Interaction Methods and Modalities of Wearable Robots Based on VR Technology

Xinkai Yu
School of Electronic Information Engineering, Sichuan Technology and Business University, Sichuan, China
yuxinkai24@gmail.com

Abstract. With the rapid development of wearable robots, their interaction with humans is being applied in various fields, such as medical rehabilitation training, daily life assistance, or as a haptic enhancement device. Simultaneous wearable robotic rehabilitation training can effectively maintain patients' motivation and interest in treating upper or lower limb injuries. As VR technology advances, customizable games or their combinations have been introduced, helping robotic therapy retain or increase patient interest so they continue exercising. This review focuses on the interaction of wearable robots based on VR technology in a VR environment, summarizing their interaction methods and modalities. These interaction methods include visual interaction, haptic feedback, and auditory interaction. The review covers both wearable robots and multimodal interactions involving wearable robots based on VR technology. Furthermore, the literature related to interaction methods and modalities is analyzed in detail. By integrating multiple sensory channels, this interaction method can provide a more immersive experience, helping users to perform complex tasks more accurately, while also stimulating neural responses and promoting functional recovery. In addition, multimodal interaction methods can compensate for the shortcomings of single interaction modes, improving the accuracy and safety of operations. Future research could explore further integration applications of these interaction methods with VR.

Keywords: VR, wearable robots, human-computer interaction.

1. Introduction

In recent years, the combination of VR and wearable robots has made significant progress in various fields. Virtual Reality (VR) is the virtual presentation of real objects, environments, or entities. According to Schultheis et al. [1], VR can be regarded as an enhanced version of Human-Computer Interaction (HCI), allowing users to interact with 3D interfaces and immerse themselves in virtual environments composed of digital objects. Various devices, such as headsets and Head-Mounted Displays (HMD), are used to achieve this technology. VR has gradually been widely applied in scientific research, music, education and training, and medical fields. In the medical field, VR combined with wearable robot training systems has been used for the rehabilitation training of stroke and other motor disorder patients. Some clinical trials have shown that this training method can significantly improve patient rehabilitation outcomes. For example, Katz et al. demonstrated the effectiveness of VR in their street plan for treating post-stroke patients. In this study [2], patients had unilateral spatial neglect (USN), usually caused by right hemisphere stroke. In addition, VR can tailor training according to the interests of the patient, which can not only enhance their motivation to continue training but also enhance their attention during training, both of which are key factors for effective rehabilitation [3].

Moreover, the interaction methods between VR and wearable robots are constantly evolving, including real-time feedback, simulated training scenarios, and data monitoring and analysis [4]. Through the VR system, the user's movements are captured and data exchanged with the wearable robot to achieve precise movement feedback. At the same time, VR can create various training scenarios, and when the user operates in the VR environment, the wearable robot provides necessary support to help them adapt to different movement requirements [5]. Furthermore, the VR system can record user performance data during training, analyze their movement patterns and progress, and combine sensor data from the wearable robot to provide comprehensive feedback [6]. Since there is currently no literature review on VR and wearable robots, this article will provide some summaries on this topic.

In conclusion, this review aims to determine the possible interactions between wearable robots and VR. Therefore, this study begins an exploratory review of the field of wearable robots, examining the topic from an additional technical perspective. This paper reviews the interaction between VR and wearable robots based on recent publications and data, focusing on: (1) human-computer interaction methods; (2) interaction modalities and architecture; (3) interaction methods and modalities of VR.

2. Human-Computer Interaction Methods

Human-Computer Interaction (HCI) involves the exchange and processing of information between humans and computers. Traditional HCI methods include interactions based on input devices such as keyboards, mice, and touch screens [7]. The development of HCI has also involved voice interaction, image recognition, augmented reality (AR), virtual reality (VR), and the recent popular body-sensing interaction technologies. For voice interaction, the entire interaction system begins by accessing the user's input information, including voice, facial expressions, and multimodal emotion-related data. This input information can be understood by the dialog system, and later, an output can be generated through this dialog component. Finally, the text can also be displayed through speech synthesis. The most crucial parts are the voice input and the dialog system, which constitute the entire process of voice interaction was shown in the Figure 1 [8].

