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A user-centric design approach for smart product-service systems using virtual reality: a case study

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Highlights

- A user-centric framework for the value-added design of smart PSS using VR is proposed.
- The case of a smart VR rowing machine is illustrated to verify the effectiveness of the design methodology.
- Objective physiological data of the users are used to evaluate user experience.
- User-generated and system-generated data can further support the solution design and improve user experience.

Abstract

Virtual reality (VR) has been applied in many different sectors, including manufacturing and engineering industries as well as in the healthcare industry where VR-equipped health products can provide better prevention, rehabilitation, and palliative care in a user-friendly environment. The smart product-service system (PSS) aims to achieve better user experience and higher user satisfaction. Limited research has been conducted on the benefits of leveraging advanced VR systems in a sustainable smart PSS via analysis of human factors. Moreover, existing VR research lacks the systematic methods that fully consider user performance and experience in a smart manner. This study aims to outline a conceptual approach for user-centric development of value-added smart PSSs based on VR, and to develop a case study with a smart VR rowing machine to illustrate the proposed approach and to verify its feasibility and effectiveness. After the VR platform is created, user-generated and VR system-generated data are collected and processed. The value-added services of VR-assisted user experience and real-time data feedback can be achieved. The results of this ergonomic experiment were determined by jointly considering the user-generated and VR system-generated data. They showed that the developed smart VR rowing machine significantly enhanced the user experience. The value-added services of VR-assisted user experience and real-time data feedback have been achieved. Theoretically, the proposed conceptual framework for a VR-assisted, user-centric, smart PSS provides an approach of specific data-driven and value-added services compared to traditional methods since it simultaneously considers user-generated and VR system-generated data. In the practical smart PSS design of VR products, this paper contributes to the design methodology of VR products and value-added services to obtain more accurate and objective user experience. It is hoped that this study can offer insightful guidance to enterprises that are involved in the process of creating the value-added design and service based on VR.

Keywords

Virtual reality; User-centric design; Smart product-service systems; Value-added services; User experience

1. Introduction

Virtual reality (VR) is a computer-based technology that can model and generate a multisensory simulated environment (Seth et al., 2011), which provides users with the immersive and interactive simulation through visual, auditory, tactile, and other forms of sensory connection (Knierim et al., 2017). Immersion, interaction, and imagination are the three characteristics of a VR system (Hu et al., 2016). VR technology can provide complex value-added services by integrating computing resources and communication services (Chandra et al., 2001). This technology has been implemented as a fusion between manufacturing and information technology (IT) (Choi et al., 2015). Healthcare products that are assisted by VR technology can offer patients with better prevention, rehabilitation, and palliative care services in a smart, connected and sustainable (SCS) environment. Previous studies mostly studied VR products from the perspective of technological innovation. Few studies have evaluated the service innovation of VR products from the perspective of user experience.

The development of new technology has triggered a broad market for smart, connected products (SCPs) (Kim et al., 2019). In addition to hardware factors, the personalized content of products is also one of the key influencing factors for SCPs in obtaining a good experience and creating user value (Zhong and Ge, 2018). Due to the market being highly competitive, enterprises are striving to achieve better user service profitability and sustainable strategies by providing personalized value-added services (Zheng et al., 2018a). The value proposition of servitization in SCPs is known as a product-service system (PSS) (Tukker and Tischner, 2006) or an Internet of things (IoT)-enabled PSS. A PSS integrates products and services into a single solution bundle to meet customer needs and create sustainability (Kim et al., 2016). An IoT-enabled PSS is facilitated by the connectivity of multiple mobile devices, which uses sensors to acquire and process large amounts of data for value-added services (Zheng et al., 2019). A smart PSS typically refers to the integration of smart products and e-Services into single solution bundles that are delivered to the market in order to satisfy the needs of individual consumers. It can iteratively update the product design after processing the collected data. A smart PSS that considers the user satisfaction in the product design stage can improve the perceived value of the product, extend the life cycle of the product, and thus enhance the sustainability of the product life-cycle management (Chang et al., 2019; González-Pérez et al., 2017). A lot of research has explored the framework of smart PSSs and evaluated the effectiveness of smart PSSs (Liu, B. et al., 2019; Zheng et al., 2019). Subjective user research methods (e.g. questionnaire) have been used to evaluate user experience in some studies (Chang et al., 2019; Vermeeren et al., 2010). However, the accuracy of subjective user research methods remains to be verified.

Context-aware computing benefits the value co-creation process and decision-making quality. Traditionally, various decision tools utilize only operational data while making decisions. Such methods can only obtain knowledge of operational aspects (Hu et al., 2016; Lee et al., 2017). Extracting user behaviors and context-aware data can provide more insights into the solution recommendation and increase the benefits from service exchange. It is important to develop context-aware computing, and to extract relevant physical, configurational, operational, and user expectation context and incorporate them in a human-centric design in the SCS environment. Furthermore, consolidation of contextual information, representation of contextual data, and the potential application of artificial intelligence (AI) gather the knowledge behind the data and further contribute to the engineering applications of smart PSSs.

Although the current research on VR development and smart PSSs has made a great development, the following major challenges still exist in the design approach for value-added smart PSSs from a user-centric perspective:

1) The existing VR products mainly focus on function realization, which cannot fully satisfy users anymore. Value-added services require continuous evaluation to maintain the sustainability of the system and to meet the dynamic and personalized needs of users in a sustainable product lifecycle. The topic of the user as the center of VR product and service development activities has been little studied. There is still a lack of proper understanding regarding user-centric, smart PSSs based on VR. Hence, a user-centric development approach for smart PSSs that comprehensively considers user-generated and VR system-generated data is needed. Meanwhile, it is necessary to define the value system of the smart PSS based on VR in order to explore new market opportunities as well as to improve user satisfaction.

2) Although user experience data based on VR has been adopted in product and service design in some novel studies, there remains a lack of a systematic approach to analyze this data. Most of the data that is used to obtain user experience is subjective as it is greatly affected by the user's mental state and the surrounding environment. The results of user experience evaluation may not be accurate and timely. Hence, the results may not have actionable and managerial insight with objective judgment on the quality of the VR product design and service. Thus, a method that can collect objective, experience-based user data in a timely manner is necessary to implement VR development and value-added services.

3) Little research has been conducted on the value-added services from VR healthcare products, which is unfavorable for the aim of motivating rehabilitation training among users. Previous studies mainly focused on the value-added design of smart PSS on industrial products, especially in IoT products. Thus, a smart VR healthcare product needs to be developed to illustrate the proposed approach.

To address the above challenges, this research aims to provide a novel, VR-assisted, user-centric framework to assist the realization of value-added design and services. Results from the study will contribute to a better understanding of a user-centric design for smart PSS based on VR and will thereby provide an approach for specific data-driven, value-added services. Meanwhile, by leveraging of hybrid data (e.g. user-generated and VR system-generated data) collection and processing will add significant value in the provision of a useful approach to perform user experience evaluation of VR products. Moreover, a smart VR rowing machine that aims to improve user experience will be developed in accordance with the proposed design methodology in this study. An ergonomic experiment incorporating brain science data is eventually performed to evaluate user experience. Following this, the value-added services of VR-assisted user experience and real-time data feedback can be achieved.

