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EC NEUROLOGY
Review Article

Sensor-Based Brain/Machine Interface with Neuromuscular Stimulation to Allow Unbraced Walking by Thoracic-Level Paraplegics

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Received: November 27, 2025; **Published:** December 22, 2025

Abstract

The paper describes a sensor-based virtual Brain-to-Machine Interface (BMI) that allows unbraced walking at will by certain complete thoracic-level paraplegics using neuromuscular electrical stimulation (NMES). The multi-sensor system is walker-mounted, using a reciprocal walker. The sensors communicate electromagnetically (via Bluetooth microchips) with the NMES stimulator. This virtual interface (BMI) facilitates at-will walking, avoiding any brain electrodes or implants and requires no manual switching to initiate any step during walking. It is based on observing the elements of steps taken by paraplegics using the Parastep NMES system at the author's lab. Based on these observations, a set of sensors is employed, to detect patients' intentions and trigger NMES stimulation pulses accordingly, to result in un-braced walking at will. The resulting sensor data is shown to disallow unintentional steps while requiring only natural movements and avoiding any unnatural or pre-trained body or limb movements.

Keywords: *Brain-Machine-Interface; Neuromuscular-Stimulation; Paraplegic; Reciprocal Walker Sensors; Spinal Cord; Thoracic-Level; Walking*

Introduction

The concept of Brain-to-Machine Interfacing (BMI) is not new [1]. Its purpose is to identify a command that is willed and generated in the brain for executing an action by a device (including a body-part or computer) and where the commands from the brain must bypass the spinal cord, without using any invasive wiring or sensors in the brain.

By definition, BMI has and will have enormous potential in medicine. Other uses of BMI may be in space, in undersea applications and beyond. Yet, within the scope of its medical use [2], BMI is almost tailored for applications to people whose spinal cord is damaged and is prevented from passing brain commands to limbs, organs, etc.., due to paralysis and other neurological movement disorders [3-6]. The present paper belongs to this particular domain of applications.

This paper describes a Brain-to-Machine Interface to facilitate at-will walking by certain paraplegic patients under Neuromuscular Electrical Stimulation (NMES), without any manual activation of their walking steps.

Specifically, this paper presents a detailed design that facilitates unbraced standing and walking with the FDA-Approved (1993) Parastep-1 [7] NMES system (or similar systems) by complete upper motoneuron paraplegics, namely, by paraplegics with spinal cord lesions at thoracic section of their spinal cord at any level between T1 and T12, thus having no sensation or motor function below that level.

The original design of the Parastep NMES system was done at the laboratory of present author in Chicago, Illinois during the late 1980's and early 1990's, using a single MANUAL finger-touch activation of a full sequence of stimulation pulses for each complete step (See [9] and related patents by D Graupe). The Parastep System was shown to facilitate reliable walking half hour or more, by certain complete paraplegics, as described in [8-10].

BMI control, using surface-EMG (sEMG) as sensor for identifying and communicating the intended will to the NMES system (namely, the "machine" of the BMI), was also developed in that lab [11-13]. However, it was considered too slow and. Hence, it was not considered as being ready approach above, for employing BMI in walking by BMI.

Recently, a re-examination of observations of hundreds of walks by patients was carried out. The re-examination concentrated on small elements of movements of different body parts involved in forming a step and their relative timing within a single step (as described in section observations of movement elements forming a step during walking below). These movement elements are related to neuromuscular stimulation (as in section neuromuscular stimulation sequence for generating steps in paraplegics). This reexamination is shown to provide information needed for uncovering the intention of patient's intention of taking a step, which is equivalent to the manual finger-touch command used in the Parastep or similar NMES systems (Section design of brain-to-machine sensor-based interface to replace manual switching for activating the neuromuscular stimulation system).

The resulting BMI approach is shown to be executed by SENSORS for certain elements within a step, thus forming a reliable BMI interface (as described in section design of brain-to-machine sensor-based interface to replace manual switching for activating the neuromuscular stimulation system). The BMI sensor system is located on the walker alone, which is electronically connected to the patient-worn stimulator-part of the NMES system.