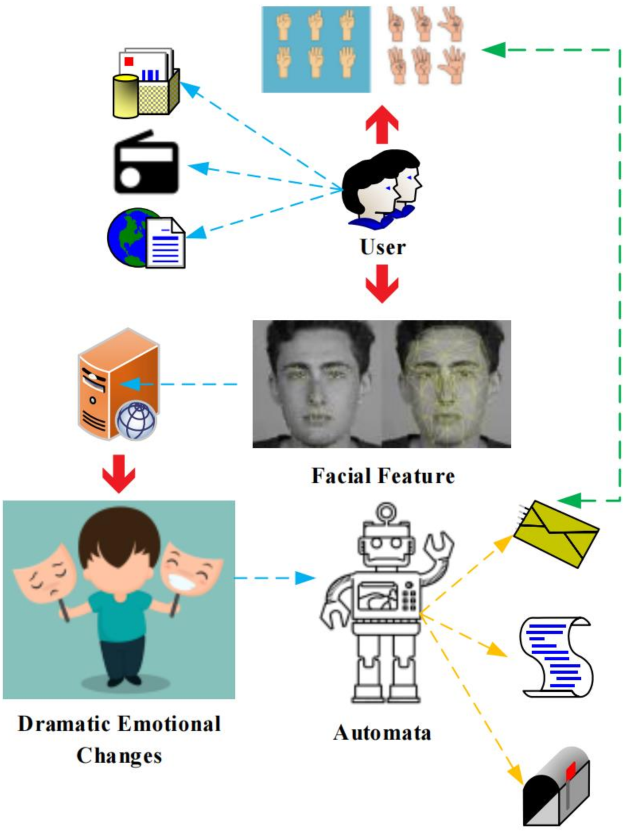

Fig. 1 Human-computer voice interaction process [8].

Human gesture recognition is also an important part of human-computer interaction, which falls under the category of image recognition. It can be applied in various fields, such as robot control, human-computer interaction, home automation, and medical applications. In computer vision, human pose estimation is a challenging task. It involves the process of inferring a pose from an image, aiming to determine the positions or spatial locations of key points on a person's body from a given image or video.It was shown in the Figure 2 [8].

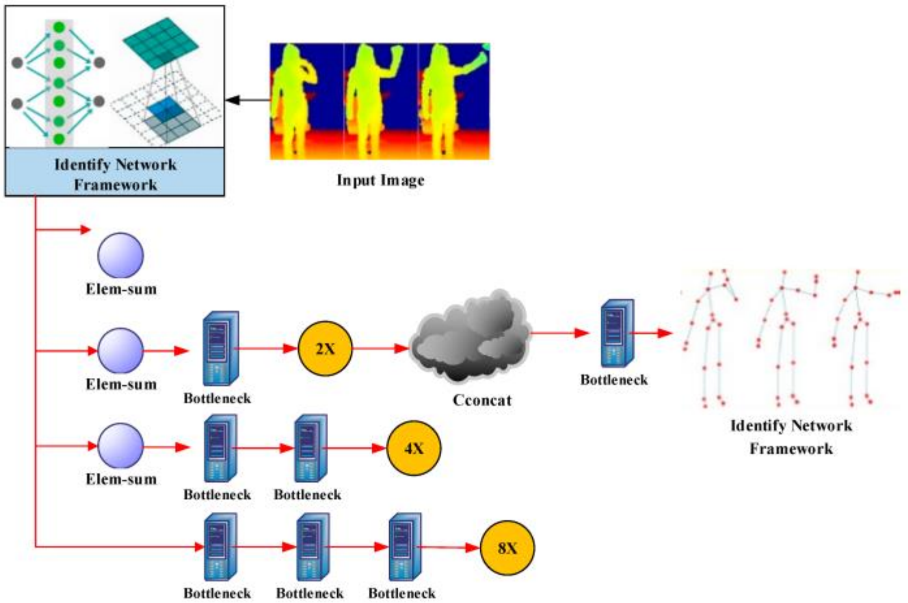

Fig. 2 Principle of human posture estimation [8]

