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Neuroplasticity and Augmented Reality Rehabilitation

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ABSTRACT

Neuroplasticity, the brain's ability to reorganize itself by forming new neural connections, is a cornerstone of recovery following central nervous system damage. This adaptability underlies functional recovery through the reconfiguration of undamaged brain areas. Augmented Reality (AR) technology offers innovative potential in rehabilitation by providing real-time visual feedback and enabling interaction with virtual stimuli in real-world environments. This paper reviews the application of AR in neurorehabilitation, exploring its efficacy in improving functions such as gait, balance, strength, sensory deficits, vision, and cognition. Through clinical studies and case examples, we demonstrate how AR integrates with the principles of neuroplasticity to enhance recovery and promote meaningful functional improvements in patients with neurological conditions.

KEYWORDS: Neuroplasticity, Augmented Reality, Rehabilitation, Central Nervous System, Functional Recovery.

INTRODUCTION

Neuroplasticity is the brain's ability to reorganize itself by forming new neural connections throughout life. The concept of neuroplasticity has allowed for renewed optimism toward regaining functional capabilities after central nervous system damage. Recovery of function following damage to the motor networks is believed to be mediated by neuroplastic changes that reconfigure the undamaged brain areas to result in functional substitution. Numerous studies showing a smooth transition of the motor command from stroke to BOLD signals in fMRI of healthy brain areas also provide evidence for neuroplasticity as the underlying mechanism of functional recovery. Technologies such as functional MRI have been essential for elucidating the potential role of neuroplasticity in rehabilitation [1]. Recent advancements in augmented reality (AR) technologies have the potential to provide real-time access to such training paradigms practiced in robot rehabilitation. AR technologies have the potential to present the patients with valuable visual feedback in real-time without being tethered to a traditional VR display, thus allowing for a more flexible and efficient form of rehabilitation. Unlike traditional screen-based VR systems, augmented reality devices permit the simultaneous presentation of virtual stimuli with the real world. The further clinical advantage is in the ability to monitor patients in real-world activities that could impact their health. The purpose of this review is to cover the objective evidence of the utility and effectiveness of augmented reality in the rehabilitation of a wide variety of physiological functions, including gait, balance, strength, sensory deficits, vision, and cognition [2].

DEFINITION AND CONCEPT

Neuroplasticity, also known as neural plasticity or brain plasticity, is the ability of the brain to reorganize itself by forming new neural connections throughout life. Neuroplasticity allows the neurons (nerve cells) in the brain to compensate for injury and disease, and to adjust their activities in response to new situations or changes in their environment. In brain injury, including stroke and traumatic brain injury, damaged neurons will heal by reorganizing or forming new connections in new brains. Following peripheral nerve injury, motor unit plasticity occurs in the central nervous system and the local circuit [3]. Neuroplasticity first came into prominence in the early 20th century as a hypothesis. The psychologist William James wrote in 1890, "The brain is by no means a rigid machine, but on the contrary is an incomparably delicate and suggestive organ in a state of continuous development." It was later progressively supported by advances in neuroscience. The term is defined as "the addition or deletion of a facilitatory action on a synaptic pathway as a result of presynaptic (or postsynaptic) neuron's repeated and persistent stimulation in a proper and regular manner. Alternatively, it has been read as the finding that afferent input from a co-activated system will lead to increases in resistance invoked at monosynaptic junctional sites. A more detailed definition was put forward by Kleim and Jones who stated it to be "the ability of the brain to reorganize its structure, function, and connections in response to afferent and efferent activity, intrinsic processes, and environmental changes." Neuroplasticity is far higher in young brains than in old brains [4].