Method

Observations of movement elements forming a step during walking

Observations of walking by thoracic T1 to T12 complete or near-complete spinal-cord-injured (SCI) patients when using commercial FDA-Approved Parastep-I NMES stimulation systems with their related reciprocal walkers, were carried out by the author over numerous hours of patient training in his laboratory and elsewhere. All Parastep users [8,9,12] have no damage to their cervical spinal cord, thus being in full control of shoulder, arm, hand and finger movements.

The observations, which considered movement elements of each step, indicate that when activating a new step (by finger-switching) during walking, the following pattern is followed.

LEFT step

a. The patient moves some additional parts of body weight than during regular standing or walking, over to his/her RIGHT arm, and therefore, onto the RIGHT hand-bar of the reciprocal walker and the patient tightens his/her grip on the RIGHT hand-bar.
b. Simultaneously with (a) above, the patient moves the LEFT hand-bar of the reciprocal walker forwards enough (several inches and unto a foot or more) to allow taking a LEFT step of anything from approximately 10 to 30 cm. Note that some additional body weight is already moving towards the RIGHT hand-bar (and therefore, towards RIGHT arm) so that the bodyweight on the LEFT arm is already being reduced, as in (a) above.

c. The LEFT leg is moving forward while being slightly bent and the body is moving forward with the LEFT leg.

d. The LEFT leg is stretching while landing on the floor/ground and the patient is ready for the NEXT step of his/her choice or just for standing.

RIGHT step

The same sequence of step-elements (a) to (d) is being repeated, when RIGHT and LEFT are interchanged consistently.

In the Parastep system, the sequence of step-elements (a) to (d) is observed when manually initiated by the patient via finger switching of a walker-mounted switches on right and left sides of the walker. However, the same sequence is valid regardless of how decision of taking the step originates. Movement elements (a) and (b) are executed by shoulder, arm and hand movements that are unaffected by thoracic-level paralysis.

In section design of brain-to-machine sensor-based interface to replace manual switching for activating the neuromuscular stimulation system below we shall describe the stimulation sequence of the present Parastep NMS system, where each step is manually activated by pressing a step-activation switch located on LEFT and on RIGHT hand-bar of a reciprocal walker. A single finger-touch on the LEFT step activation with will start as NMES sequence of different trains of stimulation pulses in different motoneurons and their related muscle contractions as needed to execute a complete step, either by lower motoneuron paraplegics (by NMES), or in able-bodied persons who walk un-aided, such that the walking, when using the Parastep system, closely resembles natural walking, shown in references [10-14].

Furthermore, in section design of brain-to-machine sensor-based interface to replace manual switching for activating the neuromuscular stimulation system we shall discuss the stimulation system with the same NMES system, but where a sensor-based virtual brain-to-machine-interface replaces manually activated switches, to facilitate walking at-will by the patient.

Neuromuscular stimulation sequence for generating steps in paraplegics

In the Parastep system, stimulation is applied transcutaneously, via 6 electrodes, 2 at the quadriceps, 2 at the common peroneal nerve (for triggering knee-bending) and 2 at the back, just below the spinal cord lesion (for trunk stability).

The NMS stimulation sequence while taken a step in the current Parastep NMS System [2-4], and its relation to on command of step activation, considering trains of pulses of 100 microsecond or similarly, at 10 to 18 pps (pulses per second) -as set by the physician responsible:

LEFT STEP

a. Increase level of stimulation by approximately 20% (from normal level at standing or at end of step) at RIGHT quadriceps (possibly also at RIGHT lower back). This action follows step's element (a) of section method above.

b. Stop stimulation at LEFT quadriceps. This action follows element (b) of section observations of movement elements forming a step during walking above.

c. Stimulate LEFT Common Peroneal Nerve (CPN) to bend LEFT knee. This action initiates element (c) of section observations of movement elements forming a step during walking.

d. Stop stimulation at LEFT CPN.

e. Stimulate LEFT quadriceps at normal level. This stimulation activates movement (d) of section method above.

f. Reduce Stimulation at RIGHT Quadriceps and back to level prior to action (A), namely to normal level. Stimulation action (F) follows element (d) of section observations of movement elements forming a step during walking above. RIGHT STEP.

