Short Communication

A Fuzzy Controller for Movement Stabilization Using Afferent Control: Controller Synthesis and Simulation

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Abstract

Stimulation of spinal sensorimotor circuits can improve motor control in animal models and humans with spinal cord injury (SCI). More recent evidence suggests that the stimulation increases the level of excitability in the spinal circuits, activates central pattern generators, and it is also able to recruit distinctive afferent pathways connected to specific sensorimotor circuits. In addition, the stimulation generates well-defined responses in leg muscles after each pulse. The problem is that in most of the neuromodulation devices, electrical stimulation parameters are regulated manually and stay constant during movement. Such a technique is likely suboptimal to intercede maximum therapeutic effects in patients. Therefore, in this article, a fuzzy controller has been designed to control limb kinematics during locomotion using the afferent control in a neuromechanical model without supraspinal drive simulating post-SCI situation. The proposed controller automatically tunes the weights of group Ia afferent inputs of the spinal cord to reset the phase appropriately during the reaction to an external perturbation. The kinematic motion data and weights of group Ia afferent inputs were the input and output of the controller, respectively. Simulation results showed the acceptable performance of the controller to establish adaptive locomotion against the perturbing forces based on the phase resetting of the walking rhythm.

Keywords: *Afferent control, central pattern generator, fuzzy controller, movement stabilizing, spinal cord injury*

Introduction

During the last decade, many studies have provided evidence that after spinal cord injury (SCI), locomotor function can be recovered by various combinations of electrical and/or chemical neuromodulation therapies.[1-5] For example, it has been proved that the epidural electrical stimulation (EES) of the thoracic and lumbosacral spinal segments has improved motor control capabilities in rodents and humans with SCI.[6,7]

Many recent evidence suggests that EES increases the level of excitability in the spinal circuits, activates central pattern generators (CPGs), and has the ability to recruit distinctive afferent pathways connected to specific sensorimotor circuits. In addition, the stimulation generates well-defined responses in leg muscles after each pulse.[8-10]

The problem is that in most of the neuromodulation devices, electrical stimulation parameters are regulated manually by visual observations and empirical knowledge. After the manual regulation of amplitude, frequency, and pulse width, the stimulation of the spinal cord stays constant during movement. Such a technique is likely suboptimal to intercede maximum therapeutic effects in patients.[11,12] An increasing number of studies have found that the tuning amplitude, frequency, and pulse width of EES can adjust the specific aspects of standing, stepping, and isolated movements in both animal models and humans.[5,13,14] Wenger *et al.* have designed a closed-loop system that "auto-tunes" the stimulation device. It will allow the paralyzed rat to move freely without being worried about adjusting electrical pulse width, frequency, or amplitude.[15] However, their proposed control strategy does work based on the stimulation of the specific afferents. It was also not inspired by any disturbance rejection mechanism.

To achieve an adaptable locomotion, phase resetting (based on sensory afferent or perturbations) can functionally modulate

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locomotor rhythm generated by the CPGs.[16,17] It has been shown that the electrical stimulations delivered to the peripheral afferent can reset the CPG's activity.[18-20] Gait responses following single, usually short-lived, perturbation forces during steady gait can be viewed as transient dynamics. Such responses often referred to as stumbling reactions in the field of neurophysiology.[21,22] The gait cycle duration may change during such reactions, but its steady-state value reestablished after the transient leading to the phase reset.[23] It has been shown that a suitable phase resetting mechanism could increase gait stability to prevent the walking humanoid from a fall.[24]

Because there is a correspondence between the CPG oscillations and the walking cycles during steady gait, the phase reset of the walking rhythm during the stumbling reaction naturally is the result of the phase resetting of the CPG by the same amount. After gait restoration using afferent control in an SCI subject, the movement stabilization is the next important problem. Preventing falls against the external perturbation is possible using the suitable phase resetting of CPG. It is also possible using the external control of intraspinal afferents. On the other hand, an appropriate online afferent control mechanism that brings a suitable phase resetting process of the CPG can be an effective approach for the gait stabilization against the perturbation in SCI subjects whose gait have been restored using intraspinal stimulation. This leads us to propose a novel approach wherein extrinsic feedback has been utilized to control locomotion against perturbation by designing a fuzzy controller that controls the phase resetting process of a neuromechanical system without supraspinal drives which simulates post-SCI situation. In this study, we conducted the simulation studies on a simple neuromechanical model to address the role of closed-loop control on the robustness of movement against the perturbations after SCI.[25] This model can also be used to simulate the complete SCI. In the case of external perturbation, the proposed fuzzy controller tunes the weights of the afferent inputs using the kinematic motion data to reset the phase appropriately.

