REINVENT: A Low-Cost, Virtual Reality Brain-Computer Interface for Severe Stroke Upper Limb Motor Recovery

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ABSTRACT

There are few effective treatments for rehabilitation of severe motor impairment after stroke. We developed a novel closed-loop neurofeedback system called REINVENT to promote motor recovery in this population. REINVENT (Rehabilitation Environment using the Integration of Neuromuscular-based Virtual Enhancements for Neural Training) harnesses recent advances in neuroscience, wearable sensors, and virtual technology and integrates low-cost electroencephalography (EEG) and electromyography (EMG) sensors with feedback in a head-mounted virtual reality display (VR) to provide neurofeedback when an individual's neuromuscular signals indicate movement attempt, even in the absence of actual movement. Here we describe the REINVENT prototype and provide evidence of the feasibility and safety of using REINVENT with older adults.

Keywords: Brain computer interface, neurofeedback, stroke, virtual reality, EEG, EMG

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities; J.3 [Computer Applications]: Life and Medical Sciences—Health

1 INTRODUCTION

Stroke is one of the leading causes of adult disability worldwide, and despite intensive physiotherapy, up to 2/3 of stroke survivors never fully recover [1]. In particular, individuals with severe motor impairments following stroke, who are unable to move their arm or hand, show the poorest outcomes, as they are unable to actively participate in traditional rehabilitation [1]. However, emerging research has examined ways to facilitate activation of the damaged motor cortex in the absence of volitional movement. Two primary ways include: 1) the action observation network (AON), and 2) neurofeedback from brain computer interfaces (BCIs). First, the AON consists of motor-related regions in the brain that are active during both the performance of an action and simply during the *observation* of an action, making it a feasible way to stimulate cortical motor regions in the absence of volitional movement [2,3]. The AON is active when stroke patients observe a limb that corresponds to their own affected limb [3] and can lead to improvements in individuals with severe motor impairments [4]. Second, BCI-based neurofeedback is typically defined as sensory feedback of biological activity in the brain (e.g., as measured with electroencephalography; EEG) that is used to control a computerized device (e.g., movement of an object on a computer screen). BCIs for severe stroke attempt to 'close the loop' between motor commands and sensory feedback, but often employ less biologically-relevant feedback, such as a moving a ball or a thermometer, which reflects brain activity.

Both AON-based therapies and BCIs typically produce only modest gains. One way to improve gains may be to combine approaches, and provide biologically-relevant action observation feedback in an immersive virtual reality BCI environment. To address this, we developed REINVENT. Designed for individuals with severe motor impairments, REINVENT pairs an individual's own neural and muscular commands with augmented, but believable, embodied feedback of one's own movements in virtual space. Visual feedback of one's own limb moving is an effective way to activate the AON and 'close the loop' between a motor command and sensory feedback. Virtual reality now makes it possible to show severe stroke patients a healthy body moving in response to their own brain activity. Augmented VR-based feedback of an impaired limb encourages greater use of that limb in stroke patients [5], and VR-based augmentations can be embodied by the user, leading to changes in behavior. REINVENT also provides flexible options to use just EEG, just EMG, or a combination of both to drive the neurofeedback, and employs a low-cost system with 3D printed components and a laptop to keep the unit affordable and portable. REINVENT builds on previous research to characterize patterns of neural and muscle activity that indicate attempted movement. When brain and/or muscle patterns indicate intended movement, the REINVENT's VR system will provide realistic, augmented visual feedback of the participant's limb moving in virtual space, even if the patient is not moving in reality. Here we report the technical specifications of REINVENT as well as preliminary feasibility and safety testing with healthy older adults.

2 SYSTEM DESCRIPTION

REINVENT is an integrated hardware-software BCI system that receives data from brain/muscle sensors, integrates and analyzes the data in near real-time, and generates virtual reality feedback for a participant and on-screen status information for a clinician.

Figure 1: Left - OpenBCI board and neoprene cap assembly. Right - REINVENT Arm IMUs attach to the forearm and palm.

2.1 Hardware

The REINVENT hardware includes an OpenBCI EEG/EMG device, a wearable forearm motion capture system including two Nine Degrees of Freedom (9DOF) interial measurement units (IMUs), a computer, and a Head-Mounted Display (HMD).

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2.1.1 Brain-Computer Interface

The OpenBCI device is a 16-channel EEG/EMG system. The OpenBCI 32-bit v3 board with Daisy Module is used to provide a total of 16-channels of sensing, connected via Bluetooth LE to a host computer. Our use case configures 12 of the 16 channels for EEG sensing, and 4 for EMG sensing, sampling at 125Hz. The EEG channels are based on the 10-10 EEG convention [6] and are concentrated over the prefrontal and motor cortex at F3, F4, C3, C1, C2, C4, CP5, CP1, CP2, CP6, P3, and P4. Dry electrodes are mounted to a neoprene cap using 3D printed retaining clips. The EMG channels are placed on the wrist flexor (Channels 1 and 2) and extensor (Channels 3 and 4) muscle bellies in the forearm of the affected limb. An EMG reference electrode is attached on the bony prominence of the elbow.