Same as LEFT step but interchange all LEFT to RIGHT and all RIGHT to LEFT consistently.

Design of brain-to-machine sensor-based interface to replace manual switching for activating the neuromuscular stimulation system

Retrieval of unique actions at start of step to facilitate BMI sensor interface

In the present Parastep system, the sequence (a) to (d) of section observations of movement elements forming a step during walking above [10] is manually initiated by the patient just prior to movement action (a) by a single finger switching of a walker mounted switch on right or left side of the walker. Also, all stimulation actions (A) to (F) follow the manual switching command. A next such single manual-switching is required only if a next step is to be executed.

However, our observations of reciprocal-walker users, paralyzed or not, indicate that the patients always execute the sub-sequence {(a),(b)} at the beginning of each step. This sub-sequence always precedes the other elements of every step and is necessary for stable walking and to avoid falling. Even people who are not paralyzed but require a walker for safety, follow the same movement sequence.

In observing hundreds of walks by paralyzed Parastep users, when a patient wishes to remove an arm off the walker for any purpose (picking up an item, shaking hands, etc..), then no patient was ever observed moving the hand-bar of the walker by 2 to 12 inches forwards. Also, patients were not observed to accidentally perform this combination. In all observations, even on non-paralyzed users of reciprocal walkers, the sub-sequence of {(a),(b)} was UNIQUE to taking steps and it always precedes other elements of a step, while it was NOT jointly implemented or not required in any other arm removal from a reciprocal-walker's hand-bar. C Therefore: When using BMI to totally avoid the need for manual switching, the stimulation actions (A) and (F) of section II(B) above, must immediately follow the occurrence of an overlapping execution of movement-element (a) and of the first 2-3 inches (or as decided by the physician in charge) of distance-increase with executing movement-element (b) of section observations of movement elements forming a step during walking above.

Sensors-setup conditions for at-will walking

The overlap conditions relating to movement-elements (a) and (b), as outlined in section observations of movement elements forming a step during walking above, are programmed into a set of 4 sensors (2 for LEFT step and 2 for RIGHT step) and one microcomputing microchip that analyses the sensors' firings. This set forms the BMI for At-Will walking with NMES systems (such as the Parastep-I) by paraplegics or by other handicapped people, thus replacing manual switching at each step, as follows:

I. Two weight or pressure sensors are attached, in order to detect element (a) of section observations of movement elements forming a step during walking above.

   One sensor, denoted SL(a), is to be located on the LEFT hand-bar of the reciprocating walker's hand-bars.

   The other sensor, denoted SR(a), is to be located on the RIGHT hand-bar of the reciprocating hand-bars.

   The weight-sensors will fire when the change in weight/pressure exerted by the patient's arms on the walker's hand-bars exceeds the incremental value that is pre-set by the physician in charge.

II. Two distance-sensors are attached, to detect the exceeding of pre-set distance between handbars while executing element (b) of section observations of movement elements forming a step during walking above.

   One sensor, denoted SL(b) relating to LEFT step.

   The other sensor, denoted SR(b) relating to the RIGHT step of section observations of movement elements forming a step during walking.

   These two distance-sensors serve to fire when the distance between given points on the RIGHT (LEFT) and the LEFT (RIGHT) hand-bar exceeds by approximately 2 to 3 inches (as set by the physician in charge).

III. A programmable microcomputing chip is attached to the reciprocal walker, which connects with all 4 sensors above. The microchip will produce an "ON" command only when and if the firing of the weight/pressure sensors and the distance sensors overlap or occur within one or very few seconds (to be determined by the physician in charge), as related to a given step.

The ON command will start the whole stimulation sequence A to F of section neuromuscular stimulation sequence for generating steps in paraplegics, to eliminate manual switch for same task, thus producing one complete step.

IV. An electromagnetic transmission chip (such as a Bluetooth [15] microchip) is attached to the walker -to transmit the output of (iii) to the patient-worn NMES stimulator.

This output thus represents the intention of the patient to take a given step, thus replacing the manual finger-switch command to the same Stimulator (Patient worn NMES stimulator).