Materials and Methods

Neuromechanical model

Figure 1 shows a schematic diagram illustrating model components and the connections between them.[25] In this computational model, locomotor CPG sends output through extensor and flexor pathways to a mechanical limb segment that in turn generates feedback signals based on muscle length/velocity and force to the CPG.[25]

The model includes a constant supraspinal drive and generates periodic oscillations over a range of drive values. The rhythm generator (RG), pattern formation (PF), and motor neuron (Mn) models incorporate some voltage-gated ionic currents. These currents in RG-F and RG-E, with

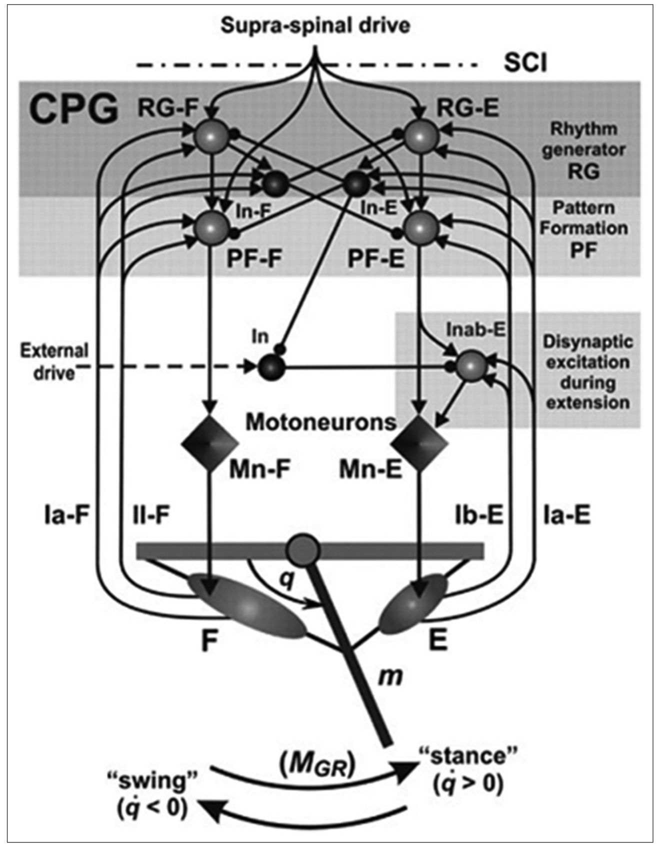

Figure 1: Schematic diagram illustrating the component of used neuromechanical model[25]

the reciprocal inhibition between these neurons (via the inhibitory In-F and In-E), define the rhythm generation in the CPG. The RG, PF, and Mn dynamics are each described by a conductance-based system of two first-order ordinary differential equations.[25]

$$C \cdot \frac{dV_i}{dt} = -I_{Nap} - I_K - I_{Leak} - I_{SynE} - I_{SynI} \quad (1)$$

Where V_i refers to the voltage drop across the membrane of neuron *i*, *C* is the membrane capacitance, I_{leak} is the leak current given by $I_{leak}(V_i)$, I_{NaP} is the persistent sodium current given by $I_{NaP}(v_i, h_i)$, I_k is the potassium current given by $I_k(v_i)$, $I_{SynE}(V_i)$ and $I_{SynI}(V_i)$ and denote excitatory and inhibitory inputs to neuron *i*.[25]

$$I_{SynE,i} = \bar{g}_{SynE} \cdot \left(V_i - E_{SynE}\right) \cdot \left(\sum_j a_{ji} \cdot f\left(V_j\right) + \sum_m c_{mi} \cdot d_m + \sum_k w_{ki} \cdot fb_k\right) \quad (2)$$

$$I_{SynI,i} = \bar{g}_{SynI} \cdot \left(V_i - E_{SynI}\right) \cdot \sum_j b_{ji} \cdot f\left(V_j\right) \quad (3)$$