AUGMENTED REALITY IN HEALTHCARE

Augmented reality presents with it an array of prospective applications, particularly in healthcare. Patients have used AR interfaces to visually superimpose organs onto their body, improve fine motor tasks, amplify magnification for surgeons, and provide real-time information for users throughout surgery. Additionally, AR rehabilitation training applications are devised to encourage a more intuitive, naturalistic interaction with the environment than traditional training. Various studies advocate for the positive use of AR either in conjunction with traditional treatment protocols or as a stand-alone treatment which includes gait balance, coordination, and posture training in Parkinson's, stroke, and SCI patients. Given the evident success of using AR as a tool in rehabilitation and the proposed conduit for transferring to everyday, real-world tasks, this section (3. Augmented Reality in Neuroplasticity) attempts to interconnect the principles of AR in general with the principles of neuroplasticity, the concept of training in a rich environment leading to meaningful and sustainable changes in physiological functioning of the patient [5]. The rationale for this review is derived from the synthesis of these principles across both theories or paradigms. To gain a deeper insight into the way these principles can interact with each other, this article explores the underpinning of neuroplasticity and the use of AR technology in healthcare. Furthermore, evidence is presented to support the use of AR as a rehabilitation tool for improvements in functional impairments in people with neurological diagnoses (stroke, PD, and SCI). Therefore, this paper proposes that AR is not only in line with principles of neuroplasticity but may maximize neuroplastic recovery of meaningful function [6].

APPLICATIONS IN REHABILITATION

Augmented reality is a live view of a physical, real-world environment that is augmented or supplemented by computer-generated graphics or sensory inputs. Augmented reality has been used in various applications such as gaming, education, and e-commerce, and has also been applied to various industries such as engineering and manufacturing. In recent years, augmented reality has been gaining popularity in the healthcare industry, including rehabilitation. Rehabilitation is a process in which a person restores lost or altered capabilities and regains normality. It can help improve functional ability and reduce symptoms. This undertaking or environmental adaptation is possible due to some degree of neuroplasticity. Neuroplasticity is the capacity of the nervous system to reconstruct itself in such a way as to restore and compensate for both alterations in the structure and functions neurological, encompassing modifications in behavior. The process of neurorehabilitation, longer than restoring the lost function, aims to also mention the patient to be able to satisfy their needs for personal life, study, work, and leisure and, socially, to be able to live normally as possible. Thus, we see that the process of plasticity characterizes the process of neurorehabilitation, since through neuroplastic changes reflect on the behavior, engagement in the replacement of sensory and motor capacities in spatio-temporal units, as well as the experimentation, construction, and later organization of new life perspectives after damage or neurological disease. In this sense, augmented reality brings a perspective close to the reality of the individual and the patient, where the logic of games brings training that is carried out in the functional activities of individuals, providing experiences and situations similar to those that have been suffered or are suffering.

NEUROPLASTICITY AND REHABILITATION

Neuroplasticity is associated with the ability of the brain to compensate for a previously injured function using its adaptive properties, and it is known for its central role in the recovery process. In other words, this 'functional reorganization of the brain' allows the central nervous system to adapt its functions and structure in diseases or injury conditions. At the same time, this functional reorganization process enables an adaptation of the brain in a neurodevelopmental disorder. By explaining the reason for some reversibility of neurological and neuropsychological signs and symptoms, the concept of neuroplasticity is crucial for rehabilitation frameworks. A previous rehabilitation study has reported the evidence of neuroplasticity through motor improvement under inhibited insult area of tDCS in which there were improved motor function in hand, reduced dystonia, and an increased movement in the proximal part of the upper limb. This phenomenon has drawn the emergence of many clinical trials with tDCS in several neurological diseases [7]. Referred to the modulation of neuroplasticity, the terms 'functional improvement' and 'structural change' are often used in an interchangeable and indistinguishable manner. However, 'functional improvement' refers to the 'visible outcome measure of clinical recovery' recognized as increased clinical scores. Conversely, 'structural change' is an atypical neural representation of function or the functional improvement recognized by imaging techniques, such as EEG, magnetoencephalography (MEG) or functional magnetic resonance image (fMRI). Electroencephalography (EEG) and brain graphics are known tools for elucidating this concept, yet the invasive character of brain graphics makes it unusable for a large-scale rehabilitation paradigm [8].

