learning model for chronic stroke survivors: Prospective comparative study," *JMIR mHealth uHealth*, vol. 8, no. 7, Jul. 2020, Art. no. e17216.

[41] E. Beani et al., "Application of virtual reality rehabilitation system for the assessment of postural control while standing in typical children and peers with neurodevelopmental disorders," *Gait Posture*, vol. 92, pp. 364–370, Feb. 2022.

[42] M. Żuk, M. Wojtków, M. Popek, J. Mazur, and K. Bulińska, "Three-dimensional gait analysis using a virtual reality tracking system," *Measurement*, vol. 188, Jan. 2022, Art. no. 110627.

[43] M. G. Maggio et al., "Virtual reality in multiple sclerosis rehabilitation: A review on cognitive and motor outcomes," *J. Clin. Neurosci.*, vol. 65, pp. 106–111, Jul. 2019.

[44] M. G. Maggio et al., "Virtual reality and cognitive rehabilitation in people with stroke: An overview," *J. Neurosci. Nursing*, vol. 51, no. 2, pp. 101–105, 2019.

[45] S. Al-Rayes et al., "Gaming elements, applications, and challenges of gamification in healthcare," *Informat. Med. Unlocked*, vol. 31, Oct. 2022, Art. no. 100974.

[46] P. Zheng, T.-J. Lin, C.-H. Chen, and X. Xu, "A systematic design approach for service innovation of smart product-service systems," *J. Cleaner Prod.*, vol. 201, pp. 657–667, Nov. 2018.

[47] L. Bu, C. Huo, Y. Qin, G. Xu, Y. Wang, and Z. Li, "Effective connectivity in subjects with mild cognitive impairment as assessed using functional near-infrared spectroscopy," *Amer. J. Phys. Med. Rehabil.*, vol. 98, no. 6, pp. 438–445, 2019.

[48] L. Zhao et al., "A multimodal data driven rehabilitation strategy auxiliary feedback method: A case study," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 30, pp. 1181–1190, 2022.