Towards Brain-Machine Interface-Based Rehabilitation for Patients with Chronic Complete Paraplegia

Solaiman Shokur

Abstract We recently interviewed Solaiman Shokur about the project that his team submitted to the BCI Research Award in 2019. We then edited the interview and added images that Dr. Shokur kindly shared to provide more information about the team and project. Their project showed how a BMI-based protocol could provide partial neurological improvements for persons with spinal cord injuries. This is a very promising research direction, and several projects focused on improved rehabilitation therapy have been nominated for BCI Research Awards.

Keywords Brain-Machine Interface (BMI) · Spinal cord injury (SCI) · Neurorehabilitation · Treadmill · Multisensory integration

1 Introduction

In the first few decades of BMI research, most works aimed to help severely disabled patients by providing tools for communication (such as spelling) and/or control (such as a robotic arm). The prospect of using BMIs to help people recover motor function had been considered, but not well explored (Kuebler et al. 2001; Wolpaw et al. 2002). However, over the last decade, numerous papers have explored BMIs to support motor rehabilitation for people with stroke (e.g., Mrachacz-Kersting et al. 2014; Guger et al. 2018; Mane et al. 2020).

This chapter presents an interview with Dr. Solaiman Shokur about his work with the Walk Again Project team in São Paulo, Brasil, to extend this approach for

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patients with chronic complete spinal cord injury (SCI). Recovering motor function is currently considered difficult or impossible for patients with some types of SCI, but Dr. Shokur describes how a new system integrating EEG-based BMI, with visuotactile feedback and locomotion could lead to new forms of treatment. Their project, team, and affiliation was (Fig. 1).

The Walk Again Neurorehabilitation Protocol: A BMI-based Clinical Application to Induce Partial Neurological Recovery in Spinal Cord Injury Patients.

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2 Interview

What was the goal of your project?

Solaiman: The goal was to study the neurological effects of BMI-based neurorehabilitation protocols for spinal cord injury (SCI) patients. The classical use of BMIs for SCI patients is as an assistive device. Simply said, it's a technique to bypass the lesion using a compensatory approach. We were interested to see how, under some conditions, it is possible to induce neurological recovery. We studied a neurorehabilitation protocol that integrated non-invasive (EEG-based) BMI with virtual reality and tactile feedback, with eight SCI patients with chronic lesion.

How did you approach this goal?

Solaiman: The current study was a follow-up to our work in 2016 when we observed improvements that, to our knowledge, had never been reported before to this extent in patients with severe motor injury (also referred to as motor-complete SCI patients; Donati et al. 2016; Shokur et al. 2018). In that study, we observed