3. Human-computer Interaction Modalities and Architecture

Interaction modalities refer to ways of interaction through different sensory channels, such as visual, auditory, tactile, and voice. Multimodal interaction enhances flexibility and user experience by combining different modalities [9]. In recent years, with the advancement of deep learning and computer vision technologies, multimodal interaction systems have become more intelligent and efficient [10]. A typical multimodal interaction architecture usually includes perception, processing, and feedback modules, where the perception module receives user input, the processing module performs data analysis, and the feedback module generates corresponding system responses [11].

4. Implementation Forms of Interaction between VR and Wearable Robots

4.1. Visual Interaction

Visual interaction is the most critical bridge when combining VR with wearable robots. Using virtual reality devices (such as Head-Mounted Displays, HMD), users can receive immersive visual feedback in a virtual environment, simulating potential real-world scenarios.

According to the research of Zhichuan Tang et al., wearable robots in VR environments use MI Electroencephalography (EEG) recognition models with Convolutional Neural Networks (CNN) and Squeeze Excitation (SE) blocks to capture the motor intentions of patients and control the exoskeleton during rehabilitation training was shown in the Figure 3. In visual interaction, VR scenes are used to provide movement cues to patients, enhancing their sense of immersion and promoting brain plasticity changes and functional reorganization by activating the mirror neuron system [12]. This visual feedback compensates for the shortcomings of traditional MI-BCI rehabilitation strategies, such as single-use scenarios, poor individual adaptability, and high susceptibility to external interference. Additionally, it provides a virtual scene to simulate and develop solutions for potential situations when wearing a wearable robot. It also enhances users' spatial awareness. According to research by Zheyuan Zhang, virtual visual feedback using HMD can significantly improve user performance in complex tasks, such as remote operations and precision control [13]. This can be applied to virtual component assembly in wearable robots. Furthermore, according to the study by Sang Hoon Chae et al., visual interaction can provide real-time feedback, ensuring operational accuracy during operations, which is particularly important in rehabilitation training, especially for upper limb function recovery [14].

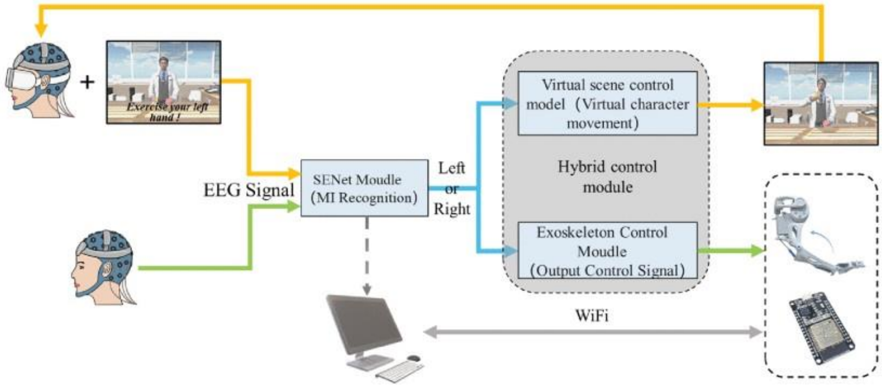

Fig. 3 Visual interaction between VR and the wearable robot [12]

4.2. Haptic Feedback

Haptic feedback plays a crucial role in the interaction between VR and wearable robots. Through sensors and actuators installed on the robot or the user, the system can simulate physical tactile sensations, allowing users to feel contact with virtual objects or environments.

This haptic feedback is usually implemented in the form of force feedback or vibration feedback. Force feedback devices can simulate the hardness, texture, and resistance of objects, allowing users to feel real physical contact in the virtual environment. For example, in rehabilitation training, force feedback provided by wearable exoskeleton devices enables users to perceive the force changes while performing specific actions, thereby more effectively engaging in motor learning and muscle rehabilitation [15].