THE ROLE OF NEUROPLASTICITY IN RECOVERY

As injuries to the central nervous system result in neuronal death, the emerging road to recovery is often unclear, seemingly impossible. The development of neuroimaging technologies over the past few decades, most notably magnetic resonance imaging, has enabled unprecedented visualization of the living human brain. These evolving techniques have provided scientists with newfound knowledge about the complex functions of the central nervous system, including the process of neuroplasticity. This innate function of the brain is the foundation for organized adaptation and recovery, including mechanisms that decline over time, that is, after the healing process has slowed [9]. In 2005, researchers focused on understanding the multifaceted and complex process of neuroplasticity in relation to recovery. To begin, the scientists studied the spontaneous plasticity phenomena known as vasomotor reactivity. Their research showed that this plasticity occurs around perilesional primary motor cortices contralateral to the injured upper limb. Restoration of hand motor function occurs as a direct result of this phenomenon. Additionally, the activity of vision-associated areas might be reorganized with improvements in activities of daily living. Our understanding of the permanence of these new connections and a way to enhance and optimize them are crucial for chronic neurological rehabilitation. Such ideas build on the foundation of neuroplasticity and serve as a basis for our research, as do frameworks that conceptualize augmented reality as a rehabilitative tool [10].

AUGMENTED REALITY TECHNOLOGIES FOR NEUROREHABILITATION

The domain of augmented reality (AR) technologies for neurorehabilitation is a fast-growing area. A significant number of papers have discussed the latest advances in AR systems, sensor systems, and haptic interfaces tailored for stroke rehabilitation and hospital-to-home AR-based training applications. There is a rapidly increasing research output for non-invasive rehabilitation focusing heavily on upper limb/hand exercises, with systems aiming to target spastic dystonia, hand motor function, and functional movement post-stroke, as well as improving weak upper limbs in children [11]. AR systems can work with a range of training methods, including computer games and exoskeletons, as well as different types of feedback, which are utilized to provide performance indicators and encourage patient engagement. Gaming systems, such as the Nintendo Wii, Kinect, and Sony PlayStation, are embraced widely due to their affordability, almost instant set-up, and ease of use. It is important for the clinician to take an active part in neurorehabilitation sessions, requiring a certain degree of physical effort to ensure patient engagement and motivation throughout. Technical support with gaming consoles is therefore beneficial for anyone at a low level of expertise. Furthermore, it is not necessary to reinvent the wheel when a range of motion detection, interactive games, and assessments already exist with easily modified capabilities. Within the Nintendo Wii software, there are a number of interactive games from yoga to skiing, as well as a balanced fitness test and cognitive activities [12].

Current Trends and Developments The emergence of virtual and augmented reality technologies has led to the burgeoning growth of neurorehabilitation. However, this article aims to delve into some important test regimes and available future directions for augmented reality rehabilitation. A trend to correlate treatment results to response performance is suggested, which necessitates a movement toward treatment assessments and the evaluation of functional performance. The latest improvements regarding post-stroke and TBI treatments are incorporated, along with other contemporary studies. Using this knowledge, it is surmised, along with possible future developments, that the most promising next direction for the treatment of a variety of afflictions will necessitate the "clinical validation of a more direct connection between treatment gains and activity outcome". Therefore, we suggest the move to treatment and a paradigm structured to assess treatment gain directly in terms of the effect on a person's daily practical performance. We propose a range of possible treatments that can be probed using this approach, including upper limb treatment for stroke, treatment for apraxia of speech, and treatment aiming to improve everyday activity following severe TBI [13].