In the above relations, $f(V)$ is the output of the presynaptic neurons to neuron *i*. *d*, f_b, and *w* are the constant supraspinal drive, sensory feedback terms, and weight of afferents, respectively. Each E_j denotes the reversal potential and g_j the maximal channel conductance of current j.[25] The interneurons (In-F, In-E, Int, and Inab-E) are each described by a single first-order equation.[25]

$$C \cdot \dot{V}_i = -I_{Leak} - I_{SynE} - I_{SynI} \tag{4}$$

The excitatory inputs to these interneurons arrive from RG, supraspinal drive, and sensory feedback.[25] The limb motion can be described by a second-order ordinary differential equation

$$\begin{aligned} I \cdot \ddot{q} &= K \cdot \cos q - b \cdot \dot{q} + M_F\left(q, \dot{q}, V_{Mn\text{-}E}, t\right) \\ &\quad - M_E\left(\pi - q, -\dot{q}, V_{Mn\text{-}E}, \mathrm{t}\right) + M_{GR}\left(q\right) \end{aligned} \tag{5}$$

Where q is the joint angle, and I is the moment of inertia of the limb with respect to the suspension point. $k\,cosq$ is the moment of the gravitational force, b is the angular viscosity in the hinge joint M_F, and M_E are the moments of the muscle forces, and M_{GR} is the moment of the ground reaction force, which is nonzero during the stance phase.[25] To model the interaction with the ground, when the limb is swinging counterclockwise ($\dot{q} \geq 0$) during the stance phase, $M_{GR}\left(q\right) = M_{GRmax}\, cos\, q$ is applied, and it is set to zero during the swing phase when the limb swings in the clockwise direction ($\dot{q} < 0$).[25]

Selecting the afferent weight suitable for controlling

In our proposed control strategy, the fuzzy controller receives the measured kinematic motion data during the gait and tunes the weights of a group of afferent inputs to control the phase resetting dynamics to maintain dynamic stability against the perturbation. In other words, during the phase resetting process, the joint angle position is controlled by adjusting the weight of afferents. Therefore, before designing the controller, it is better to look for the afferents, among the available afferents in the neuromechanical model, in which tuning their weights can lead to better controllability of joint angular displacement.

The Mn-F falls to zero, with an increase in the weight of both Ia-E and Ib-E between 2 and 4 s. Following this, the joint angle dropped to its minimum after 760 and 800 ms, respectively [Figures 2 and 3]. The further increase in the weight of Ia-E between 13 and 15 s has led to a further decrease of the joint angular displacement, whereas this is not true for the Ib-E. It should be noted that the joint angle reached to its minimum value after 260 and 760 ms for an increase in the weight of Ia-E and Ib-E, respectively, that shows a considerable shorter time for Ia-E.

It is known that during the phase resetting process, as stumbling corrective reaction, the joint angle should reach to its minimum value as fast as possible to confront the external perturbation. The simulations show that by adjusting the weight of Ia-E afferent not only the joint angle can be controlled in a wider range but also the flexion time can be shorter. Consequently, to control the joint flexion angle, adjusting the weight of Ia-E is more appropriate.

As one can see in Figures 4 and 5, the Mn-E falls to zero, with an increase in the weight of both Ia-F and

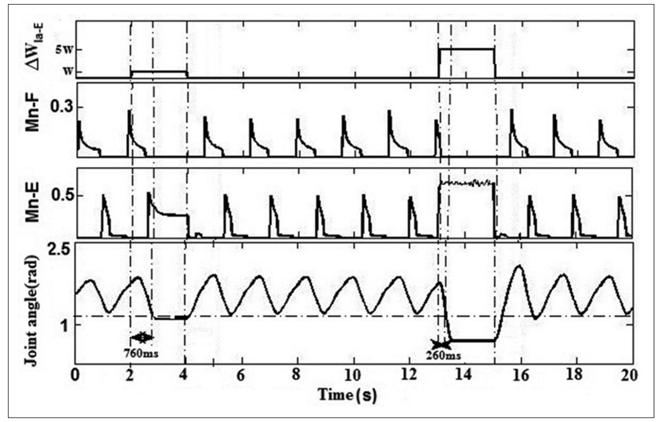

Figure 2: An increase in weight of Ia-E between 2 and 4 s has made the Mn-F zero which in return has led to a decrease in the minimum of the joint angle. Further increase in the weight of Ia-E between 13 and 15 s has led to a further decrease of the joint angular displacement. In addition, the fall time of angular displacement has been decreased considerably