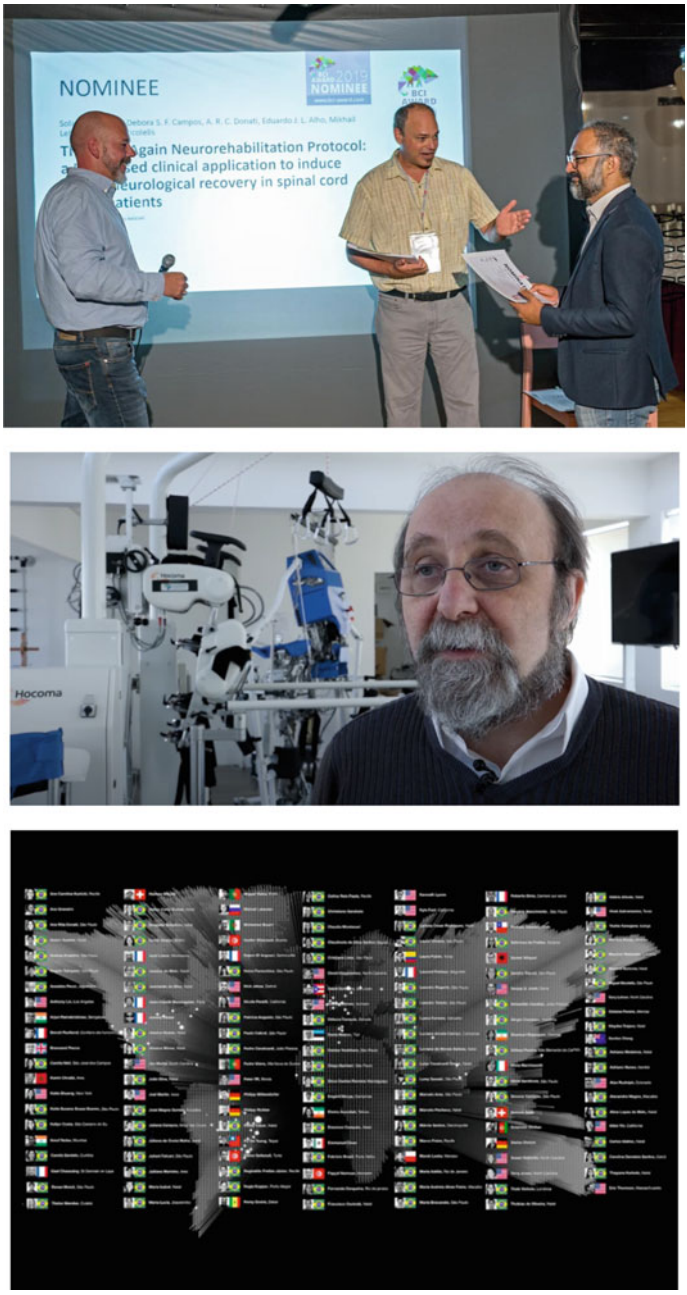

Fig. 1 (Top) Dr. Solaiman Shokur, Senior scientist at the Walk Again Project, at the 2019 BCI Award Ceremony (right). The left and middle persons are Drs. Gunther Krausz and Brendan Allison. (Middle) Prof. Miguel Nicolelis, Principal Investigator of the Walk Again Project. (Bottom) The Walk Again Project consortium included researchers from 25 countries

significant motor and sensory recovery levels below the lesion of the patient. These were patients at the chronic phase of their lesion and had a complete loss of motor functions (some also sensory). After twelve months of training, they had recovered significant levels of sensation below the lesion and motor function in the lower limbs. Our goal for this second study was to isolate the effects of the non-invasive BMI to see if we could (a) reproduce our initial results and (b) investigate the impact of the BMI on top of locomotion training.

Our approach was to do a small clinical trial with a group of eight chronic complete SCI patients. We divided them into two subgroups. One group performed locomotion training only. The other group did the same locomotion training and had, additionally, one BMI session per week.

Which technologies did you use?

Solaiman: We chose a purely noninvasive approach with EEG-based BMI, including event-related synchronization (mu rhythms in the motor cortex). We were looking specifically for leg motor imagery. We wanted to encourage our patients to imagine moving their legs—not imagining locomotion in an abstract way—and alternate between the left leg and right leg motor imagery. We used this decoding to move the corresponding leg of a 3D avatar in a virtual reality (VR) environment.

The BMI was connected to a VR simulation of walking? Are you extending this to robotic devices?

Solaiman: Absolutely. We also did it with robotic devices and functional electrical stimulation (FES). The work is presented in another published paper from last year (Selfslagh et al. 2019), where we had BMI and FES, alone or in combination. We have also observed motor improvements in BMI-FES and BMI-exoskeleton.

How did you use exoskeletons and treadmills?

Solaiman: In the study presented for the BCI Award, we used two modalities for locomotion training. We call it active locomotion training, as opposed to passive mobilization. In one paradigm, the patient was using a robotic gait trainer (Lokomat, Hokoma), and the physiotherapist was constantly motivating the patient to try to perform the task. So, the patient had an incentive to perform the task. The second locomotion paradigm was with body-weight supports on a rail (the ZeroG system, Aretech). Both subgroups had the exact same physical training and the same number of sessions (Fig. 2).

What results did you get?

Solaiman: First, we observed some improvement in both motor and sensory functions for patients that followed the locomotion training alone. Therefore, the first conclusion is that even patients who were completely paraplegic and in the chronic stage of their lesion could benefit from an active locomotion training with the Lokomat and the body weight support. Second, importantly, we observed a systematically larger improvement for the group that followed both the locomotion and BMI training. When we reviewed their progress after five months, and again after