The rest of this paper is organized as follows: Section 2 reviews the related literature. Section 3 proposes the overall architecture of the VR-assisted framework for the value-added design of smart PSSs. Section 4 illustrates the key technologies of the VR-assisted framework. Accordingly, a smart

VR-assisted rowing machine is developed to validate the proposed approach. The discussion and conclusions are described in Section 5 and Section 6, respectively.

2. Literature review

Two streams of literature are relevant to this research, namely, the literature that studies VR development (see Section 2.1) and that which studies value-added designs of smart PSSs (see Section 2.2). The proposed user-centric framework for the value-added design for smart PSSs is shown in Section 2.3.

2.1 VR development

In the 1980s, Jaron Lanier, one of the founders of the American company called VPL Research, introduced the term “VR”. VR is a computer-based technology that generates a multisensory simulated environment that immerses the user in the environment (Hirota et al., 2019; Moro et al., 2016). The VR environment is interactive, can be assisted, and is customizable for different applications (Kaplan et al., 2020). User actions in the real world are captured and transferred into the VR computing system through the VR input interface system. Following this, the system calculates and implements adjustments to the virtual environment.

Advances in VR technology in recent years have provided the impetus for its use in different fields. Firstly, VR showed prospect in its applications in the field of healthcare, specifically with respect to rehabilitation activities (Rose et al., 2018). Recently deployed brain imaging techniques suggest that certain areas of the brain can be activated through VR interactions (Moro et al., 2016; Sjölie et al., 2010). A study reported that a semi-immersive visual-motor VR task activated the ventrolateral prefrontal cortex (Moro et al., 2016). VR has been widely used in product design, assembly, inspection, training and simulation in manufacturing (Choi et al., 2015; Mujber et al., 2004). The benefits of VR technology can also improve tourist satisfaction (Bruno et al., 2010; Guttentag, 2010). As a digital content service, VR will increase the effective supply of information consumption and be integrated with cutting-edge technology (e.g. big data, cloud computing, edge computing, artificial intelligence) to produce more innovative applications (Bastug et al., 2017; Olshannikova et al., 2015).

Furthermore, the design iteration can be shortened, resulting in a shorter time to market and lower product costs (Mujber et al., 2004). Users are the center of product design and development activities (Bu et al., 2020). User needs are the driving force of the VR product development process. The level of user satisfaction can reflect product-services. Hence, product design and development should be carried out with a focus on users in order to provide a good user experience. However, research regarding VR products/services from the user's point of view is lacking. To understand the user's role in VR development, it is important to pay attention to user experience.

2.2 A value-added design for smart PSSs

The combination of the physical functions of products and the digitization and informatization of services has led to the formation of a PSS model that can systematically and innovatively meet user needs (Song and Sakao, 2017). In the context of the growing maturity of the IoT, enterprises not only need to provide the physical products but also need to meet the specific needs of users to provide necessary, valuable functions and services (Balaji and Roy, 2017; Liu, B. et al., 2019).

The smart PSS, first proposed by Valencia et al. (2015), can realize smarter product and service solutions, fulfill individuals' requirements and provide users with more value-added product services sustainably. Mainstream service marketing theories (Vargo and Lusch, 2016), smart technology, and the co-creation paradigm (Liu, Z. et al., 2019) are the core areas research that concerns smart PSSs.

A lot of research has contributed to the construction of the theoretical framework in the literature, including user needs through developments and applications (Mourtzis et al., 2018), technological mapping of the smart PSSs (Chowdhury et al., 2018), and the value co-creation and cost-and-benefit analysis of smart PSS (Kuhlenkötter et al., 2017). Zheng et al. (2018a) proposed a data-driven cyber-physical approach for SCP development. Regarding medication management for the elderly, Chang et al. (2019) proposed a user-centric smart PSS development approach. Meanwhile, other studies have explored the application of smart products in services (Guo et al., 2020; Lay-Khim and Bit-Lian, 2019; Yuniar et al., 2020).

The increase in user demand requires distinct different assessments of the value of products and service levels. Value-added service innovation is an important issue to improve the competitiveness of enterprises in competitive markets (Gupta et al., 2017). Effective evaluation of value-added services can help enterprises improve their service capabilities in the design stage and achieve a higher level of service quality (Chen et al., 2019). The evaluation of value-added services is a typical multi-criteria decision-making process (Tseng et al., 2015). The subjective investigation was used to evaluate service innovations in previous studies (Wang et al., 2017; Ye and Kankanhalli, 2018). The subjective survey method is simple and easy to use but it cannot provide objective and accurate data because of the differences in the level of education, mental health, and the environments of the subjects (Li et al., 2018). Therefore, it is necessary to conduct research regarding a human-centric design for smart PSSs using an objective, effective, and accurate method. The emerging value-added services in smart PSSs can also meet individual needs (Zheng et al., 2018b). Kowalkowski and Kindström (2009) proposed a three-level structure of value standards for PSS design. However, there is little research that provides information about value-added services for smart PSSs. In this regard, the existing research focuses on the concept and the framework of smart PSSs while research on value-added designs of smart PSSs is rarely conducted from the perspective of the users.

2.3 Knowledge gaps

As reviewed in Section 2.1 and 2.2, user-centric product and service development activities, especially objective and quantitative research methods, have not been fully considered in value-added smart PSS. This may be due to the difficulty in the acquisition of quantitative data from research regarding smart PSSs. Subjective qualitative methods are mostly used when evaluating product and service innovation. This can lead to inaccurate and poorly formulated results of product and service assessments. Therefore, decision-makers may find difficulties in consolidating subjective assessments regarding product design. Meanwhile, there is little information to study the VR-assisted and user-centric framework for the value-added design of smart PSS. To address the above issues, studying value-added, smart PSSs based on VR products from the perspective of users is desirable.

3. Overall architecture of the proposed framework for smart PSSs

Based on the literature review and analysis of related theories, a VR-assisted, user-centric framework for the value-added design of smart PSSs is proposed in this study. As shown in Figure 1, the overall architecture consists of three layers, including the VR platform development layer, the VR data layer, and the VR value-added service layer.