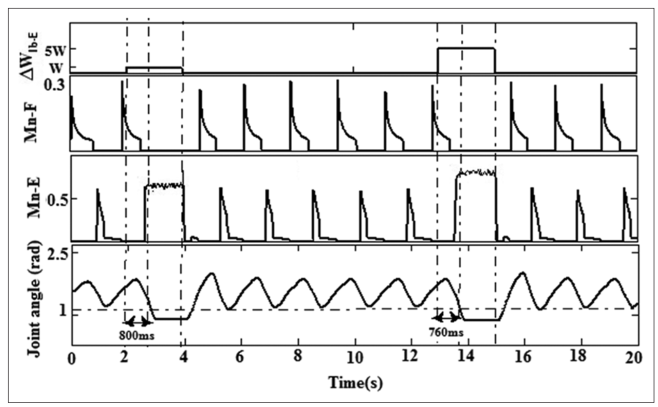

Figure 3: An increase in the weight of Ib-E between 2 and 4 s has made the Mn-F zero which in turn has led to a decrease in the minimum of the joint angle. Further increase in the weight of Ib-E between 13 and 15 s has not led to a further decrease of the joint angular displacement. In addition, the fall time of angular displacement has been decreased

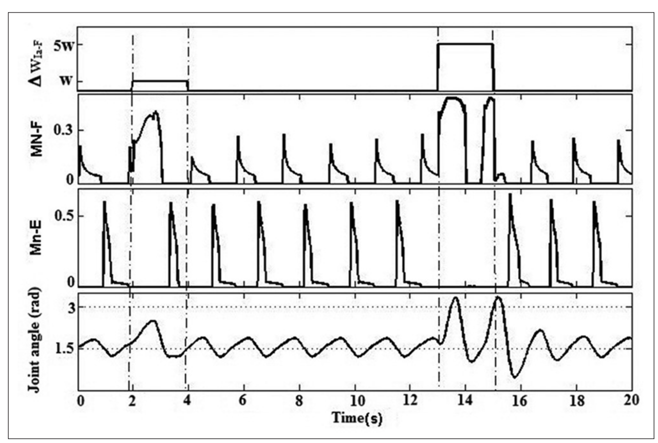

Figure 4: An increase in the weight of Ia-F between 2 and 4 s has made the Mn-E zero which in return has led to an increase in the maximum of joint angle. Further increase in the weight of both Ia-F between 13 and 15 s has led to further increase in the maximum of the joint angle. Moreover, the maximum value of the joint angle has been increased from 2.47 to 3.03 rad

II-F between 2 and 4 s. This was followed by a rise in the maximum of joint angle up to $\max q_{\text{Ia-F}} = 2.47\,\text{rad}$ and $\max q_{\text{II-F}} = 2.02$. Further increase in the weight of both Ia-F and II-F between 13 and 15 s has led to further increase in the maximum of the joint angle up to $\max q_{\text{Ia-F}} = 3.03\,\text{rad}$ and $\max q_{\text{II-F}} = 3.26\,\text{rad}$. However, the joint angle responds faster to the change in the weight of Ia-F, which means that it is a better choice as a manipulated variable to control the joint extension angle.

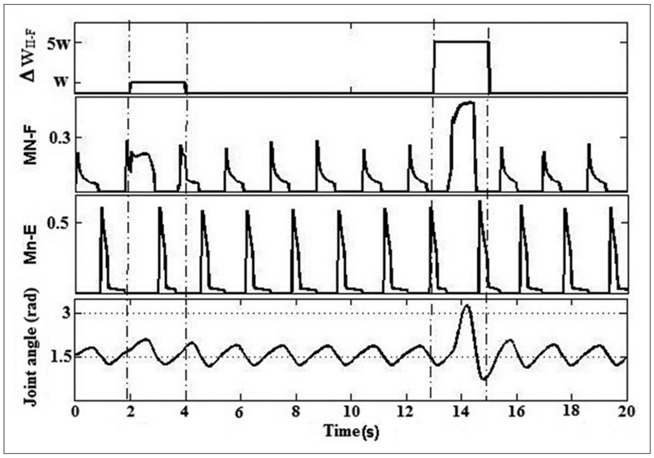

Figure 5: An increase in the weight of II-F between 2 and 4 s has made the Mn-E zero which in return has led to an increase in the maximum of joint angle. Further increase in the weight of both Ia-F and II-F from 13 to 15 s has led to further increase in the maximum of the joint angle. Moreover, the maximum value of the joint angle has been increased from 2.02 to 3.26 rad

According to the mentioned simulation studies on the neuromechanical model, it seems more appropriate to adjust the weight of Ia-E afferent to control joint flexion angle and the weight of Ia-F afferent to control joint extension angle, during the phase resetting process. This means that the joint angular displacement can be controlled in a wider range as fast as possible.

