Development of a Brain-Controlled Robotic Exoskeleton with Virtual Reality-based Feedback for Motor Rehabilitation

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***Abstract*—In a matter of seconds, an inadvertent misstep or unforeseen circumstance can cause sudden and often traumatic injuries even to the healthiest among us. Knee injuries, such as anterior cruciate ligament injury (ACL tears), meniscus tears, and patellar dislocation, can significantly impair knee mobility and functionality. The proposed work aims to develop a Brain-controlled robotic leg-exoskeleton that uses Virtual Reality-based feedback for knee rehabilitation. The system leverages real-time brain signals (EEG) to activate the robotic exoskeleton and provides visual feedback through a Virtual Reality (VR) environment. Additionally, the system is designed to provide an immersive and interactive experience for knee rehabilitation patients through gamification of rehabilitation exercises, with the aim of enhancing motivation and engagement in the rehabilitation process.**

***Index Terms*—BMI, VR, Knee Rehabilitation, Robotic Exoskeleton, Cognitive-Motor Training, Gamification.**

I. INTRODUCTION

Knee injuries and disorders can have a significant impact on a person's quality of life, causing limited mobility and constant pain. Some injuries can heal quickly, while others may take longer or never fully recover. Knee injuries are a common occurrence and can be caused by a variety of factors such as sports injuries, falls, or accidents [1]. Knee rehabilitation is an essential part of the recovery process and can help patients regain their mobility and strength [2].

The approach to recovery therapy is contingent on the specific injury that has occurred. Among the most frequently implemented exercises are the straight leg raise and the short arc knee extension. The former exercise targets the strengthening of hip flexors, which may experience debilitation due to surgical procedures or injury. Additionally, it is often used to enhance the range of motion and flexibility of the hip joint. The latter exercise focuses on building up the quadriceps muscle, an essential muscle group for a wide array of daily activities, including walking, climbing stairs, and rising from a seated position. Furthermore, common exercises in rehabilitation programs include a short-arc knee extension with hamstring co-contraction, a squat, and an isometric knee co-contraction exercise [3]. Rehabilitation is often necessary to prevent further damage and restore knee function. However, traditional knee rehabilitation methods that rely on physical therapists can be time-consuming, require the patient to go to the rehabilitation clinic, and in many cases, the sessions are monotonous and boring. In order to provide patients with an in-home rehabilitation solution, researchers have proposed robotic-based rehabilitation systems with diverse characteristics. Koller-Hodac A. *et al*, for instance, proposed the use of a robotic physiotherapy device to help with patellar mobilization during knee rehabilitation, allowing for regular exercise throughout the recovery period and quantification of therapy progress. A personalized training protocol is created by the physiotherapist based on the patient's pathology, and the progress is supervised in the clinic. The patient repeats predefined training sequences at home using the robotic device, which provides immediate feedback to the patient and therapist [2]. On the other hand, De la Iglesia *et al.* presented a low-cost exoskeleton for the elbow that is connected to a Context-Aware architecture, allowing patients to perform interactive rehabilitation exercises using a Virtual Reality (VR) system. The system has the ability to generate new exercises, monitor user performance, and dynamically modify the characteristics of exercises [4]. Moreover, Mingxing Lyu *et al.* introduced Artificial Inteligence (AI) agents to enhance a knee exoskeleton, enabling autonomous control and introducing a new assist-as-needed method. The human-robot cooperative control methods indicate that using AI agents to assist rehabilitation is possible and effective [5]. Miguel A. Padilla-Castaneda *et al.* explored the use of robotics and virtual reality in upper limb rehabilitation for orthopedic patients. Their system allows patients to simulate their upper limbs and actions, providing intensive training and motor control with visuomotor and haptic feedback. Specific tasks can be assigned within virtual environments, and the system can evaluate patient mobility to personalize therapy difficulty and measure progress [6]. Although the aforementioned systems are primarily designed for knee and upper extremity rehabilitation, they incorporate a feedback mechanism to a certain extent and leverage emerging technologies such as VR and AI. However, the way that these devices are activated does not consider the most natural way we control our own limbs; by leveraging the brain signals produced by our own brain motor activation. In the following section, we expound on our proposed system that aims to address this challenge.

This paper proposes a new approach to knee rehabilitation using a brain-controlled robotic exoskeleton (BCRE) integrated with Virtual Reality (VR) technology to enhance patient outcomes and provide personalized and targeted assistance to patients during rehabilitation exercises. AI algorithms analyze the user's brain signals to identify intended knee rehabilitation movements, which are then translated into corresponding movements of the robotic exoskeleton (RE). The VR environment provides a cognitive-motor training platform that improves patient engagement and motivation while providing visual feedback. Furthermore, we present the results of a pilot study aimed at evaluating the feasibility and usability of the system.