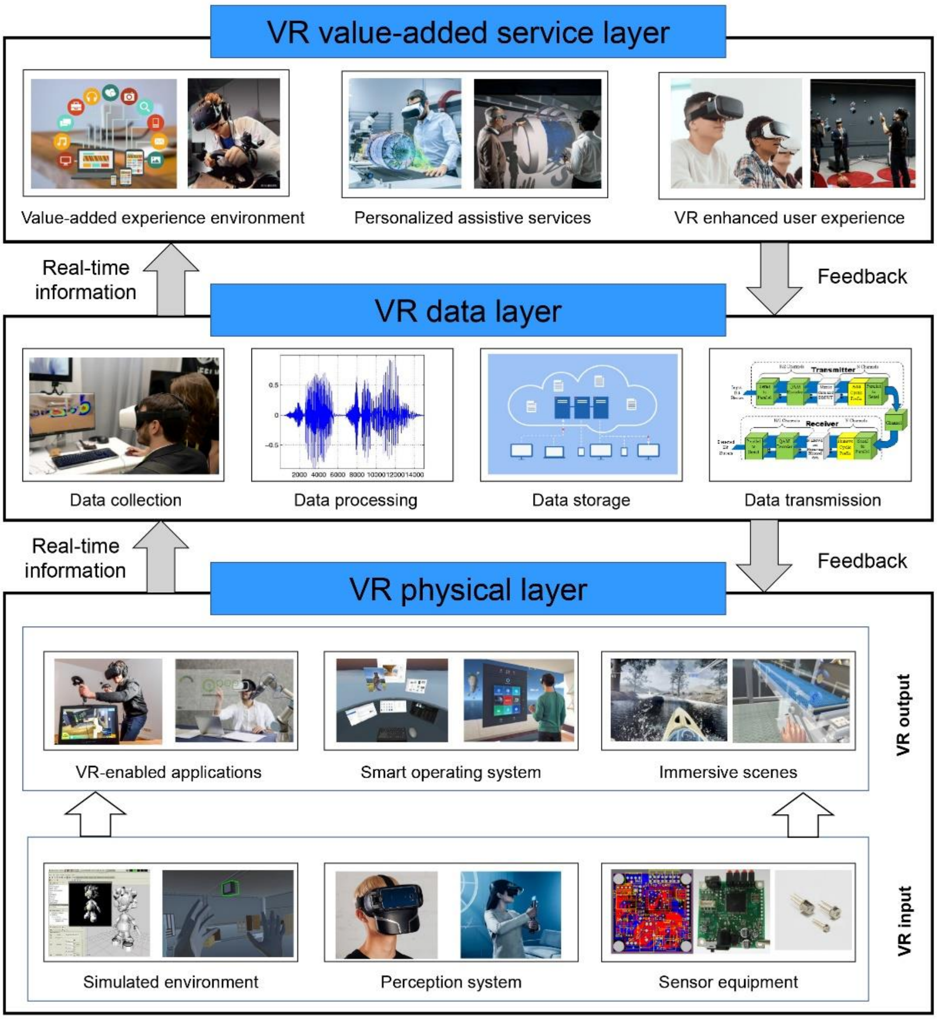

Figure 1. The architecture of the VR-assisted, user-centric framework for the value-added design of smart PSSs.

3.1 VR platform development layer

The VR platform development layer represents the hardware configuration of VR technology. VR can establish a more natural and harmonious human–machine environment through the two-way perception between the user and the virtual environment (Shin, 2018). The simulated environment, which formed via the perception system and sensor equipment provides a real-time, dynamic, three-dimensional (3D), and the realistic image generated by computers (He et al., 2018). On the one hand, VR technology needs to perceive the input information of multiple sensory channels (e.g. muscle movement, body posture, language, and body tracking of the user). On the other hand, it can simulate a realistic model of the real world using multiple sensory channels (e.g. human vision, hearing, touch, smell and feel). The sensor equipment refers to the system that is worn on the user and set in a real environment. Users can freely interact with the virtual world and product models using the sensor equipment (Lee et al., 2020). 3D visual display devices (e.g. smart glasses), sound devices (e.g. 3D sound system) and interactive devices (e.g. position tracker, motion capture device, and force feedback device) are important tools that enhance the degree of simulation (Wheeler et al., 2018). The redesign of the structure and the functions of the VR platform to enable them to have remote access capabilities will greatly change the modes of product manufacturing, operation and maintenance, and customer service. Computing devices and smart sensors that realize perception, transmission, and processing of information are placed into VR devices. For an example, smart and connected VR products for healthcare can provide more help for the effective implementation of user rehabilitation training.

3.2 VR data layer

The data layer includes data collection, data processing, data storage and data transmission. The smart VR platform selects a flexible and secure data transmission and interaction mode after obtaining data through a variety of data collection methods. A secure, stable, high-speed and extensible data management platform and strengthened capabilities of visualization and advanced analysis can be established (Keung et al., 2020; Zhong et al., 2016). VR system-generated data and user-generated data will be collected, processed, and integrated into this layer. A large amount of scene data needs to be processed during VR development. With respect to the aspect of graphic image generation, the VR system needs to synthesize the graphic data to generate a realistic panoramic simulation video. Hence, a user-centered VR development environment using user-generated data can be provided.

VR product user experience evaluation can be performed based on physiological signals (e.g. brain science data). The physiological signals can monitor the user's mental state in real-time and reasonable feedback (Liu et al., 2009). For example, the user emotions and physiological signal changes can be extracted in user experience assessment of VR. Emotion-related feature sets can be used to further analyze the original physiological signals by feature extraction and corresponding physiological and psychological models, which can be used for product design or user experience evaluation (Shu et al., 2018).

3.3 VR value-added service layer

Some VR applications and services can be achieved to different stakeholder interests (e.g. suppliers, users) after hardware upgrading and data processing (Ottosson and Holmdahl, 2007). Smart VR platform can provide users with an environment of value-added experience (e.g. smart and connected technical scenarios, mutually beneficial and symbiotic ecological organization of the service, product and service value co-creation network, open customer participation, and innovation environment). The suppliers can offer personalized assistive devices and services and users can gain personalized service experience through the smart VR platform (Buhalis et al., 2019). The smart VR platform, after the addition of new functions, can provide value-added services by creating an affordable, collaborative and highly participatory method. The functionality of the VR devices can further incorporate a design that is responsive to the user's perception and cognitive boundaries as part of a personalized product/service experience. The devices can also enhance the automation and participation of the user experience process.

4. Case study of a smart VR rowing machine

This study developed a smart VR rowing machine to illustrate the proposed architecture and approach, which is detailed in this section. The machine is a 3D limb-sensing device that offers a visual, tactile, and auditory simulation of the natural, bare-handed, and interactive experience of rowing a boat in the environment, thus providing users with an immersive experience. The simulator can provide practical feedback from its users and further, support the analysis when designing the real system. It is possible to use peripheral boating equipment to complete the boating projects in a VR environment. The smart VR rowing machine collected system-generated data. An ergonomic experiment was used to evaluate the user experience.

4.1 VR platform development

This smart VR rowing machine is mainly composed of seven parts: a controller, the body of the rowing machine, a damper, a draught fan, three actuators, a pull rod, and a tension sensor. The function of the controller is to provide the control signals that correspond with the scene of the game. The seat for the user is provided on one side of the body of the rowing machine and the damper is arranged on the other side. The damper provides the lever with a modifiable resistance after receiving the damping signal provided by the controller. The draught fan is placed on the other side of the smart VR rowing machine body relative to the seat. Three actuators are arranged at the bottom of the rowing machine body. They shake the rowing machine body in response to the shaking signal that is received from the controller. The damper is provided with a pull rod pushed and pulled by the user when rowing. The tension sensor is connected with the pulling rod to collect the pulling force received by the pulling rod and sending the collected data of pulling to the controller. Stepper motors are used to drive the smart VR rowing machine. Thus, the device provides a more realistic simulated experience. SolidWorks and 3ds Max were used for modeling, and Unity3D was used as the virtual development engine.

As shown in Figure 2, the platform can use sensors to collect the VR-system generated data (e.g. rowing time). The platform integrates brain science to collect user-generated data (e.g. brain activity of users). After data collection and processing, the tracked data can be obtained for further analysis.