The proposed control strategy

In practice, an accurate model describing the relationship between the stimulation intensity of afferent neurons in the spinal cord with the leg joint angle changes is not available. However, by delivering electrical stimulation to the afferents and recording the changes of joint angles, an uncertain prior knowledge about the system can be achieved. In such circumstances, the use of fuzzy logic systems for designing the controller is a logical approach. Therefore, in this study, a Mamdani-type fuzzy controller has been developed to reject the external disturbance by tuning the weight of afferent neurons for the desired performance of gait resetting process. Figure 6 shows the structure of closed-loop control system. In fact, the phase resetting process must be performed in such a way that the joint angle change with maximum speed and minimum overshoot and undershoot.

The rules of the developed fuzzy controller are dividing into two parts. The first part of fuzzy rules adjusts the weight of Ia-E afferent to control the joint angle flexion,

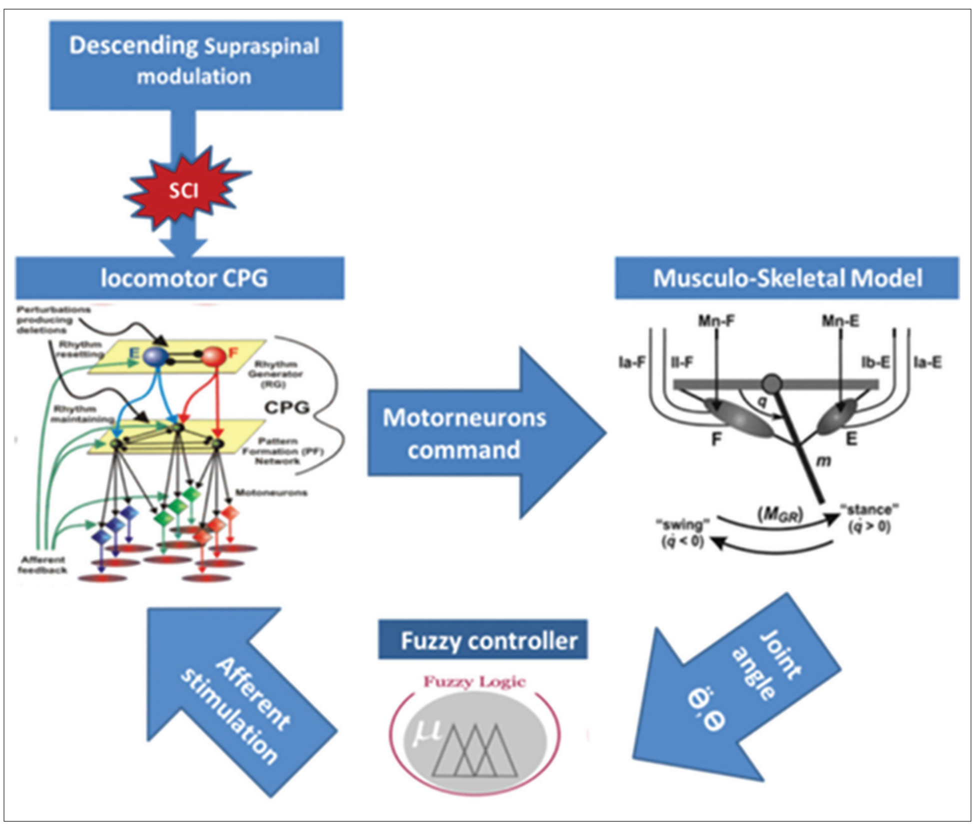

Figure 6: The structure of the proposed closed-loop control system

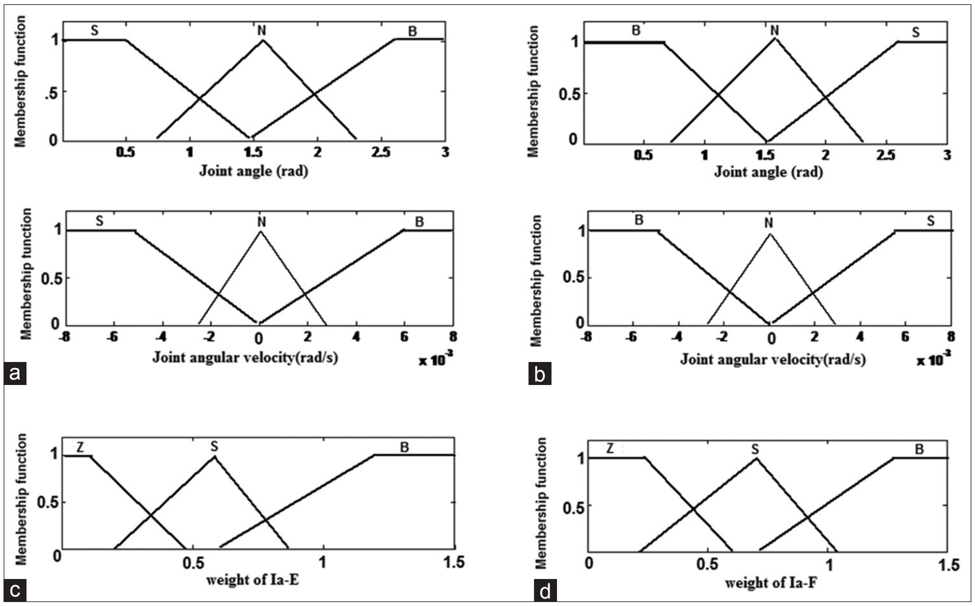

Figure 7: Three triangular fuzzy membership functions assigned to the inputs of the fuzzy controller, joint angle, and joint angular velocity: (a) when the angle q is bigger than $\pi/2$, the first part of fuzzy rules is activated and (b) when the angle q is smaller than $\pi/2$, the second part of fuzzy rules is activated. Three triangular fuzzy membership functions were also assigned to the output variables of the fuzzy controller (c) weight of Ia-E afferent, and (d) weight of Ia-F afferent