The combination of haptic feedback with VR can also help users better perceive danger or warning information in virtual environments. For example, in virtual reality games or training, when users approach a dangerous area, wearable devices can alert them through vibrations [16]. This multi-sensory feedback not only enhances user immersion but also improves the intuitiveness and safety of interactions.

Research on haptic feedback in VR and wearable robot interaction also involves how to enhance its realism and user experience. For instance, researchers have explored using multipoint haptic feedback to simulate more complex tactile experiences. According to the study by Seung-Won Kim et al., an improved wearable VR interaction device can provide diverse thermal tactile feedback, enhancing user immersion and realism was shown in the Figure 4, especially in the correlation between the color and temperature of virtual objects [16]. This study demonstrates the great potential of haptic feedback in enhancing VR interaction experiences.

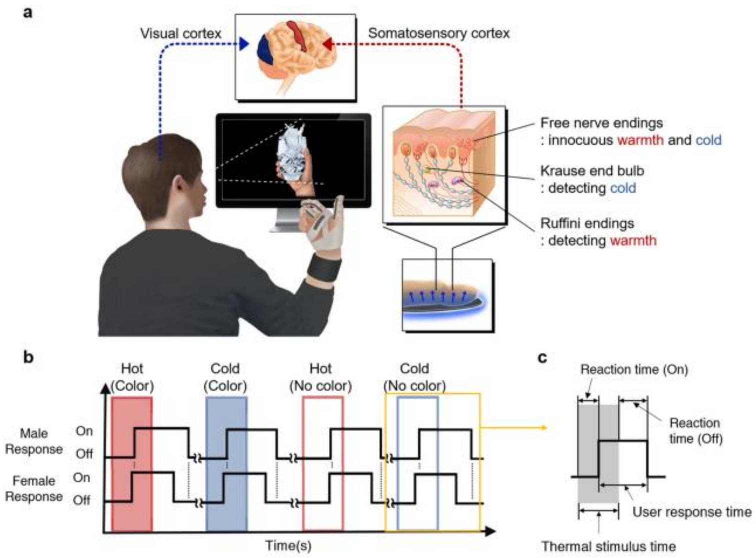

Fig. 4 Thermal display glove for interacting with virtual reality[16]

4.3. Auditory Interaction

Auditory interaction is another important modality, mainly playing a supporting role, and is often combined with other interactions to provide a convenient control method. Users can control the movements of wearable robots or interact with virtual environments through voice commands. This contactless interaction method is particularly suitable for scenarios where both hands are required for other operations, such as surgical training or complex mechanical operations [17]. According to the research by Smith J et al., voice interaction can simplify operations, reduce users' cognitive load, and improve task completion efficiency [18].

Additionally, auditory interaction can be combined with other modalities, such as haptic feedback, to provide synchronous information through voice prompts and vibration cues when a user performs a specific operation, thereby improving accuracy and safety.

5. Interaction Modalities of Wearable Robots

5.1. Multimodal Human-computer Interaction

Multimodal interaction for wearable robots primarily refers to the interaction between human-worn devices (such as exoskeletons, prostheses, etc.) and robotic or computer systems through multiple sensory and control methods. It mainly collects human intentions and state information through various sensors, such as electromyography (EMG), electroencephalography (EEG), acceleration, posture, and force feedback. The comprehensive processing of these signals provides the robot with more information to recognize human actions and intentions, mostly applied in medical rehabilitation to enhance user capability and assistive technologies.

According to Park et al., multimodal control methods combine EMG signals, finger bend sensors, and contact pressure sensors to more accurately infer user intentions. When EMG signals are insufficient, finger bend or pressure sensors provide supplementary information, better adapting to different injury patterns in stroke patients, and enhancing control precision and applicability of hand orthoses in rehabilitation scenarios [19].

Similarly, according to the research by Xueshan Gao et al., a motion intensity perception model based on multimodal information fusion, combining acceleration signals with heart rate signals, is applied in the trajectory planning and control of upper limb rehabilitation exoskeleton robots. The proposed motion intensity perception model can improve the effectiveness of rehabilitation training and human-computer interaction performance, and can thus be applied to upper limb rehabilitation exoskeleton robots [20].