The structure of this paper is as follows: The design and execution of the BCRE system, including the AI algorithms and VR platform, are covered in Section II. In the final section, We perform an assessment of the system's functionality in Section III. The improvements to be made and future directions of this study in Section IV. We hope that this study stimulates additional research in this field.

II. SYSTEM ARCHITECTURE

In our previous work, we proposed brain-computer interface applications to explore the feasibility of enhancing human cognitive-motor skills [8], [9]. Based on our previous work, we propose a Fig. 1 illustrates the architecture of our system, which comprises five components. Initially, the user wore an EEG headset to acquire his brain activity. Secondly, we train the system's IA to calibrate while imagining leg movements and at rest. Thirdly, the participant adjusts the RE, which is connected to the system, on the leg that requires rehabilitation treatment. Fourthly, The user or specialized footwear with integrated grips shown in Fig. 2 is then used to operate the virtual reality (VR) environment, one controller goes on the foot, the other on the hand and then is defined the actions and exercises. Lastly, taking into account the rehabilitation exercises described in the medical literature which indicates the movements for the types of common injuries on the knee [10], we developed an interactive virtual reality environment based on them that gives the experience of taking soccer penalties to a goalkeeper, the user engages with the aforementioned environment, and the efficacy is evaluated through cognitive engagement. In the subsequent sections, it is explained how we developed the VR environment and how the AI algorithm utilized the data obtained from the hardware components to identify the movements of the leg.

A. VR Implementation

The VR environment was created using Unity 2020.3.41f1 and built for the Oculus Quest 2 headset. The Oculus Quest 2 was selected based on its wireless capability, which simplifies and encourages system usage by eliminating the complexity associated with BMI integration.

Fig. 3 depicts the virtual reality (VR) environment we created, comprising a soccer stadium with enthusiastic spectators and music from previous soccer World Cups to enhance immersion and user experience. The VR scenario features a goalkeeper guarding a goal while a soccer ball is in play. We opted for this specific scenario and sport owing to its striking resemblance to the leg movements delineated in the earlier sections, which is precisely what we aim to rehabilitate. Utilizing the controller in their hand, users have the ability to navigate an imperceptible rectangular area bounded by the penalty area and the goal range. The primary objective of this feature is to provide users with the freedom to make their own shooting decisions and fully experience gamification, while simultaneously establishing limitations that prevent users from straying too far from the intended environment. Upon determining their desired shooting location, users are able to leverage the BCRE to facilitate the kicking action. The overarching objective of this design is to enable users to manipulate the RE, ultimately propelling the leg forward to strike the virtual ball, all while utilizing the BMI to seamlessly initiate the desired movement without any physical exertion.

B. BMI Integration

In order to control the virtual leg to kick the virtual ball, an EEG processing module and a control decision module were integrated to the system.

1) *EEG pre-processing module*: The EEG processing module functionality consists of acquiring EEG data from the hardware (AURA headset from Mirai Innovation, Japan) and calculate the power spectral density data to the Training module. EEG data from 8 selected electrodes (F3, Fz, F4, C3, Cz, C4, P3, P4 according to the 10-20 electrode position system) is sampled at 250 Hz, cutting off artifacts by a notch filter at 60 Hz, bandpass filtered between 0.5 and 60 Hz. The short-time Fourier transform (STFT) is used to compute the power spectral density (PSD) of five frequency bands: δ (1-4Hz), θ (4-8Hz), α (8-12Hz), β (12-30Hz) and γ (30-60Hz).
2) *Training module*: The calibration process encompasses the acquisition of output signals from the Electroencephalography (EEG) processing module, which are then utilized to train a binary regression model to differentiate between two distinct states: 1) when the user is contemplating the act of kicking or moving the leg during rehabilitation, and 2) when the user is in a state of rest. Data is accumulated via a single trial of 60 seconds. To initiate the trial, a set of instructions are provided either by the system via the screen, or by the instructor himself. The user is then prompted to visualize kicking the ball for 30 seconds before subsequently visualizing relaxation of the leg for an equivalent duration. Lastly, the system delivers a notification to the user at the conclusion of the test. The reason why we choose a Binary Logistic Regression model is due to its ease with problems with a linear decision boundary. It is computationally efficient, relatively easy to interpret, and