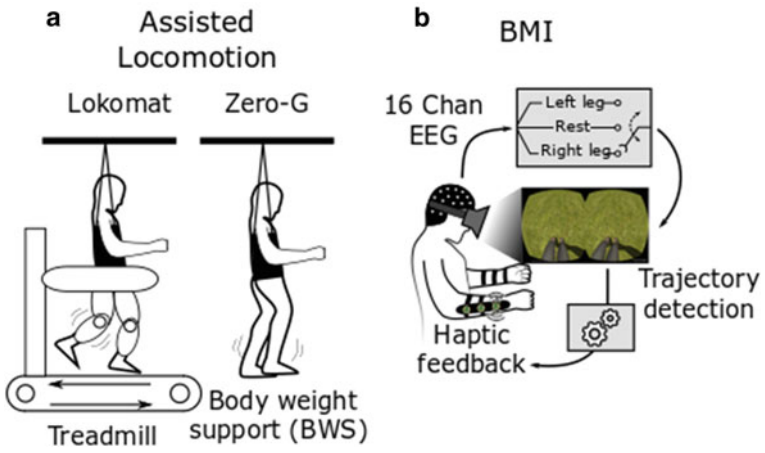

Fig. 2 (A) The assisted locomotion training included training with a Lokomat and body weight support system (B) During the BMI task, the patient used left/right leg motor imagery to trigger the stepping of the corresponding leg of a 3D avatar seen in the first-person view

nine months, we saw that the BMI+locomotion group was always better than the locomotion-only group. This was specifically true in the motor domain. The biggest differences we saw were in the motor domain and proprioception.

How many training sessions did you perform, and how long was each session?

Solaiman: The patients came two times per week for approximately 30 weeks. The Locomotion-only group would do one day of Lokomat training and another day of body-weight support training. The BMI+Locomotion group would do the BMI the same day as the Lokomat (the BMI training was done right before the Lokomat), and then the body-weight training on another day. Therefore, both groups came twice per week.

The Lokomat and body-weight training lasted 45 min each. The BMI training was 4 times 6-minute runs.

How important are these results for patients?

Solaiman: Our result was quite important for demonstrating, for the first time, that AIS A or AIS B patients could recover neurological functions. To our knowledge, that had not been systematically shown to that extent. From a rehabilitation point of view, it is crucial to show that it is possible to improve those patients. The original paper had an important impact on the neurorehabilitation field. For clinicians, it's interesting because it's a relatively cheap technology. For hospitals or other clinical environments that already have Lokomats, adding a BMI is not very complicated. Even for the BMI itself, we are using well-known technologies, and you (Christoph) are engineering them and already using them for stroke patients. Since those techniques already exist and are even commercially available for stroke patients, they could be used in this protocol without changing too much. So, both the locomotion and BMI components

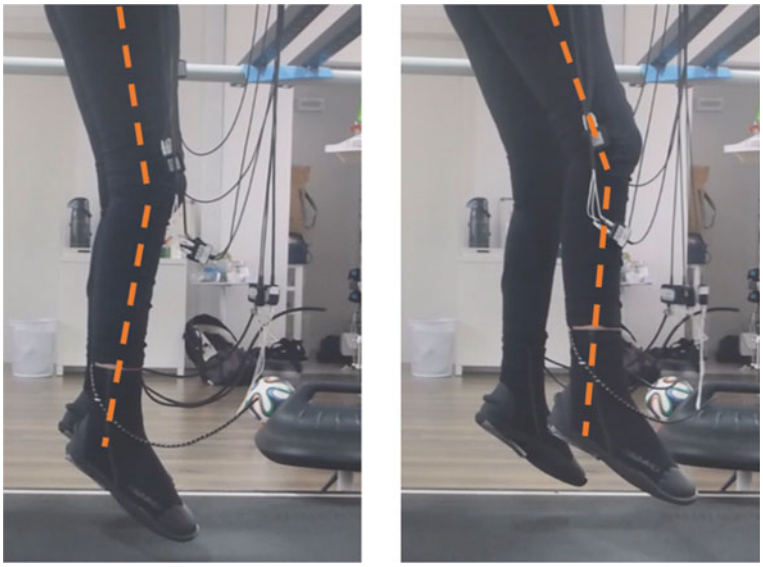

Fig. 3 Patients who were initially diagnosed with complete loss of sensory-motor functions due to Spinal Cord Injury recovered significant motor function levels after training with the Walk Again Neurorehabilitation Protocol. Some of them could voluntarily contract their leg without external help (from Shokur et al. 2018)

are relatively easy, and the results were stronger than we expected and quite important for the field. However, the protocol is not yet optimized in time, and 30 weeks of training is certainly too long for this protocol to be deployed in an extended manner. We are currently working on optimizing the protocol and believe that intense training over a shorter time might induce the same recovery level, or maybe better (Figs. 3 and 4).