and the second part adjusts the weight of Ia-F afferent to control the joint angle extension. When the joint angle (q) is bigger than $\pi/2$, the first part of the rules is activated and tunes the weight of flexor afferents. Otherwise, whenever the angle is smaller than $\pi/2$, the second part of rules is activated and tunes the weight of extensor afferents. The inputs of fuzzy controller are the values of joint angle (q) and joint angular velocity ($\dot{q}$), in which three and three are the triangular fuzzy membership functions assigned to them, respectively, as depicted in Figure 7. Three triangular fuzzy membership functions are also assigned to the output variable of the fuzzy controller, which is the weight of afferent [Figure 7]. The triangular function is the most common choice for membership function. The product inference rule, singleton fuzzifier, and center average defuzzifier are used to implement the fuzzy controller. All 18 fuzzy rules belonging to first and second are as follows:

When q is smaller than $\pi/2$:

IF q is B and $\dot{q}$ is S, THEN Ia-F weight is S
IF q is B and $\dot{q}$ is N, THEN Ia-F weight is Z
IF q is B and $\dot{q}$ is B, THEN Ia-F weight is B
IF q is S and $\dot{q}$ is S, THEN Ia-F weight is Z
IF q is S and $\dot{q}$ is N, THEN Ia-F weight is Z
IF q is S and $\dot{q}$ is B, THEN Ia-F weight is B
IF q is N and $\dot{q}$ is S, THEN Ia-F weight is Z
IF q is N and $\dot{q}$ is N, THEN Ia-F weight is S
IF q is N and $\dot{q}$ is B, THEN Ia-F weight is B.