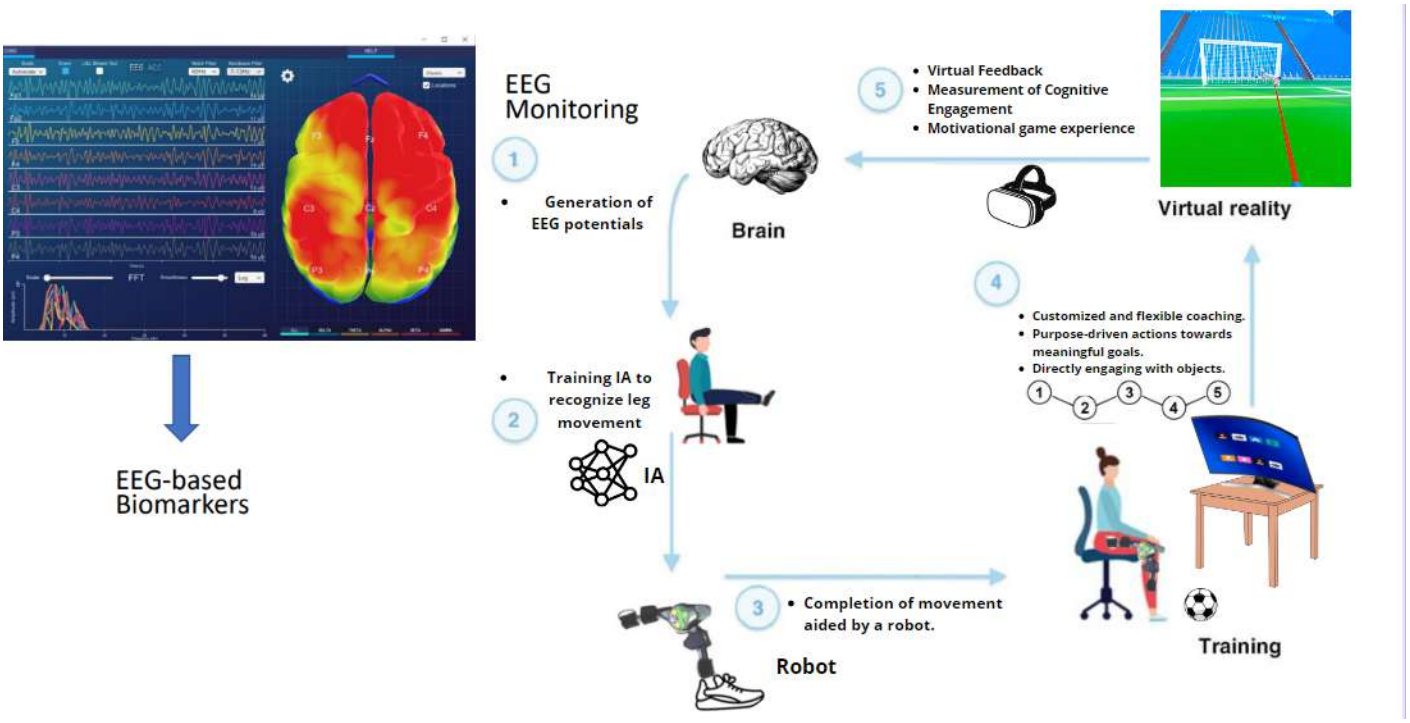

Fig. 1. System architecture

Fig. 2. VR Controller Grip for the footwear

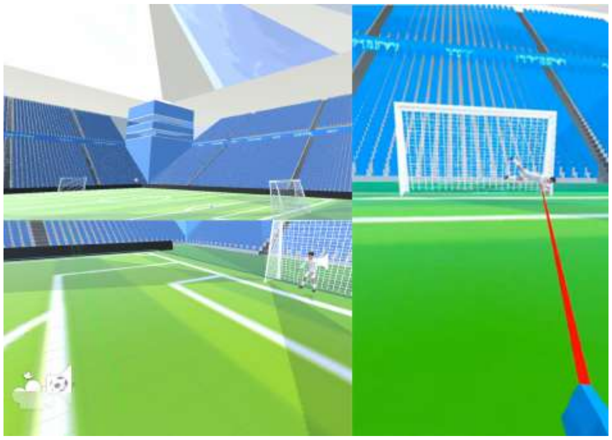

Fig. 3. VR soccer stadium environment

can achieve high accuracy. Although, it may not be as robust to outliers, noisy data, or unbalanced classes compared to other algorithms like: Support Vector Machines (SVM), Random Forest and Neural Networks as are mentioned in the literature [11], [12]. Nevertheless, in the case of this system, we took all the necessary precautions to avoid these issues.

3) *Control decision module*: The control decision module receives the trained model from the calibration process. Alternatively, an imported pre-trained model can be utilized, eliminating the need to undergo the calibration phase. Therefore, to determine the RE action (Extend the leg to kick the virtual ball or stay still). The selection of the action to execute is streamlined via the Cognitive State Accumulator (CSA). This functions as a real-time meter that gauges the user's mental intention by accumulating the outputs of the trained model, which are generated by processing the user's Power Spectral Density (PSD) from real-time EEG data as input. In the event that the model perceives the user's brain signals as indicative of a movement intention, the control system shall increment the value of the CSA by one. Conversely, if the model identifies that the user's brain signals are indicative of the desire to remain still, the CSA value shall be decremented by one, while ensuring that it remains above zero. Once the CSA reaches a

predetermined threshold (With all the subjects, the value has been explicitly set to 1000), it activates the option to move the leg via the RE, subsequently resetting to zero and the user is given a grace period of five seconds to relax, ensuring that the CSA value remains close to zero and is not inadvertently triggered. This approach provides a safe and reliable means of preventing unintended activation of the control system and facilitating optimal user experience. In contrast, if the threshold is not met, the option to move the leg remains inactive, as shown in the Fig. 4.