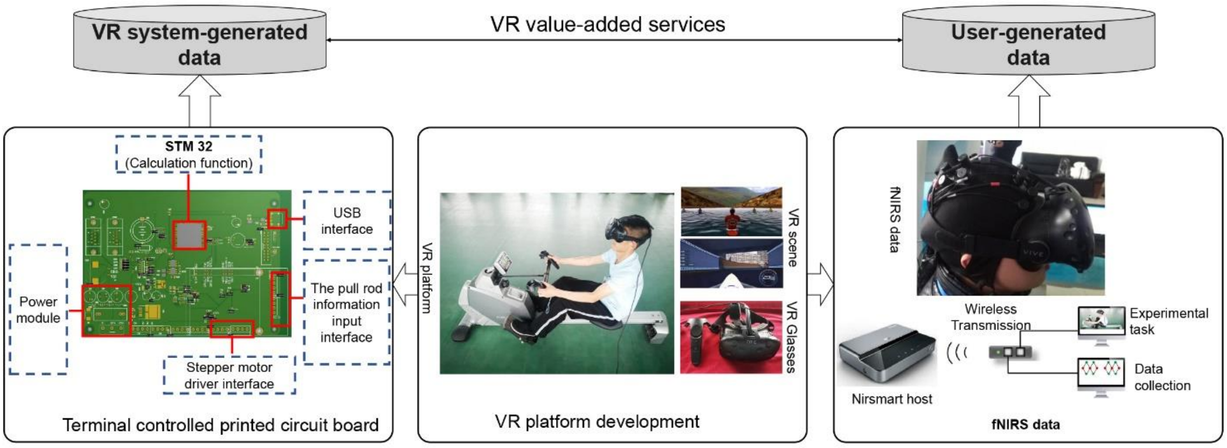

Figure 2. The system architecture of the smart VR rowing machine.

4.2 VR data collection and processing

VR data collection and VR data processing considering the VR system and user experience are included in this section.

4.2.1 VR data collection

The data collection proposed in this case consists of two modules, namely user-generated and VR system-generated data.

4.2.1.1 User-generated data collection

The integrated method from the literature is insufficient to support VR tools. Studies that are focused on evaluating the connection between VR-based rowing machines and user experience are limited. Moreover, a method that combines qualitative and quantitative evaluation is proposed in this work.

In this case, the Rate of Perceived Exertion (RPE) scale has been used to describe the subjective degree of users' feeling of difficulty. Functional near-infrared spectroscopy (fNIRS) was selected to evaluate the relationship between the VR rowing machine task and brain function. It mainly applies the characteristic rate difference of oxyhemoglobin (Δ HbO_2) and deoxyhemoglobin (Δ HHb) to absorb near-infrared light at different wavelengths of 600–900nm to detect the hemodynamic activity of the cerebral cortex in real-time (Lenkov et al., 2013; Tsytsarev et al., 2012). The technology has the characteristics of portability and strong resistance to interference, so it is more suitable for experiments that require stronger interactivity or brain activity detection in the natural environment.

Thirty healthy right-handed male volunteers (average age: 32.07 ± 4.83 years) were recruited from a local community. Those with neurological diseases were excluded. It was ensured that the subjects did not have a history of hypertension and other diseases. This research complied with the American Psychological Association Code of Ethics and was approved by the Institutional Review Board at Shandong Sport University. To eliminate the effect of gender on the experimental results, only male subjects were recruited in this study.

A 34-channel commercial fNIRS system (NirSmart from the Danyang Huichuang Medical Equipment Co., Ltd., China) with a sampling rate of 10 Hz was used to collect the **Δ** HbO_2 signals in this study. This system has been proven to be reliable and stable (Bu et al., 2019).

To arrange the light sources and the detectors, the spatial positioning information was obtained using a 3D magnetic locator and spatial positioning acquisition software. The distance between each light source and the detector is 30 mm. As shown in Figure 3, the 34 fNIRS channels are located in the left and right prefrontal cortices (LPFC/RPFC), left and right motor cortices (LMC/RMC), left and right occipital lobes (LOL/ROL), and the left and right temporal lobes (LTL/RTL).

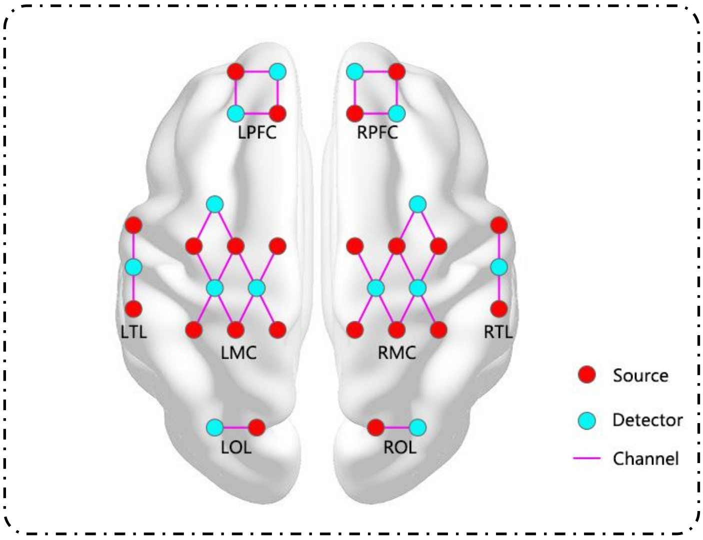

Figure 3. Configuration of the fNIRS channels according to the international 10/10 system.

As shown in Figure 4, this study is divided into three stages for the experiments, namely, the resting state, rowing machine task without VR (RMT without VR), and the rowing machine task with VR (RMT with VR). To alleviate the effect of the exercise on the subject's body, the three-phase experiment was performed on three consecutive days. Firstly, in the resting state, the subject wore a polar watch and a near-infrared instrument. In order to capture the brain functions for the purpose of benchmarking, the signal acquisition time was 600 seconds. Secondly, the subject was required to row by using the rowing machine at a basic damping setting. During the rowing activity without a VR device, the observer asked questions from the RPE scale at intervals of 200, 400, and 600 seconds. The fNIRS data were also recorded during the experiments. Finally, the subject was required to row using the rowing machine equipped with a VR device. The rating of the RPE scale was obtained at 200, 400, and 600 seconds.

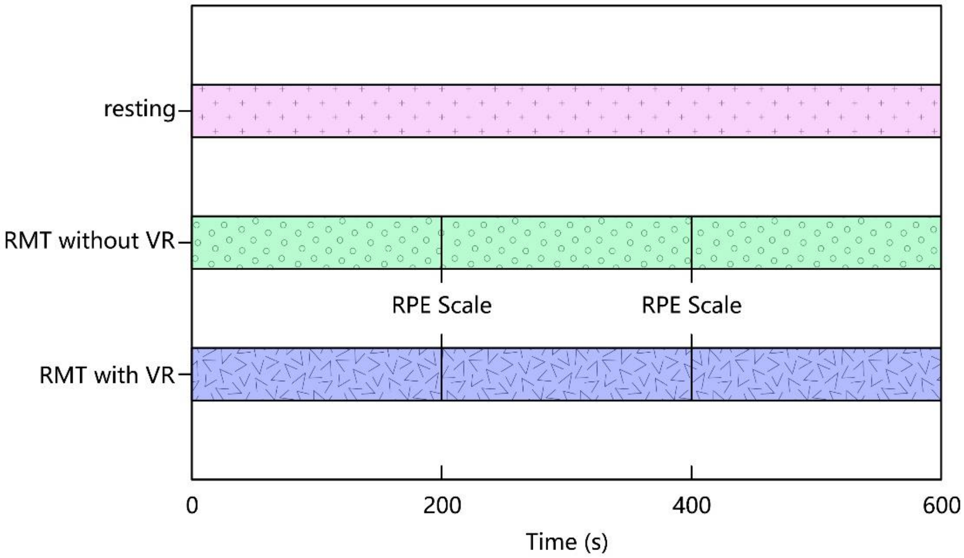

Figure 4. The protocol of the experiment.