Items (i) to (iv) above constitute the Virtual Brain/Machine interface for At-Will walking using NMES.

Proof for the validity of conditions (I) to (III) to activate a step at-will

The set of conditions (i) to (iii) of section proof for the validity of conditions (I) to (III) to activate a step at-will constitute the complete sensor-based BMI system.

The proof of the validity of this set of conditions, as being necessary and sufficient to deliver the patient's will to take a step despite the breach in his/her spinal cord, is neither statistical nor is it based on complex equations. It is based only on fundamental kinematics of human walking (taking steps), as follows:

- Regarding the distance sensors (condition (i) above)- steps in human walking require that one leg moves forwards (or even sideways) while the other remains stationary. Therefore, this cannot happen if there is no space to move it to. Hence, in the present case, the appropriate side of the reciprocal walker must be moved away from the side supporting the stationary leg. This takes care of condition (i) as a prerequisite to taking e step. Furthermore, the condition must be satisfied at the very start of taking a step.
- Regarding the weight sensors (condition (ii) above) - by definition, a step requires that body weight be moved to the stationary leg, since the moving leg may eventually be in the air. This condition must also be satisfied at the vert start of taking a step.
- Finally, regarding condition (iii) - Both conditions (i) and (ii) are necessary for producing a step. Both conditions are a prerequisite for the step and must start at starting the process of taking it. Also, they occur close together whenever the paralyzed patient wishes to take a step. Furthermore, the paralyzed patient can execute the moving of the bar of the walker or his/her body weight at will with his shoulders and arms. Finally, each of conditions (i) or (ii) can be realized even if the patient does not wish to take a step. However, when executed together, these conditions always relate to an intention to take a step, as in condition (iii). Hence, condition (iii) must be included in the BMI design. At worst, the leg will lift and land with no harm done.

Discussion

The movement-elements of a step, as described in section observations of movement elements forming a step during walking above, are essential, unavoidable, in the order given, as proven in section proof for the validity of conditions (I) to (III) to activate a step at-will above, and as is naturally occurring for executing a step while walking with a reciprocal walker. This justifies their use as components of the BMI application described above.

When using BMI as above, stimulation actions (A) and (B) of section neuromuscular stimulation sequence for generating steps in paraplegics await detection of forward-moving of arm on walker's hand-bar by a pre-set distance in order to activate the related sensor. This identification should take place as EARLY as possible during the execution of element (b) of section observations of movement elements forming a step during walking above. Therefore, the distance sensor should fire when the total change in distance reaches approximately two inches from the beginning of action (b), noting that element (b) must reach total extension of 6 to 12 inches to allow taking one step. This implies that most of the forward movement of the arm during action (b) must still follow the respective sensor has been triggered.

Since the distance sensor is activated early in the execution of element (b), the activation of stimulation actions (A) and (B) of section neuromuscular stimulation sequence for generating steps in paraplegics is delayed by only a fraction of a second per each step namely, until distance reaches 2-3 inches, rather than waiting till it reaches 6-12 inches.

The BMI-controlled system described in this paper does not require any change in the FDA approved NMES or its programming. All sensors and related microchips are to be placed on the walker and are standard components in themselves. BMI is totally non-invasive. Also, the use of Bluetooth facilitates wireless connection to the stimulator.

The medical benefits attributed to using the Parastep with manual switching, as reported in [16-20], also apply to the Parastep when using BMI instead. The step activation by BMI helps in making walking with NMES more natural both for the patient and also for the observer.

The Sensor-based BMI approach above is shown to be executed by SENSORS for certain elements within a step, thus forming reliable BMI interface (As described in section discussion). The resulting BMI is superior to using EMG sensors as tried earlier [9], if only by avoiding the burden on the patient in the need to daily precisely place and to replace surface-EMG electrodes on their arms. It is also faster, since using surface-EMG Based signals for identifying patient intention requires taking thousands of samples of signal data-points over a few seconds to satisfy mathematical convergence constraints [5,11], regardless of computer speed.