5.2. Multimodal Interaction based on VR Technology for Wearable Robots

Multimodal interaction combines visual, auditory, tactile, and other sensory channels to provide users with a richer and more comprehensive VR interaction experience. Research shows that visual feedback is most considered helpful in reinforcing behavior [21]. In multimodal interaction, users can simultaneously perceive virtual environments through multiple senses and control wearable robots, greatly improving operational accuracy and efficiency. Additionally, MI therapy may also be used to reinforce knowledge learned in VR [22].

In the multimodal interaction between VR and wearable robots, wearable robots are mainly divided into upper limb exoskeleton rehabilitation robots and lower limb exoskeleton rehabilitation robots. For example, in the lower limb exoskeleton rehabilitation robot studied by Chih-Jer Lin et al., a combination of Virtual Reality (VR) glasses and Motor Imagery (MI) Brain-Computer Interface (BCI) algorithms is used to control the Lower-Limb Rehabilitation Exoskeleton Robot (LLRER). The VR-enhanced MI-BCI system allows users to simultaneously receive visual, motor imagery, and EEG signal feedback was shown in the Figure 5. In other words, VR provides a first-person perspective of exoskeleton walking videos, enhancing user immersion and motor imagery effects, thereby improving the accuracy of the BCI model [23]. This method helps to more effectively stimulate neural responses and promote motor function recovery in rehabilitation training.

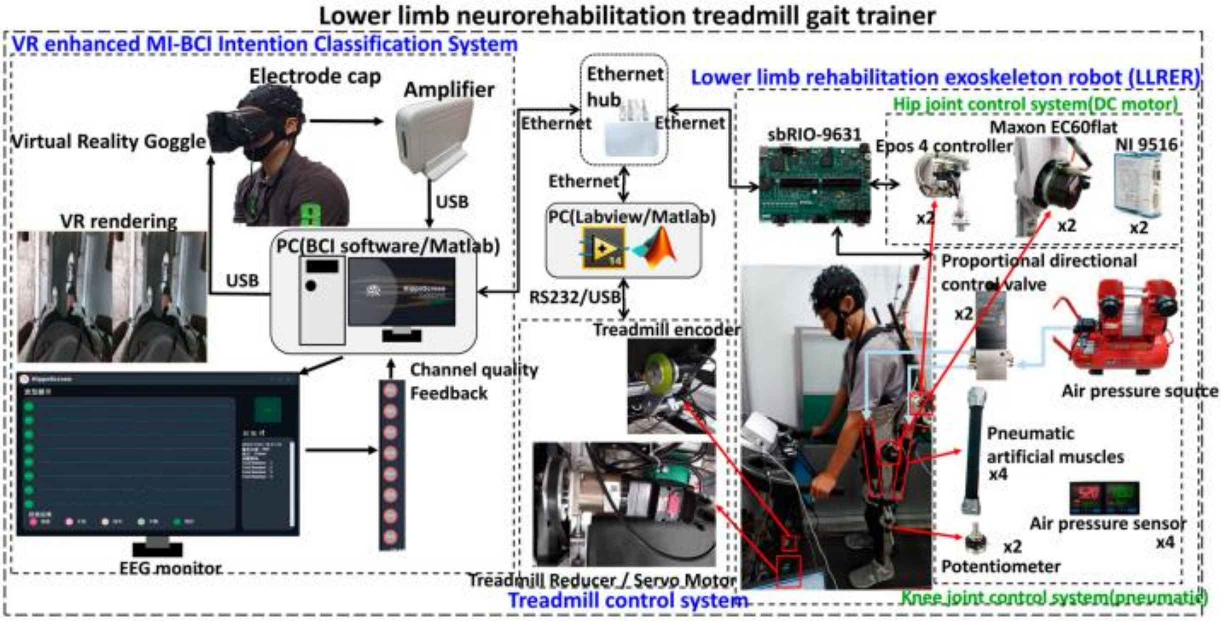

Fig. 5 Lower-limb neurorehabilitation treadmill gait trainer architecture [23]

The combination of auditory interaction with other modalities also shows great potential for application. For example, in remote medical operations, doctors can visually observe the patient's virtual model while tactilely perceiving the feedback of surgical instruments and adjusting the operation through voice commands. This multimodal interaction method improves operation accuracy and reduces error rates [24]. However, the characteristics of these applications have not yet been systematically studied in combination with VR.