4.2.1.2 VR system-generated data collection

The pulling rod in the VR system outputs a low-frequency voltage signal, while 32-bit microcontroller integrated circuits by STMicroelectronics (STM32) uses its own analogue-to-digital converter (ADC) to take samples (Figure 2). The pulling rod outputs digital switching value and analogue voltage when rocking. The switching value that representing the rocking direction is detected by the digital input of STM32 and the analogue voltage representing the rocking amplitude is sampled by the ADC of STM32. In this way, STM32 obtains the data of rocking direction and amplitude of the pulling rod and transmits it to the computer program via USB to control the oscillation of a model ship.

Multiple VR platforms are connected through Wi-Fi interconnection technology. The smart VR rowing machines distributed in different areas form a smart and connected system through database technology. The scenes created by Unity3D were executed on the terminal computer of the smart VR rowing machines (e.g. codes 1, 2, 3, etc.). The user operation data (e.g. training task name, training time, task ranking) were stored in log files in .txt format. Terminal computers can transmit action data to a cloud server regularly. Following this, the data is stored in the database through the cloud server.

Client–server framework is used to attain a Wi-Fi connection that links multiple smart VR rowing machines. The C# programming language is used to develop the client program on the terminal computer. The program reads user operational data and sends it to the server based on the HTTP protocol. The server-side stores the data sent by the client-side into the database. At the same time, the data required by the client can be queried and sent from the database. The server is developed based on the Beego framework of the Go programming language. SQLite was selected as the database.

4.2.2 *VR data processing*

The data processing proposed in this case consists of two modules, namely, user-generated and VR system-generated data.

4.2.2.1 User-generated data processing

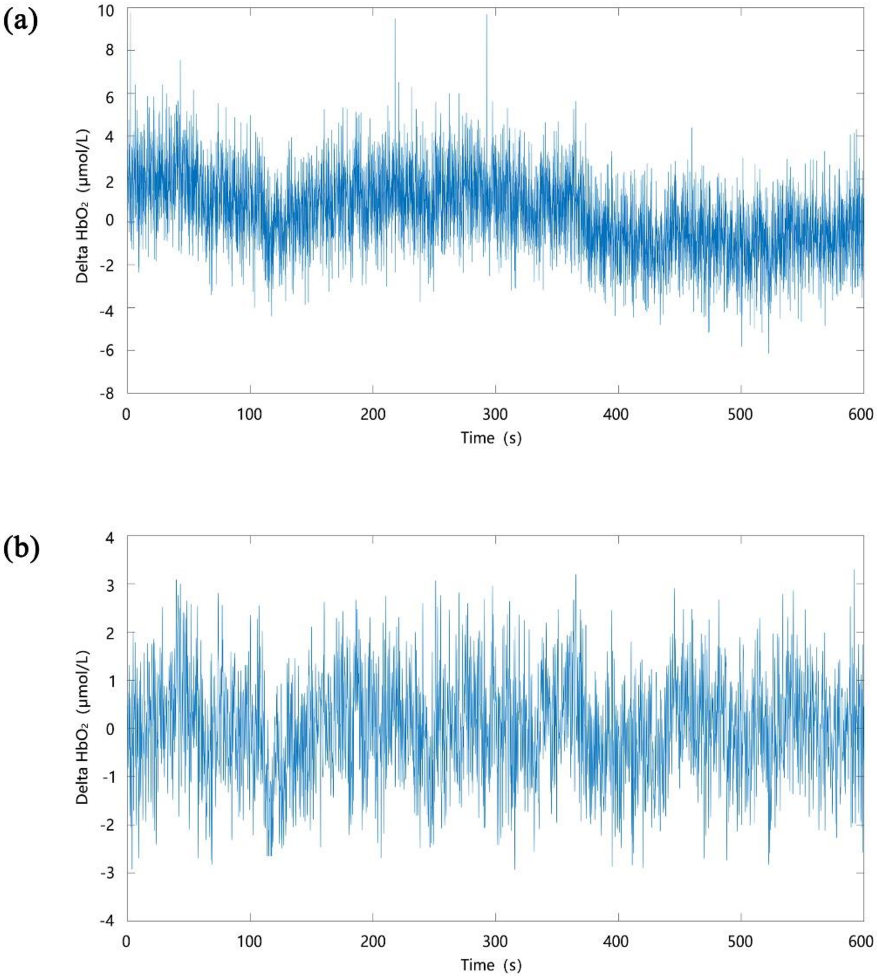

Figure 5. **Δ** HbO_2 signals (a) before the data processing; (b) after the data preprocessing.

The fNIRS signals may suffer interference from components such as movement artifacts (MAs). The interference caused by MAs is mainly due to the subject's head movement or the detector's sliding caused by facial expressions during signal acquisition. Firstly, the obvious anomaly in the fNIRS signals was preprocessed using the moving average method (Bu et al., 2019). Secondly, a method based on moving standard deviation and spline interpolation was used to detect and remove MAs (Scholkmann et al., 2010). Butterworth filtering was used to reduce the interference of high-frequency noise and low-frequency fluctuation signals (Figure 5).

The brain is responsible for forming a distributed and complex dynamic network of different functional areas based on the principle of separation and integration of functions (Felton et al., 2012). Effective connectivity (EC) provides an integrated analysis of the brain's complex distributed information systems' function (Friston, 2011). The EC reveals the effects that are exerted by one nervous system on another. The effect is dynamic (depending on different activities) and relies on interaction or coupling models (Bu et al., 2019). The method based on dynamic Bayesian inference (DBI) can assess the causality of interactions between brain regions and thus detect the EC between phase-coupled oscillation factors (Stankovski et al., 2016; Stankovski et al., 2015). In this study, the EC was calculated in the frequency range of 0.01–0.08 Hz. The calculation method of the EC value was divided into the following steps. Firstly, the sequence of complex functions at each window scale was obtained by wavelet transforms. Secondly, a series of coupled phase oscillator models were built from the phase information in each filtered time series. Thirdly, based on Bayesian theory, a likelihood function $\zeta(\chi|M)$ is established. Given a prior density $p_{prior}(M)$, the posterior density $p_{\chi}(M|\chi)$ can be calculated:

$$p_{\chi}(M|\chi) = \frac{\zeta(\chi|M)p_{prior}(M)}{\int \zeta(\chi|M)p_{prior}(M)dM} \tag{1}$$

The minus log-likelihood function can be expressed as:

$$\mathcal{S} = \frac{N}{2}\ln|\mathrm{D}| + \frac{h}{2}\sum_{l=0}^{L-1}(c_k\frac{\sigma\Phi_k(\phi_{\cdot,l})}{\sigma\phi} + \left[\dot{\phi}_l - c_k\Phi_k\left(\phi^*_{\cdot,l}\right)\right]^T(D^{-1})[\dot{\phi}_l - c_k\Phi_k\left(\phi^*_{\cdot,l}\right)]) \tag{2}$$

where h is the sampling step and the dot index in Φ is substituted with the relevant index.