2.1.2 Orientation Tracking

The position of the participant's forearm is tracked by two IMUs attached via elastic straps to the back of the palm and the upper forearm. These are used to provide a sense of embodiment and contingency between an experimenter moving the participant's arm in reality and the participant seeing "their" arm move in VR. The IMU hardware consists of a Teensy 3.2 microcontroller and two LSM9DS0 9DOF sensors on AdaFruit development boards in 3d-printed cases. The LSM9DS0 sensors communicate with the Teensy via SPI. The IMUs sample at 120Hz, and sensor orientation is recovered via the Madgwick algorithm [7]. These orientations are transmitted via a binary protocol over USB serial.

2.1.3 Head-Mounted Display

REINVENT currently uses an Oculus DK2 HMD, which includes positional and rotational tracking. A current version of the Oculus VR SDK is employed, which preserves forward-compatibility with the Oculus CV1 hardware.

2.2 Data Integration and Processing

The REINVENT software stack includes the REINVENT VR application itself and the REINVENT Peripheral Interface.

2.2.1 REINVENT Peripheral Interface

Data received from the OpenBCI and IMU systems are processed via a .NET 4.5 application, which connects to the peripherals via USB Serial, and hosts a TCP/IP server. Other applications, namely REINVENT VR, connect as clients and are sent EEG/EMG and IMU orientation data via a simple binary protocol. The Peripheral Interface implements the OpenBCI binary streaming protocol to communicate with the OpenBCI headset.

2.2.2 REINVENT VR

REINVENT VR is implemented in Unity 5.4 and presents a VR display including a virtual arm and simple room scene including a desk surface, similar to the physical setting of the experiment. The Unity application receives streamed EEG/EMG and IMU data, performs EEG data processing, and updates the representation of the arm to reflect the participant's input. The clinician may select the input modality (IMU only, EEG only, EMG only, or a hybrid of EMG and EEG activity). In the case of IMU input, the user's virtual arm is directly animated. In EEG and EMG input, the virtual arm's position is incremented towards the goal position, or decays towards the rest position, based on an instantaneous comparison of the activity level to a resting baseline.

Data processing occurs online. Changes in activity of the EEG channels over the contralateral motor cortex are used while the participant is asked to imagine moving their arm. For each channel, the data is low-pass filtered (second order Butterworth with cutoff of 0.5Hz), the newest N=256 samples are windowed, and FFT transformed. Power is computed for the bins corresponding to the range between 8Hz and 24Hz, which is used to capture broad activity in alpha and beta bands in the motor cortex that may correspond to motor imagery.

3 Feasibility and Safety with Older Adults

To test the feasibility and safety of REINVENT with older adults, we recruited 12 individuals for this 1-hour experiment (11 female/1 male, aged: M=83±10.5). Eligibility criteria included healthy individuals with no previous experience with virtual reality. Informed consent was obtained from all subjects, and the experimental protocol was approved by the Institutional Review Board at USC and performed in accordance with the 1964 Declaration of Helsinki. We assisted participants with putting on the REINVENT device. Participants were asked to rest for a 30-second baseline calculation of EEG and EMG signals. Participants were then asked to try to control their virtual arm in REINVENT and move it towards goal positions using either actual arm movements (IMUs), just muscle activity (EMG), or just brain activity (EEG; using motor imagery), for up to thirty trials of each. The experimenters provided verbal instructions to guide the participants. Afterwards, the Simulator Sickness Questionnaire was administered to assess physical discomfort across 15 categories (e.g., fatigue, nausea, headache; 1 being none, 4 being severe). Participants were also asked to rate how interesting and enjoyable they found REINVENT (on a scale of 1 to 10, 1 being "not at all" and 10 being "extremely"), and whether they would be willing to try the device again. After using REINVENT, participants reported little to no physical discomfort across all categories of the Simulator Sickness Questionnaire (total m:1.16±0.29). Participants also rated REINVENT extremely interesting (m:9.67±0.62), extremely enjoyable (m:8.92±1.19), and all twelve were willing to try the device again.

4 Conclusion and Future Work

We have described a novel low-cost, portable VR-based brain computer interface and demonstrated the feasibility and safety of using this device with older adults. Feedback from these individuals was used to further refine the REINVENT interface. Future research will examine the feasibility and preliminary effectiveness of using REINVENT with older adults after stroke.

References

[1] Kwakkel, G., et al., Probability of regaining dexterity in the flaccid upper limb impact of severity of paresis and time since onset in acute stroke. *Stroke*, 34: 2181-2186, 2003.

[2] Garrison, K.A., et al., The mirror neuron system: a neural substrate for methods in stroke rehabilitation. *Neurorehabilitation and Neural Repair*, 24:404-412, 2010.

[3] Garrison, K.A., et al., Modulating the motor system by action observation after stroke. *Stroke*, 44:2247-2253, 2013.

[4] Franceschini, M., et al., Clinical relevance of action observation in upper-limb stroke rehabilitation. *Neurorehabilitation and Neural Repair*, 26: 456-462, 2012..

[5] Ballester, B.R., et al., The visual amplification of goal-oriented movements counteracts acquired non-use in hemiparetic stroke patients. *Rehabilitation*, 12:50, 2015.

[6] Electrode Position Nomenclature Committee. (1994). Guideline thirteen: guidelines for standard electrode position nomenclature. *J Clin Neurophysiol*, *11*, 111-3.

[7] Madgwick, S.O. et al., Estimation of IMU and MARG orientation using a gradient descent algorithm, *2011 IEEE International Conference on Rehabilitation Robotics*, Zurich, pp. 1-7, 2011.