When q is bigger than $\pi/2$:

IF q is B and $\dot{q}$ is S, THEN Ia-E weight is S
IF q is B and $\dot{q}$ is N, THEN Ia-E weight is Z
IF q is B and $\dot{q}$ is B, THEN Ia-E weight is B
IF q is S and $\dot{q}$ is S, THEN Ia-E weight is Z

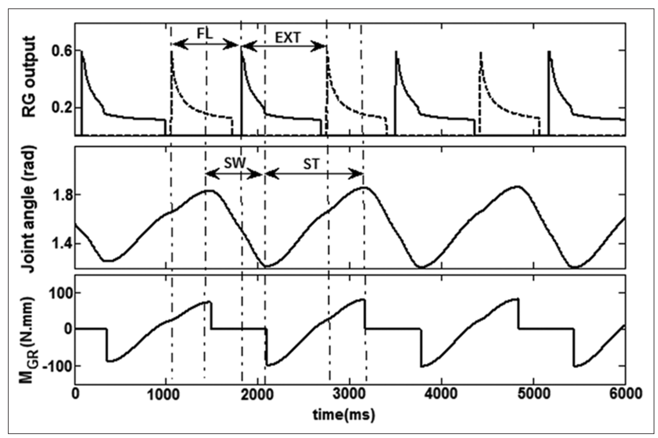

Figure 8: Restoration of the rhythmic behavior of CPG by increasing the weight of afferents

IF q is S and $\dot{q}$ is N, THEN Ia-E weight is Z
IF q is S and $\dot{q}$ is B, THEN Ia-E weight is B
IF q is N and $\dot{q}$ is S, THEN Ia-E weight is Z
IF q is N and $\dot{q}$ is N, THEN Ia-E weight is S
IF q is N and $\dot{q}$ is B, THEN Ia-E weight is B.

Results

In the simulation studies on the neuromechanical model related to the SCI, at first, the weights of afferents were increased to restore the rhythmic behavior of CPG as suggested in Markin *et al.*[25] [Figure 8]. In the next step, two different perturbations were exerted once during the stance phase (+0.2 N.m) and once again during the swing phase (−0.2 N.m). At first, the simulation performs in the absence of the fuzzy controller. The transient changes of the joint angle were obtained as the response of the neuromechanical model to an external disturbance. Then the simulation performs in the presence of the fuzzy controller. When an external perturbation is exerted, the fuzzy controller is activated and tunes the weight of afferents (Ia group) in such a way that the joint angle changes with desirable transient response. Figure 9 shows the obtained results both with and without the fuzzy controller. Comparing the achieved results elucidates that in the presence of the fuzzy controller, the value of maximum overshoot and the absolute value of minimum undershoot have been reduced considerably. Tables 1 and 2 show the calculated quantitative measures. In addition, the transient time of resetting in the absence of controller is 400 ms, whereas it is 200 ms in the presence of controller. Consequently, in the presence of the fuzzy controller, the resetting process is faster with less joint angular fluctuation.

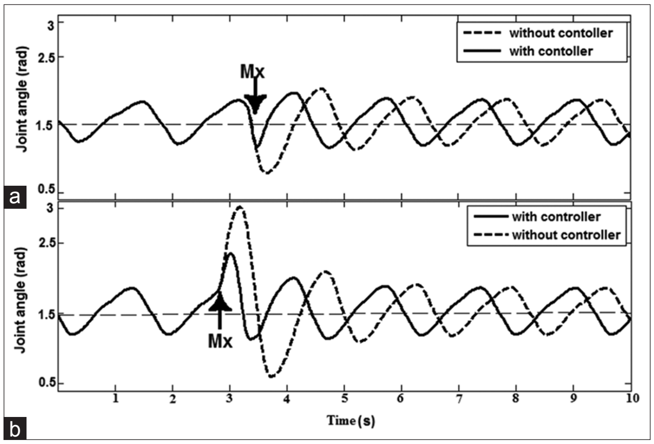

Figure 9: Two perturbations (|Mx| =0.2 N.m) with different direction were exerted during (a) the stance phase and (b) swing phase

To visualize the dynamic behavior of the neuromechanical locomotor systems after the recovery of locomotion, the phase plane of the system is analyzed. Figure 10 indicates the changes of joint angle versus angular velocity. It is clear that the system has a unique stable limit cycle. Figure 10 shows the behavior of the system in the absence/presence of fuzzy controller when an external perturbation exerted during the stance and swing phase, respectively. In fact, this figure indicates the system behavior without and with online afferent control. Obviously, after removing the disturbance, the trajectories have converged to the