According to the coupling parameters c， the e stationary point of S can be obtained recursively using the following equations (Stankovski et al., 2015):

$$\mathrm{D} = \frac{h}{L}\left(\dot{\phi}_l - c_k \Phi_k\left(\phi^*_{.,l}\right)\right)^T \left(\dot{\phi}_l - c_k \Phi_k(\phi^*_{.,l})\right) \tag{3}$$

$$\mathrm{r}_w = (\Xi_{prior})_{kw} c_w + h\Phi_k\left(\phi^*_{.,l}\right)(\mathrm{D}^{-1})\dot{\phi}_l - \frac{h}{2}\frac{\sigma\Phi_k\left(\phi_{.,l}\right)}{\sigma\phi} \tag{4}$$

$$\Xi_{kw} = (\Xi_{prior})_{kw} + h\Phi_k\left(\phi^*_{.,l}\right)(\mathrm{D}^{-1})\Phi_w(\phi^*_{.,l}) \tag{5}$$

$$c_k = (\Xi^{-1})_{kw}\mathrm{r}_w \tag{6}$$

The Euclidean norm of inferred parameters from oscillators ϕ_i and ϕ_j was defined as the coupling strength. A total of 100 surrogate signals were finally generated to test the effectiveness of the EC values. The amplitude of each channel was adjusted by Fourier transform.

4.2.2.2 VR system-generated data processing

In this study, a low-frequency digital filter was designed to filter the signals and filter out high-frequency interference. Considering the difficulty of implementation and the effect requirements, a digital filter is designed based on the first-order resistor-capacitance (RC) circuit filter. The cut-off frequency is selected as 30Hz.

In the signal processing of this VR system, the digital filter method is as follows:

1) The differential equation of Input voltage u_i and output voltage u_o, based on Kirchhoff's circuit laws as follows:

$$u_i = RC(du_o/dt) + u_o \tag{7}$$

2) Based on the differential equation above, the Laplace transposition forms $H(s)$ is:

$$H(s) = 1/(RCs + 1) \tag{8}$$

3) The relationship of Complex variable S in a Laplace transposition and Z transformation operator is:

$$S = 1\text{-}Z^{-1}/\mathrm{T} \tag{9}$$

where T is the sampling period, and the Z -transform function $H(Z)$ after S substitution is as follows:

$$H(z) = T/(RC(1 - Z^{-1}) + T) \tag{10}$$

4) The difference equation of output $Y(n)$ and input $X(n)$ obtained from the Z equation is:

$$Y(n) = \frac{T}{T+RC}X(n) + \frac{RC}{T+RC}Y(n-1) \tag{11}$$

Taking $q = \frac{t}{RC}$, where t is the sampling interval, the difference equation can be written as:

$$Y(n) = qX(n) + (1-q)Y(n-1) \tag{12}$$

The Cutoff frequency f_l is:

$$f_l = \frac{q}{2*pi*t} \tag{13}$$

5) The differential equation is converted into C language.

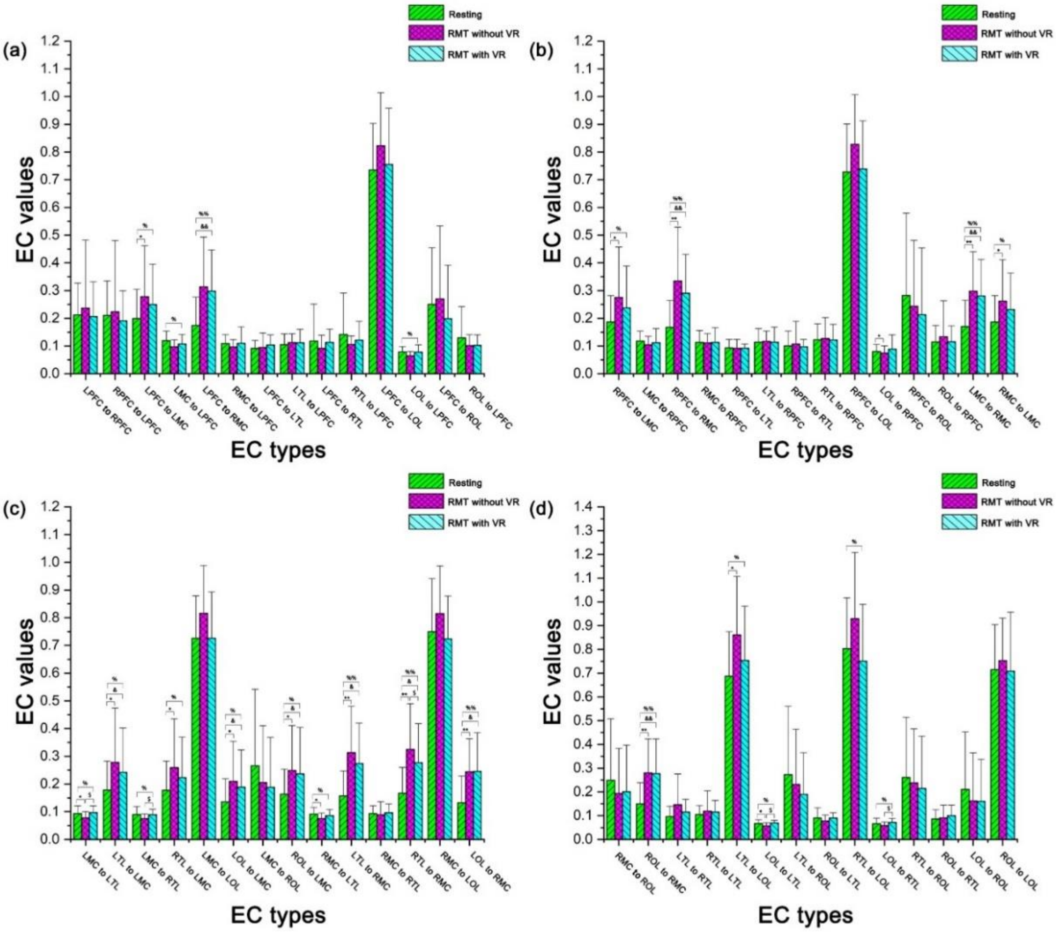

Figure 6. Comparisons of WPCO in the 56 EC types. Significant differences in EC values were marked with $^{\$}p < 0.05$ or $^{\$\$}p < 0.001$ between the RMT without VR and the RMT with VR states, $^{*}p < 0.05$ or $^{**}p < 0.001$ between the resting and RMT without VR states, $^{\&}p < 0.05$ or $^{\&\&}p < 0.001$ between the resting and RMT with VR states,

and $^{\%}p < 0.05$ or $^{\%\%}p < 0.001$ in all three different states).

4.3 VR value-added services

The value-added services, including assisted user experience and real-time data feedback, were generated using a user-centered VR platform design in this case.

4.3.1 VR assisted user experience

In this section, the user-generated and VR system-generated analysis results reveal that the smart VR rowing machine can significantly enhance the user experience.