How are your results applicable in clinical or real-life environments? Could you imagine this could be used in hospitals, rehab centers, or homes in a few years?

Solaiman: All of the above. Our idea is to use BMIs in a neurorehabilitation protocol for SCI patients. Our protocol integrates BMI and locomotion training; we believe both aspects were essential to induce recovery. Indeed, other groups that have trained patients with the same kind of trauma with BMI alone did not observe this type of improvement. In the future, it might be possible to have the BMI part done at home and the locomotion part in a rehab center, but we have not tested it yet. So, it could be done to some extent at home.

What are the next steps in your research?

Solaiman: I think this first pilot-test was essential to show a proof of concept and reproduce our results from 2016; seeing the same effect in the second group

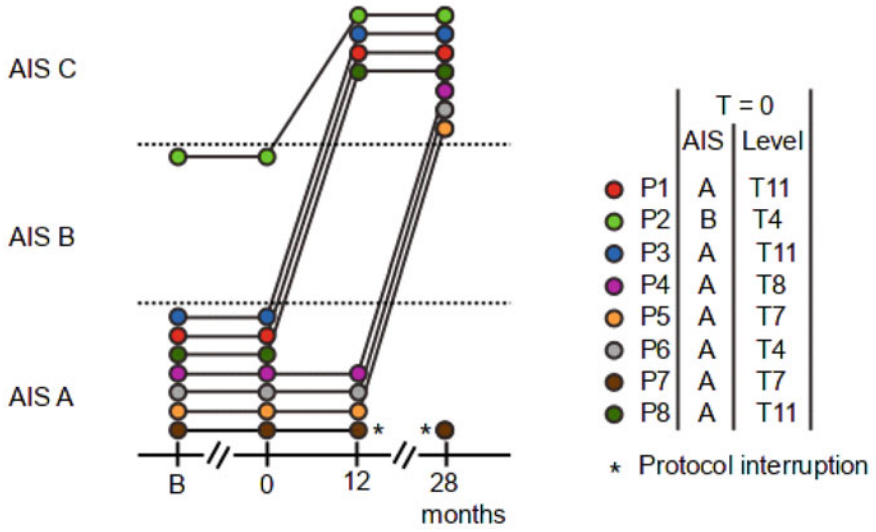

Fig. 4 Prior work (Shokur et al. 2018) showed that training integrating non-invasive BMI, locomotion and visuotactile feedback induced significant recovery in a group of SCI patients. As a result, all seven patients that followed the protocol for 28 months improved to AIS C. Patient P7 voluntarily dropped out from the protocol after 12 months (personal reasons). Baseline measurement (B) was done by the clinical institution that followed the patients before they joined the protocol, and was done 1-3 years after the lesion. T = 0 stands for the first measurement done at the onset of the training, the 'Level', corresponds to the neurological level of the injury measured via with the ASIA test (see https://asia-spinalinjury.org/wp-content/uploads/2019/04/ASIA-ISCOS-IntlWorksheet_2019.pdf)

was very interesting. Similar results have been reported in animal models, such as by Courtine and colleagues at EPFL (Bonizzato et al. 2018). We are interested in understanding the mechanism of what is going on because this is something missing at the moment. We have some hypotheses about why the patients improved to this extent. We are trying to understand this mechanism through fMRI protocols. One important step would be to understand what happens at the spinal cord level and the brain level and reproduce results with a larger group of patients and a sham BMI control group, which was not the case in our protocol.

What is your experience in terms of the BMI performance of your spinal cord injury patients? Did they perform well?

Solaiman: Yes. The results were good. There are differences among patients. There were good performers and some average ones. We didn't have people who were completely at chance level. We didn't observe the effect that has been reported in the past called *BMI illiteracy*, which has been a major challenge for many years (Allison and Neuper 2010; Viduarre and Blankertz 2010; Thompson 2019). Maybe that's because the number of patients we had was small, but we didn't observe that. The people who were really good were so from the beginning. The other ones reached

around 80% accuracy after a few sessions. We had six sessions at the beginning to check how they were performing, and then people stabilized around 75–80%.

This is also our experience. In my understanding, a patient doesn't exist who is not able to control a BMI. Everybody can control it. Just people are doing something wrong if they don't reach an accuracy above chance level.

Solaiman: That was our observation, too, absolutely.

Thank you. That was a very nice explanation of what you did.

Solaiman: Thank you

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