Having presented a brief outline of this subsection, it can also be observed that it would be profitable to consider the latest trend and development of augmented reality technology in neurorehabilitation, which can be expected to integrate the mentioned improvements. Certainly, another promising improvement, approved for the trends in Table 1, post-stroke treatment, is the study by Ehl stark, J. orich and S. obucki, an assessment of post-stroke mesial cortical ischemic patients. Such assessments using research TMS are becoming more frequent and therefore extra excitability of PSP FDI represents a trend in research focus.

CASE STUDIES AND CLINICAL OUTCOMES

Case study 2. A middle-aged, experienced arborist with recurrent right axillary skin cancer underwent an extended vacuum-assisted fibroblast surgery and skin graft from the same axilla to irradiated and rotated necrosis. The motor branch of the long thoracic nerve, lateral pectoral nerve, and axillary lymph nodes were involuntarily removed during resection. She presented with shoulder girdle apraxia, scapulocostal dyskinesia summarized as a large SICK scapula, and inability to use her right arm. Shoulder girdle stability and dynamic scapulohumeral rhythm are crucial in tree climbing, either maintaining position. Seventy recorded tree climbing ascents as an arborist were compared five years apart and showed that primary kinetic chains between the shoulders ($n = 96.2\% < 105\%$ LLN) with large shoulder girdle dyskinesis and stiffness of her lower kinetic chains compared to expected working full-time (n = 747% > 1.96 SDs above MLN). Her shoulder girdle improvements correlated well clinically and statistically with the UQPAR, PSEQ, and VAS scores. Eighteen specific tree-climbing recommendations were identified that accurately reflected therapist-generated individualized rehabilitation recommendations. Case study 3. Virtual reality (VR) environments are considered as one of the settings that can benefit individuals with autism's lives. The results from using VR in treating various behavioral therapy outcomes are promising and allow for exposure and adaptation to situations and environments in a controlled manner. This case report details a 5-day, 2.5-hour seated VR intervention less than 48 h apart for a 16-year-old male diagnosed with autism spectrum disorder. A complete 2D to VR usability trial was conducted on the day prior where he remained within the VR environment for 2.5 h over five sessions. Eye tracking was utilized to observe gaze behavior. The participant spent 12.5 of a possible 12.5 h within the VR system. We found that treatment adherence and retention was higher when compared to traditional VR exposure therapy techniques for individuals with autism. He showed improvement in 14 out of 20 the Symptom Checklist-90-Revised (SCL-90-R) sub-scales by between 22.5% and 100%, for a measure that evaluates psychological and somatic human functioning and was characterized by a 90% retention rate or higher. Treatment adherence and retention outcomes between the use of 2D to VR headset showcases the added advantage of individuals' abilities and willingness to transition from 2D to VR with fewer sessions and the even greater improvement of treatment evaluation outcomes [14]. Case study 4. Augmented Reality System provides Immediate Feedback for Unilateral Reaching after Stroke. The purpose of this case report was usage and improvement of a patient-specific augmented reality system providing target ID, the ellipsoidal mid-course of movement, as well as provided genic movement, deduced from his successful hand movements. Directional diagrams are in radial coordination, in order to track motor learning of rotation in reaching in aging or stroke cohorts. Following informed consent, term arm reach outcomes in the patient were collected over 5 weeks after stroke, publisher outcomes were symmetric with their non-paretic stroke arm, or with published gains in the version with the recovery arm reaching in a primitive direction didn't increase further. Genic moves normally cluster with our paretic data, before and after using the augmented reality system [15].

CONCLUSION

The integration of neuroplasticity principles with augmented reality technology marks a significant advancement in rehabilitation. AR provides an engaging, flexible, and efficient platform for delivering therapeutic interventions that align with the brain's adaptive capabilities. Evidence from clinical studies and case examples underscores AR's potential to facilitate substantial functional improvements across various neurological conditions. As AR technology continues to evolve, its application in neurorehabilitation is poised to expand, offering new opportunities for personalized and effective treatment strategies that leverage the brain's remarkable plasticity.

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