4.3.1.1 User-generated data analysis results (EC)

The data collected from the repeated experiments were analyzed with a one-way analysis of variance (ANOVA) in order to compare the differences in coupling strength (CS) values in the three different states (resting, RMT without VR and RMT with VR). A post hoc test was performed. Each test was performed using Bonferroni's comparison test. As shown in Figure 6 (A–D), the CS values of LPFC to LMC ($F = 4.233$, $p = 0.019$), LMC to LPFC ($F = 4.403$, $p = 0.017$), LPFC to RMC ($F = 14.958$, $p < 0.001$), LOL to LPFC ($F = 4.313$, $p = 0.018$), RPFC to LMC ($F = 6.226$, $p = 0.004$), RPFC to RMC ($F = 18.39$, $p < 0.001$), LMC to RMC ($F = 19.303$, $p < 0.001$), RMC to LMC ($F = 7.313$, $p = 0.001$), LMC to LTL ($F = 5.566$, $p = 0.006$), LTL to LMC ($F = 7.896$, $p = 0.001$), LMC to RTL ($F = 4.172$, $p = 0.02$), RTL to LMC ($F = 5.955$, $p = 0.004$), LOL to LMC ($F = 8.45$, $p = 0.001$), ROL to LMC ($F = 7.714$, $p = 0.002$), RMC to LTL ($F = 4.123$, $p = 0.022$)，LTL to RMC ($F = 20.503$, $p < 0.001$), RTL to RMC ($F = 21.903$, $p < 0.001$),　LOL to RMC ($F = 16.552$, $p < 0.001$), ROL to RMC ($F = 21.688$, $p < 0.001$), LTL to LOL ($F = 5.104$, $p = 0.009$), LOL to LTL ($F = 7.302$, $p = 0.001$), RTL to LOL ($F = 4.302$, $p = 0.018$) and LOL to RTL ($F = 4.231$, $p = 0.019$) showed significant differences under different conditions (resting, RMT without VR, and RMT with VR states).

The CS values of LMC to LTL ($F = 10.028$, $p = 0.011$), LMC to RTL ($F = 7.84$, $p = 0.014$), LOL to LTL ($F = 16$, $p = 0.002$) and LOL to RTL ($F = 6.76$, $p = 0.02$) were significantly higher in the RMT with VR than in the RMT without VR state. The CS value of RTL to RMC ($F = 7.644$, $p = 0.03$) was significantly lower in the RMT with VR state than in the RMT without VR state.

The CS values of LPFC to RMC ($F = 19.612$, $p < 0.001$), RPFC to RMC ($F = 24.206$, $p < 0.001$), LMC to RMC ($F = 19.36$, $p < 0.001$), LTL to LMC ($F = 6.554$, $p = 0.044$), LOL to LMC ($F = 7.023$, $p = 0.037$), ROL to LMC ($F = 8.526$, $p = 0.018$), LTL to RMC ($F = 17.46$, $p = 0.001$), RTL to RMC ($F = 18.226$, $p = 0.001$), LOL to RMC ($F = 16.287$, $p = 0.001$), and ROL to RMC ($F = 23.859$, $p < 0.001$) were significantly higher in the RMT with VR states than in the resting state.

The CS values of LPFC to RMC ($F = 16.714$, $p = 0.001$), RPFC to LMC ($F = 8.801$, $p = 0.018$), RPFC to RMC ($F = 20.372$, $p < 0.001$), LMC to RMC ($F = 24.237$, $p < 0.001$), RMC to LMC ($F = 10.919$, $p = 0.009$), LTL to LMC ($F = 11.111$, $p = 0.007$), RTL to LMC ($F = 8.369$, $p = 0.021$), LOL to LMC ($F = 12.417$, $p = 0.004$), ROL to LMC ($F = 12.417$, $p = 0.004$), LTL to RMC ($F = 27.388$, $p < 0.001$), RTL to RMC ($F = 25.684$, $p < 0.001$), LOL to RMC ($F = 23.713$, $p < 0.001$), ROL to RMC ($F = 27.04$, $p < 0.001$), and LTL to LOL ($F = 12.11$, $p = 0.005$) were significantly higher in the RMT without VR state than in the resting state. The CS values of LOL to LPFC ($F = 6.76$, $p = 0.036$), LMC to LTL ($F = 9.911$, $p = 0.01$), RMC to LTL ($F = 7.111$, $p = 0.033$), and LOL to LTL ($F = 6.25$, $p = 0.039$) were significantly lower in the RMT with VR than in the resting state.

In the RMT without VR state, the average RPE scores at 200, 400, and 600 seconds were 10.03, 11.07, and 12.2, respectively. Meanwhile, in the RMT with VR state, the average RPE scores at 200, 400, and 600 seconds were 10.07, 11.63, and 13.13, respectively. In the RMT without the VR state, the RPE scores showed significant differences at these three time-points ($F = 16.108$, $p < 0.001$). Additionally, in the RMT with the VR state, the RPE scores showed significant differences at these three time-points ($F = 26.235$, $p < 0.001$).

4.3.1.2 VR system-generated data analysis results (Rowing times)

The tasks in both the RMT without VR and the RMT with VR states were performed for 10 minutes. In these two tasks, the subject pulled the lever closer to their body and then pushed the lever away from the body when rowing. The rowing times of the subjects were expected to differ in different experimental environments. After statistical analysis, the rowing times were significantly higher in the RMT with the VR state than those without the VR state ($F = 5.1155$, $p = 0.027$).

4.3.1.3 Interpretation of results

(1) Physiological meaning

The brain activity reflected in the fNIRS signals mainly derives from the task-induced regional neural vascular coupling (Shiogai et al., 2010). The transmission of oxygen to the brain caused relaxation of regional blood vessels in the brain, which increases the capillary blood flow, leading to regional cerebral blood flow and an increase in cerebral blood volume. EC provides an integrated analysis of the brain's complex distributed information systems' function (Friston, 2011). EC reveals the effects exerted by one nervous system on another, which is dynamic and relies on interaction or coupling models (Bu et al., 2019). Hence, the EC level is an intuitive expression of the degree of user participation during the task.

(2) Improving user participation

In this study, the higher EC values represent that the smart VR rowing machine task significantly enhances the information transmission efficiency between brain regions. The results showed that after the VR rowing exercise, the CS values between multiple brain regions of the user increased significantly. It is found that the rowing task needed to coordinate different brain regions where the motor, vision, and cognition functions were located. Data from behavioral and subjective surveys also revealed that the VR task significantly increased task participation of subjects. Combined with these results, the VR rowing task significantly enhances user experience. Hence, VR healthcare products using the method proposed in this study can increase the user's training participation and bring forth value-added services (e.g. user experience).

4.3.2 Real-time data feedback

Users can interact with the environment in a virtual 3D space by wearing a designated device to achieve an immersive experience. The results of the VR system-generated data analysis showed that VR technology can stimulate the user's potential and improve the training effect. VR scenes inspire user initiative. From the perspective of user experience, the VR method can make users engage in training more actively and mobilize the enthusiasm of users for rehabilitation training.

According to the user-centric principle, the VR system can also provide value-added services with real-time feedback data. A system based on the relationship between EC values and the user experience scales was developed in this study. VR systems improved customer satisfaction by providing faster response times, higher accuracy, and more consistent results.