6. Discussion

From the above literature, the most well-known interaction methods for VR are visual, haptic, and auditory interactions. Visual interaction serves as a bridge, haptic feedback plays a dominant role, while auditory interaction mainly serves as an auxiliary and is often combined with the first two interaction methods. In interactions with wearable robots, VR can create a virtual environment that allows users to immerse themselves, see real-time interactions between their body and the wearable robot, and make adjustments and simulations. Haptic feedback is most common in the interaction between VR and wearable robots, allowing the user to have realistic tactile feedback in the virtual reality constructed by the VR environment. Although haptic feedback can significantly enhance immersion, improvements are still needed in terms of accuracy and delay. To solve this problem, more precise and fast-responding haptic sensors and actuators could be developed to improve the resolution and real-time nature of haptic feedback. For example, high-precision micro-actuators could be used to generate more delicate tactile sensations. In terms of algorithm optimization, improving signal processing and data transmission algorithms could reduce system delay and enhance real-time haptic feedback. Prediction algorithms or compression algorithms could be used to accelerate data transmission and processing. Auditory interaction, which plays an auxiliary role, can make the interaction between VR and wearable robots more convenient by allowing voice control. The interaction modality between VR and wearable robots is an interaction through these sensory channels combined with the user, which is multimodal interaction. Multimodal interaction also has its advantages and disadvantages. It combines visual, auditory, tactile, and other sensory channels to provide a rich VR experience. Research shows that visual feedback most reinforces behavior, while the combination of VR and wearable robots' multimodal interaction can effectively improve rehabilitation outcomes. Combining VR technology with BCI systems can enhance user immersion and rehabilitation effects. However, multimodal interaction also has obvious drawbacks, such as complex design, difficulty in learning, and significant consumption of time and energy. To solve this problem, various tutorials could be recorded to help people get started better. Beginners could also be guided step-by-step to familiarize themselves with each function, reducing the difficulty of learning. Additionally, AI could be used to analyze users' operating habits and behaviors, automatically optimize interaction methods, and provide personalized suggestions and assistance, reducing users' learning burdens.

7. Conclusion

In summary, this review summarizes the interaction methods and modalities of VR and wearable robots and analyzes and discusses them one by one. It explains the three interaction methods: visual interaction, haptic feedback, and auditory interaction, as well as the two types of multimodal interactions: wearable robots and wearable robots based on VR technology. In the future, the combination of VR and wearable robots can significantly improve the immersion of human-computer interaction, allowing users to interact more naturally with VR and wearable robots. However, VR and wearable robots also face many challenges, such as response speed and data transmission delay in VR and wearable robot interactions, as well as the comfort of wearing VR and wearable robots. These are challenges for VR and wearable robots in the future. I believe that in the future, wearable robots will be combined with the newly emerging Extended Reality (XR) technology, allowing wearable robots to not only be limited to Virtual Reality (VR) but also be used in XR, enabling wearable robots to switch freely between virtual and real worlds.

References

[1] Schultheis, M., & Rizzo, A. The application of virtual reality technology in rehabilitation. Rehabilitation Psychology, 2001, 46(3): 296-311.

[2] Katz, N., Ring, H., Naveh, Y., Kizony, R., Feintuch, U., & Weiss, P. L. Interactive virtual environment training for safe street crossing of right hemisphere stroke patients with unilateral spatial neglect. Disability and Rehabilitation, 2005, 27(20-21): 1235-1244.

[3] Sveistrup, H. Motor rehabilitation using virtual reality. Journal of NeuroEngineering and Rehabilitation, 2004.

[4] Xie, P. Research on rehabilitation training strategies using multimodal virtual scene stimulation. Frontiers in Aging Neuroscience, 2022, 14.

