Studia i Materiały Informatyki Stosowanej, Tom 16, Nr 3, 2024
str. 38-41

Applications of Internet of Things in hand exoskeletons

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Abstract: *Hand therapy using a novel robotic exoskeleton can reduce motor deficits and improve functional recovery in patients. Robotic therapy can therefore effectively complement standard rehabilitation by providing therapeutic support to patients. The group of hand exoskeletons is at the beginning of its development and requires further research, and supplementing it with Internet of Things technologies will further increase its capabilities. The aim of this article is to determine the current state of research and development opportunities in this area.*

Słowa kluczowe: *Internet of Things; exoskeleton; artificial intelligence; home rehabilitation; human–machine interaction; remote treatment; robot-aided rehabilitation*

Zastosowania Internetu Rzeczy w egzoszkieletach ręki

Streszczenie: *Terapia ręki z wykorzystaniem nowatorskiego exoskeleton robotycznego może zmniejszyć deficyty motoryczne i poprawić odzyskiwanie funkcji u pacjentów. Terapia robotyczna może zatem skutecznie uzupełniać standardową rehabilitację zapewniając wsparcie terapeutyczne pacjentom. Grupa hand exoskeletons znajduje się na początku swojego rozwoju i wymaga dalszych badań, a uzupełnienie jej o technologie Internetu Rzeczy dodatkowo zwiększy jej możliwości. Celem artykułu jest określenie obecnego stanu badań i mozliwości rozwojowych w tym zakresie.*

Słowa kluczowe: *Internet rzeczy; egzoszkielet; sztuczna inteligencja; rehabilitacja domowa; interakcja człowiek-maszyna; leczenie zdalne; rehabilitacja wspomagana robotem*

1. Introduction

Traditional rehabilitation systems are evolving towards systems based on exoskeletons and virtual reality (VR) environments that improve the effectiveness of rehabilitation techniques and physical exercises in various patient groups, especially with upper limb deficits, which are the most painful for patients. Thanks to the widespread use of combined paradigms such as the Internet of Things (IoT), VR, smart home systems or intelligent ambient (AmI), it is possible to develop not only effective but also increasingly cheaper medical tools (e.g. exoskeletons) that patients can have in their homes [1-3]. The genesis of hand exoskeletons began with mechanical systems designed to assist or rehabilitate people with impaired hand function, relying on basic motors and sensors. With the development of sensor technology, pressure, motion and muscle sensors became an integral part, enabling more precise control of exoskeletons tailored to the users' needs. The rapid development of IoT around 2010 introduced opportunities for connected devices, paving the way for smart exoskeletons capable of communicating with other systems and cloud platforms. Wearable technologies such as fitness monitors showed the potential for real-time monitoring, which was soon applied to hand exoskeletons for tracking movement and health data. The growing demand for personalised and remote rehabilitation solutions motivated researchers to integrate IoT into exoskeletons, enabling continuous monitoring and adaptive therapy programmes. The development of reliable wireless protocols, such as Bluetooth and WiFi, has enabled exoskeletons to seamlessly transmit data to mobile devices or healthcare providers. The combination of IoT with artificial intelligence and machine learning has enhanced the ability of exoskeletons to interpret sensor data, adapt to user behaviour and provide predictive information [4-6]. IoT-enabled exoskeletons have begun to use the cloud to store and analyse large data sets, supporting real-time decision-making and remote diagnostics. The Internet of Medical Things (IoMT) has emerged, and hand exoskeletons have become an area of interest due to their potential to improve patient mobility and independence. Research collaborations between the robotics, IoT and healthcare industries have led to end-to-end solutions, resulting in smart, connected hand exoskeletons that have a wide range of applications [7-9].

The aim of this article is to determine the current state of research and development opportunities in this area.

2. Areas of application

IoT-enabled hand exoskeletons can monitor and guide patient movements in real time, providing personalised therapy plans and remote progress tracking. These devices help people with movement disorders perform daily tasks by integrating IoT sensors and connectivity to provide seamless and adaptive control. IoT enables healthcare professionals to remotely track users' muscle activity, movement data and rehabilitation outcomes, facilitating timely interventions. IoT connectivity can enable hand exoskeletons to interact with AR systems, enhancing virtual therapy sessions or training simulations for users. IoT-based hand exoskeletons can be used in immersive games, translating the user's hand movements into virtual environments for entertainment or skill training. These devices help workers with tasks requiring fine motor control or repetitive movements, while IoT systems monitor performance and prevent fatigue or injury [1-4]. IoT facilitates the use of hand exoskeletons to control robotic arms or machines in remote locations, offering precision and less physical strain. IoT-enabled exoskeletons can help teach fine motor skills, such as playing musical instruments or mastering tasks that require the use of the hands, with interactive feedback [5-7. Real-time data analysis: IoT integration enables the collection and analysis of biomechanical data, aiding research and improving the design of future hand exoskeletons. IoT-enabled hand exoskeletons can help first responders or rescuers by improving dexterity and grip strength in critical operations.