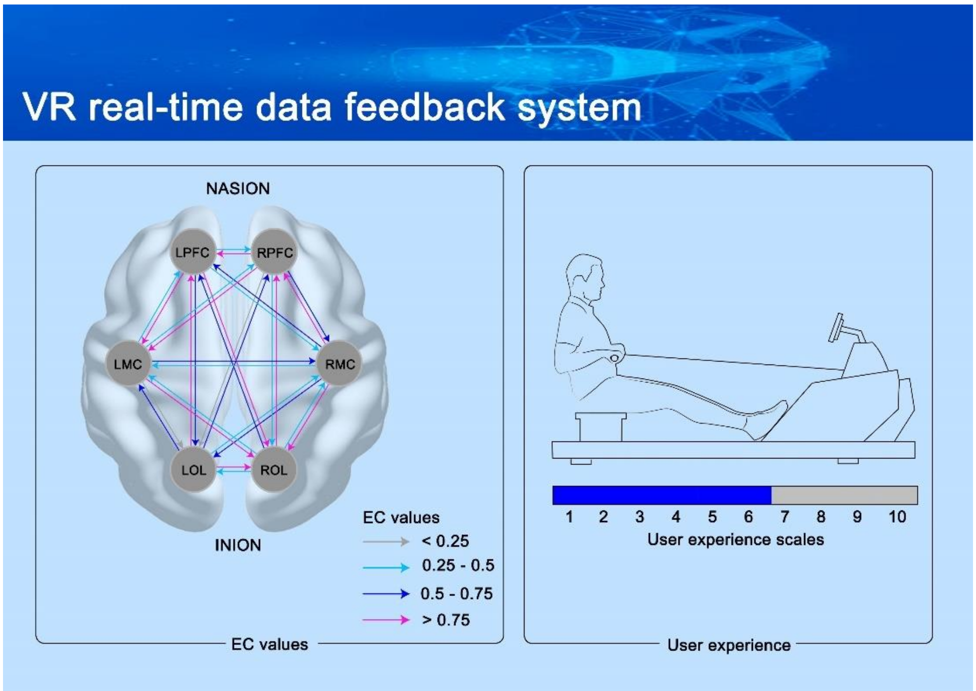

Figure 7. System interface for the VR real-time data feedback system.

As shown in Figure 7, users can obtain data feedback in real time during training through the data feedback system. Based on the brain activity signals collected online by the fNIRS system, the instantaneous EC values of the user can be obtained in real time through calculation. Compared with the value before the start of the training, the dynamic change of the EC value can also be used tos evaluate the user’s degree of participation, thereby obtaining the user experience.

5. Discussion

The development of VR technology has led to an increase in its applications, particularly in the field of healthcare. The development of user-centric VR products is committed to designing the product in such a way that can better meet customer needs, thereby improving the competitive advantage of new products. VR products can provide more value-added services from the perspective of user experience. To the best of our knowledge, this is the first time that fNIRS technology has been used to analyze the effects of semi-immersive smart VR rowing machine tasks on brain function from the perspective of EC in the brain.

Transition curve geometry is a popular topic in track and road engineering (Brustad, 2020). There are different criteria when deciding the type of curve. The VR tests include a comparison of the physical model against the virtual model to investigate the accuracy between them. The results showed that with small adjustments to the Blender physics, a virtual vehicle model can give a satisfactory prediction of the behavior of a physical vehicle model using VR. The results of our study revealed that the smart VR rowing machine can significantly enhance user experience. These studies confirm that VR technology is an effective application in many sectors (e.g. railway, road design, and healthcare product development).

There are academic and practical contributions in this paper. Academically, this paper contributes to the smart PSS theory by proposing a novel understanding of the conceptual framework of a user-centric smart PSS based on VR and offers the approach of specific data-driven and value-added services. This paper proposed a novel VR-assisted, user-centric framework based on VR, consisting of a VR platform development layer, a VR data layer, and a VR value-added service layer. Meanwhile, this paper contributes to the user experience evaluation method by proposing a novel data collection and processing methodology that provides a useful reference for researchers to perform user evaluation of VR products. The method provides more accurate and objective analysis results of smart PSS user experience analysis compared to traditional methods since it simultaneously considers both VR sensor data and real-time physiological data of when using the product. In reality for practical values in the smart PSS design of VR products, this paper contributes to the design methodology of VR products by using the hybrid intelligence strategy that comprehensively considers user-generated data and system-generated data to obtain more accurate and objective user experience. This method helps designers and engineers successfully recognize the key values of user-centric information with respect to both high-performing designs and user satisfaction.

In order to adopt the proposed user-centric design approach in practice, several managerial insights should be addressed. Firstly, the VR-assisted, user-centric framework for the value-added design of smart PSS can offer insightful guidance to enterprises in the process of VR product development and service innovation. After data collection and processing, the value-added services of user experience improvement and real-time feedback manners are achieved. Secondly, this approach can contribute to the VR development of future decision-making strategies. The data which contains user-generated data (e.g. physiological data) and VR system-generated data can be used to the decision-making process for value-added services. The data can help to find the optimal design elements which parts need improvement, to support the design and development of different modes of VR products.

6. Conclusions

Nowadays, VR technology is being continuously developed, improved, and widely used in various fields and industries. It enhances the user's perceptual experience. However, there is still few value-added smart PSS development and service approach based on VR from a user-centric perspective. To bridge the gap, this study proposed the novel conceptual framework of a user-centric design approach for value-added smart PSS based on VR. To validate the effectiveness of the proposed approach, an ergonomic experiment jointly considering the user-generated and VR system-generated data was conducted. The results showed that the smart VR rowing machine can significantly enhance the user experience. The main contributions of this paper can be summarized as follows:

i) A novel overall framework for the value-added design of smart PSSs based on VR technology from the user's perspective was proposed. Compared to traditional methods, the proposed framework takes full account of user experience and bring value-added services to users bases on VR.

ii) The fact that this novel data collection and processing methodology can intuitively reflect and evaluate user experience was presented. In addition to considering the data of the VR sensor, the objective physiological data of the user when using VR products are also fully considered.

iii) A design methodology for VR products by using the hybrid intelligence strategy was proposed. Following this, the implementation of the smart VR rowing machine case according to the framework was developed according to the approach.

iv) The value-added services based on the user-centric framework were achieved, i.e. user experience assistance and real-time data feedback.

Despite the abovementioned advantages, there are still some limitations to this research. For instance, the user-generated fNIRS data is known to have systemic interferences where short-channel or spatial regression will need to be applied in order to separate the effect in further study. Meanwhile, more rounds of user experiments are expected to further validate and improve the developed VR products/services in future work. The proposed framework of the VR-assisted framework and relevant method of user-generated and VR system-generated data in this study can only provide a new insight for VR product design from the perspective of user value-added services. Hence, future research works will mainly focus on the quantitative relationship between the physiological data of the users and the value-added services based on VR. Additionally, the calculation model between EC values and user experience should be considered holistically.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Symbols	**Mean**
$\zeta(\chi\|M)$	Likelihood function
$p_{prior}(M)$	Prior density
$p_{\chi}(M\|\chi)$	Posterior density
$\mathcal{S}$	Minus log-likelihood function
ϕ_l	Phase oscillator
h	Sampling step
C	Coupling parameters
u_i	Input voltage
u_o	Output voltage
R	Resistance
C	Capacitor
$H(s)$	Laplace transform function
$H(Z)$	Z-transform function
S	A complex variable in a Laplace transposition
T	Sampling period
Z	Z transformation operator
t	Sampling interval
f_l	Cutoff frequency
$Y(n)$	Difference equation output
$X(n)$	Difference equation input