[5] Tang, Z. C. An upper-limb rehabilitation exoskeleton system controlled by MI recognition model with deep stressed informative features in a VR scene. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 2023, 31: 4390-4401.

[6] Tiboni, M., Borboni, A., Vérité, F., Bregoli, C., & Amici, C. Sensors and actuation technologies in exoskeletons: A review. Sensors, 2022.

[7] Shneiderman, B. Direct manipulation: A step beyond programming languages. IEEE Computer, 1983, 16(8): 57-69.

[8] Lv, Z., Poiesi, F., Dong, Q., Lloret, J., & Song, H. Deep learning for intelligent human–computer interaction. Applied Sciences, 2022.

[9] Baltrusaitis, T., Ahuja, C., & Morency, L. P. Multimodal machine learning: A survey and taxonomy. IEEE Transactions on Pattern Analysis and Machine Intelligence, 2019, 41(2): 423-443.

[10] D'Mello, S., & Kory, J. A review and meta-analysis of multimodal affect detection systems. ACM Computing Surveys (CSUR), 2015, 47(3): 1-36.

[11] Lin, C.-J., & Sie, T.-Y. Integration of virtual reality-enhanced motor imagery and brain-computer interface for a lower-limb rehabilitation exoskeleton robot. Actuators, 2024.

[12] Delisa, J. A., & Gans, B. M. Rehabilitation of individuals with spinal cord injuries. Archives of Physical Medicine and Rehabilitation, 2009, 90(10): 1604-1609.

[13] Hoffman, L., Mathews, H., Murray, S., Perez, J., & Schmidt, S. A review of remote cognitive assessment using the telephone or internet. Journal of Medical Internet Research, 2020, 22(8): e17216.

[14] Li, Y., Wang, X., Zhang, Z., Chen, H., & Wu, J. Enhanced virtual reality systems with haptic feedback for improved hazard perception and safety. Research, 2023.

[15] Liu, Y., et al. Multisensory integration in VR environments for enhanced interaction. Frontiers in Robotics and AI, 2022.

[16] Kim, S. W., Kim, S. H., Kim, C. S., Yi, K., Kim, J. S., Cho, B. J., & Cha, Y. Thermal display glove for interacting with virtual reality. Scientific Reports, 2020.

[17] Kaczmarek, W., Panasiuk, J., Borys, S., & Banach, P. Industrial robot control by means of gestures and voice commands in off-line and on-line mode. Sensors, 2020.

[18] Smith, J., Liu, M., & García, R. Voice-controlled wearable robotics for enhanced interaction in virtual environments. Mechatronics, 2022.

[19] Park, S., Meeker, C., Weber, L. M., Bishop, L., Stein, J., & Ciocarlie, M. Multimodal sensing and interaction for a robotic hand orthosis. IEEE Robotics and Automation Letters, 2019.

[20] Gao, X., Zhang, P., Peng, X., Zhao, J., Liu, K., Miao, M., Zhao, P., Luo, D., & Li, Y. Autonomous motion and control of lower limb exoskeleton rehabilitation robot. Frontiers in Bioengineering and Biotechnology, 2023, 11: 1223831.

[21] Kohli, V., Tripathi, U., Chamola, V., Rout, B. K., & Kanhere, S. A review on virtual reality and augmented reality use-cases of brain-computer interface-based applications for smart cities. Microprocessors and Microsystems, 2022, 88: 104392.

[22] Mirelman, A., Maidan, I., & Deutsch, J. E. Virtual reality and motor imagery: Promising tools for assessment and therapy in Parkinson’s disease. Movement Disorders, 2013, 28: 1597-1608.

[23] Lin, C.-J., & Sie, T.-Y. Integration of virtual reality-enhanced motor imagery and brain-computer interface for a lower-limb rehabilitation exoskeleton robot. Actuators, 2024.

[24] Khan, M. M. R., et al. Development of a robot-assisted telerehabilitation system with integrated IIoT and digital twin. IEEE Access, 2023, 11: 70174-70189.