3. Current results

IoT-enabled rehabilitation provides the best possible path to recovery by allowing patients to rehabilitate in their home under the remote supervision of specialists and adjust the rehabilitation plan based on the patient's progress with personalized milestones. The IoT-enabled wheelchair "XoRehab" is an exoskeleton for rehabilitation with control of the patient's flexion and extension speed and repetitive flexion and extension movement to increase the efficiency of the treatment. It also allows to upload rehabilitation data and logs to a cloud server, which together with the results of functional tests provides a scalable solution. This study highlights that the introduction of an exoskeleton into the rehabilitation process improves the level of efficiency and speed of functional recovery [1]. The same approach can be applied to the hand exoskeleton, as combining robot-assisted exercises with remote measurement, as well as (in some cases) preprogramming based on it, is a promising solution. This can be realized by controlling the rehabilitation exoskeleton via its digital twin in virtual reality. This solution can potentially be used for hand remote kinesitherapy, combined with safety systems and the universality of application to various hand dysfunctions in the case of rehabilitation robots [2]. The alignment of the robot visualization with its actual movements is difficult to verify, causing visual-proprioceptive mismatch in patients, which may limit the assessment reflected by the digital twin in 2D and 3D tasks [3,4]. To compare the effects of using an IoT-assisted tenodesis-induced gripping exoskeleton (continuous passive motion and functional mode of pin grasping) and task-specific motor training (different components of wrist and hand movement) as post-stroke home rehabilitation programs for upper limb function. In addition to traditional rehabilitation, 30-min self-guided exercises twice daily for four weeks, the former offers greater potential for improving upper limb function in stroke patients [5]. Current prototypes allow therapists to record specific movements as part of a rehabilitation program. The interconnected exoskeleton components operate independently and remotely within a distributed software architecture, which works well in a controlled environment. Functional systems must then be tested in a real-world scenario with real patients [6]. An inexpensive and accessible elbow exoskeleton can be connected to the Context-Aware architecture, and the patient can interactively perform rehabilitation exercises through the VR system. It also provides an AI-based ability to monitor exercises and identify progress or potential problems, generate new exercises, and modify their characteristics based on medical sensors [7].

4. Limitations

The application of IoT in hand exoskeletons has limitations related to the poor understanding of robot-induced motor learning and the adaptation of robotic therapy to patients' potential for recovery at the beginning of therapy [8,9]. Hand exoskeletons rely on real-time feedback and control, but IoT systems often suffer from latency due to network congestion, which can delay responses and reduce performance. IoT integration increases the power requirements of hand exoskeletons, and current battery technologies can struggle to support long-term, uninterrupted operation. Dependence on stable internet connectivity means that these devices may not perform optimally in areas with poor or no network coverage. IoT-enabled hand exoskeletons are susceptible to hacking or unauthorised access, potentially compromising user security and privacy. Adding IoT features such as sensors, communication modules and cloud services increases development and deployment costs, limiting accessibility for some users. IoT systems introduce additional layers of hardware and software that require specialised maintenance and troubleshooting that may not always be available or affordable. Different IoT devices and platforms often use different protocols, making integration with existing systems or other smart devices difficult. Customising IoT functions to meet different user needs, such as different hand conditions or rehabilitation goals, is difficult and may not be scalable for widespread use. IoT-enabled hand exoskeletons may not work reliably in harsh environments where factors such as electromagnetic interference or extreme temperatures may interfere with connectivity. The collection of sensitive user data for IoT functions raises ethical questions and concerns about misuse of data, especially in healthcare applications.

5. Directions for further research

Research should focus on optimising IoT algorithms and communication protocols to ensure very low latency and smooth data exchange for real-time control of hand exoskeletons [10,11]. The development of low-power IoT modules and innovative battery technologies is essential to increase the usability and runtime of hand exoskeletons [12]. Designing robust security frameworks, such as advanced encryption techniques and intrusion detection systems, is crucial to protect sensitive data and ensure user safety [13]. Exploring modular IoT architectures that can be easily adapted to different rehabilitation scenarios and individual needs will increase the versatility of hand exoskeletons. Establishing universal IoT communication standards and protocols will simplify integration with other smart devices and systems in healthcare ecosystems. Incorporating machine learning and artificial intelligence into the analysis of user data can enable more personalised control strategies and adaptive feedback systems for rehabilitation. The development of IoT components and systems capable of operating reliably in a variety of environmental conditions is essential for wider adoption [14]. Research into affordable IoT hardware and software can reduce overall costs, making manual exoskeletons accessible to a wider population [15,16]. Conducting long-term clinical trials to evaluate the effectiveness and user acceptance of IoT-enabled hand exoskeletons in rehabilitation and daily activities will provide valuable insights. Establishing guidelines for ethical data collection, storage and use will address privacy concerns and increase confidence in IoT applications for sensitive health technologies.

6. Conclusions

Determining the most effective rehabilitation intervention using a hand exoskeleton is important for research on the rehabilitation of hand function in neurological deficits. Even a short-term training program using new technologies has a positive effect on upper limb motor skills and self-care. The genesis of IoT applications in hand exoskeletons stems from a combination of advances in robotics, sensor technologies, and connected systems. Initially developed for mechanical assistance, hand exoskeletons have evolved into intelligent devices capable of real-time data collection and adaptive control through IoT integration. Innovations in wireless communication, cloud computing, and artificial intelligence have enabled these devices to address personalized rehabilitation, assistive needs, and remote monitoring. The growing emphasis on IoT in healthcare has further accelerated their development, making them essential tools in improving mobility recovery and quality of life. This evolution represents a synergy between technology and healthcare, paving the way for smarter, more accessible solutions.

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