Conclusion

The design of a sensor-based brain-machine interface, as in section design of brain-to-machine sensor-based interface to replace manual switching for activating the neuromuscular stimulation system, is intended for at-will walking by thoracic level complete paraplegics, who have full upper-body movements. It is based on detailed observations of the movements of all parts of the upper body during walking by such patients when using the FDA-approved Parastep NMES system invented and developed at the present author's lab. It aims to replace the only manual switching required in that NMES system and which detracts from the natural appearance and feel of the walk.

All components of this interface are mounted on the reciprocal walker used by the patients and require no changes in the stimulation system itself.

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Bibliography

1. A Kawala-Sterniuk., *et al*. "Summary of 50 years with brain-computer interfaces-a review". *Brain Sciences* 11.1 (2021): 43.
2. J J Shih., *et al*. "Brain computer interfaces in medicine". *Mayo Clinic Proceedings* 87.3 (2012): 268-279.
3. M A Bockbrader., *et al*. "Brain computer interfaces in rehabilitation medicine". *PM&R* 10.9 (2018): S233-S243.
4. X Navarro., *et al*. "A critical review of interface with the peripheral nervous system for the control of neuroprostheses and hybrid bionic systems". *Journal of the Peripheral Nervous System* 10.3 (2005): 229-258.
5. D Graupe and W K Cline. "Functional separation of EMG signals via ARMA identification methods for prosthesis control purposes". *IEEE Transactions on Systems, Man and Cybernetics* 5.2 (1975): 252-259.
6. D Graupe. "Multi-function control of an artificial upper-extremity prosthesis for above-elbow amputees". US Patent 4,030,141 (1977).
7. Food and Drugs Agency, FDA approval P900038 (1994).
8. D Graupe., *et al*. "Ambulation of traumatic T4-12 paraplegics using functional electrical stimulation". *Critical Reviews in Neurosurgery* 8.4 (1998): 221-231.
9. D Graupe., *et al*. "Microprocessor-controlled enhanced multiplexed functional electrical stimulator for surface stimulation in paralyzed patients". US patent 5,081,989 (1992).
10. D Graupe., *et al*. "Walking performance, medical outcome and patient training in FES of innervated muscles for ambulation by thoracic-level complete paraplegics". *Neurological Research* 30.2 (2008) 123-130.
11. D Graupe. "EMG pattern analysis for patient-responsive control of FES in paraplegics for walker supported walking". *IEEE Transactions on Biomedical Engineering* 36.7 (1989): 711-719.
12. D Graupe and K H Kohn. "Functional electrical stimulation for ambulation by paraplegics -twelve years of clinical observations and system studies". Krieger Publishing Company, Melbourne, FL (1994).
13. D Graupe and S Basseas. "Method and apparatus for electrically stimulating quadriceps muscles of a upper motor neuron paraplegic". US Patent 5,070,873 (1991).
14. D Graupe. "Parastep I system WALK" video (1993).
15. B A Miller and D Disdikian. "Bluetooth revealed". Prentice Hall Publishing Company, Saddle River, NJ (2001).
16. Jacobs., *et al*. "Evaluation of a training program for persons using the Parastep-1 ambulation system-Part 2: Effects on physiological responses of peak arm ergometry". *Archives of Physical Medicine and Rehabilitation* 78.8 (1997): 794-798.
17. M S Nash., *et al*. "Evaluation of a training program for persons using the Parastep-1 ambulation system-Part 5: Lower extremity blood flow and hyperemic responses to occlusion are augmented by ambulation training". *Archives of Physical Medicine and Rehabilitation* 78.8 (1997): 808-814.
18. A Lichy., *et al*. Presentation at 12th annual conference of IFFES, Philadelphia, PA (2007).

19. R I Guest., *et al*. "Evaluation of a training program for persons using the Parastep-1 ambulation system-Part 4: Effects on physical self-concept and depression". *Archives of Physical Medicine and Rehabilitation* 78.8 (1997): 804-807.

20. M Belanger., *et al*. "Electrical stimulation: Can it increase muscle strength and reverse osteopenia in spinal cord injured individuals?" *Archives of Physical Medicine and Rehabilitation* 81.8 (2010): 1090-1098.

Volume 18 Issue 1 January 2026