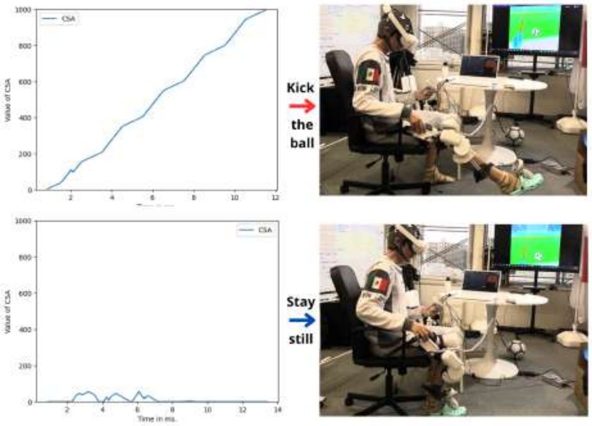

Fig. 4. Pre-defined actions due to the Cognitive State Accumulator by the control module

III. SYSTEM FUNCTIONALITY ASSESSMENT

The primary objective of this system functionality assessment was to demonstrate the functional assistance and explore the experience offered by the proposed system. To gauge the user learning activity, successful goal attempts were monitored throughout the learning process. Likewise, we incorporated user feedback pertaining to user experience, user interface, and other aspects of system interaction to facilitate future enhancements.

A. Experimental User Study

The assessment involved 5 healthy subjects, around the ages of 20 to 25 years old, through a total of 42 trials. The test consisted of the following; the subjects were seated in front of a computer screen placed at a distance of approximately half a meter. An EEG cap was fitted on each participant's head to compute the CSA and to control the system in the second stage of the study. To simulate leg movement difficulties, a resistance band was attached to the bottom of the chair and their foot.

The dynamic of the test included the subject to equip the entire system, as described in the preceding sections (including calibration of the system, adjustment of the RE, donning the VR glasses, and positioning one control in each hand and foot). They were then asked to score the maximum number of goals against the virtual goalkeeper in 60 seconds.

B. Results

From the 42 trials done, in 31 of them the participants were able to connect to the system and trigger the action of the exoskeleton in order to interact with the VR environment. This gives us a success rate of **73.80%**. Moreover, the trials also included the surveying of user experience and desired additions from the subject's point of view.

C. User Feedback

Within the conducted trials, the subjects were asked to describe their experience in order to improve the functionality of the proposed system. The following feedback was obtained:

- ”Using the brain-controlled exoskeleton with VR was like stepping into a sci-fi adventure. However, I did find the initial setup a bit time-consuming, and it took some mental effort to get everything calibrated. Also, while the exoskeleton provided great support, adjusting it for comfort was a bit tricky due to its weight and stability.”
- ”The VR environment made the exercises feel like a fun game, and I could see my progress in real-time, which was super motivating. However, I did struggle a bit with navigating the interface, clearer instructions on all the the features would make the whole experience more immersive.”
- ”While the cap for measuring brain signals was a bit finicky when I moved around, the combination of the robotic exoskeleton and VR was unlike anything I'd ever experienced. If it could stay put better, it would make the whole process even smoother.”

The subject's comments, led to the identification of the following critical areas of improvement, including:

- Reducing the system calibration time to minimize cognitive load.
- Improving the method of adjusting the RE to enhance ease of operation and comfort, given its weight and low stability
- Refining the user interface to offer better guidance on the different options and customization available in the system
- Modifying the design of the cap used for measuring brain signals to enhance its resilience against external movements or artifacts
- Enhancing the immersion of the VR feedback to increase the realism of the exercises and the user engagement, thereby improving the gamification of rehabilitation.

IV. FUTURE WORK

Our subsequent phase, subsequent to addressing the feedback provided by the users in the preceding section, is to conduct an experiment with a cohort of individuals using conventional rehabilitation methods, followed by the proposed method, for a longitudinal study to monitor the improvement process in both groups of patients and substantiate the superiority of our system over existing approaches. Additionally, we will incorporate the functionality of real-time monitoring of cognitive engagement using the same EEG signals computed in the system. Studies exploring the physiological factors associated with cognitive impairment have revealed that EEG signals can effectively distinguish between high and low states of cognitive engagement [12].

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