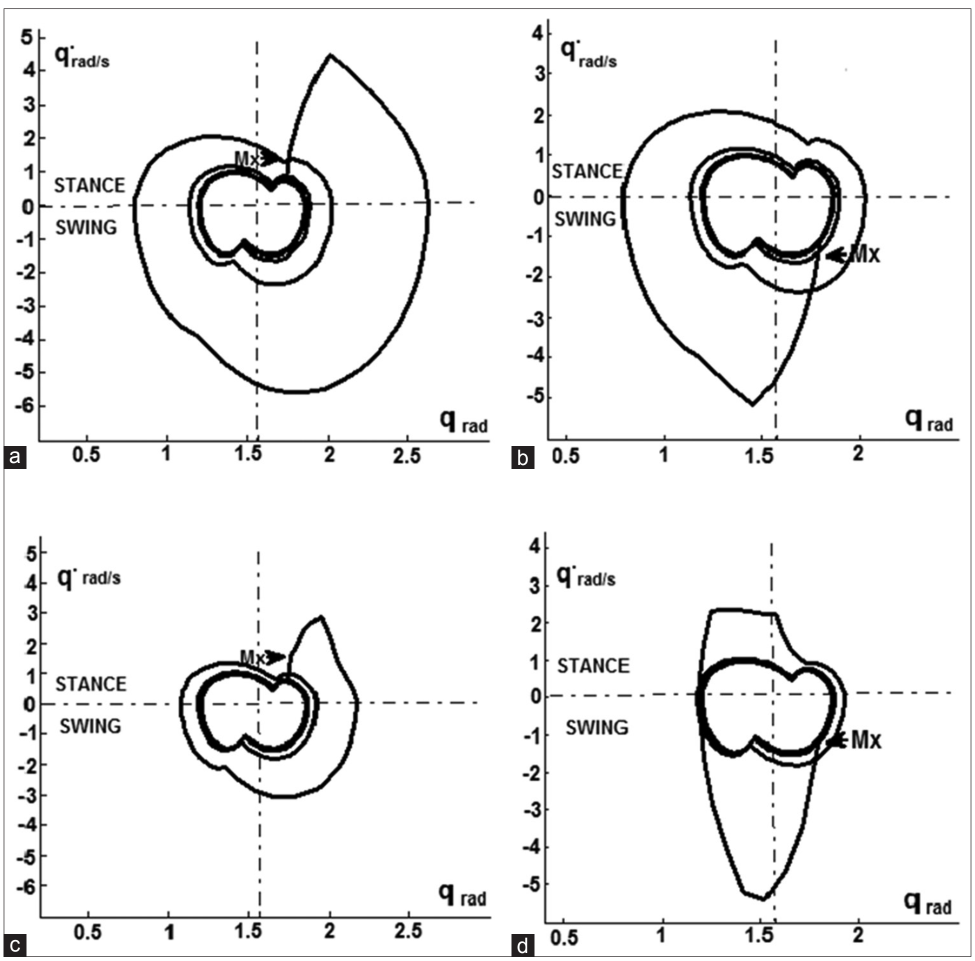

Figure 10: The phase plane of the neuromechanical model when (a) the perturbation was exerted during the stance phase in the absence of the fuzzy controller. (b) The perturbation was exerted during the swing phase in the absence of the fuzzy controller. (c) The perturbation was exerted during the stance phase in the presence of the fuzzy controller, and when (d) the perturbation was exerted during the swing phase in the presence of the fuzzy controller (Mmax = 0.2 N.m)

Table 1: Calculated the maximum and minimum values that the joint angles reached, during phase resetting process with and without the controller, when the disturbance was exerted during the stance phase

	With fuzzy controller	Without controller
Maximum joint angle (rad)	2.3	3
Minimum joint angle (rad)	1.138	0.6

Table 2: Calculated the maximum and minimum values that the joint angles reached, during phase resetting process with and without the controller, when the disturbance was exerted during the swing phase

	With fuzzy controller	Without controller
Maximum joint angle (rad)	1.9	2.1
Minimum joint angle (rad)	1.17	0.79

unique stable limit cycle. Comparing the achieved results elucidates that in the presence of the fuzzy controller, the amplitude of the trajectories during the convergence interval is lower. Lower amplitude during the convergence interval means less maximum overshoot and the absolute value of minimum undershoot.

Discussion and Conclusion

Neuromodulation therapy with an open-loop control of spinal sensorimotor circuits can improve motor control after SCI.[6,15] In this paper, we demonstrated that the fuzzy strategy for the closed-loop control of spinal afferent yielded superior control of limb movement. The main contribution of this research is to utilize the fuzzy controller to perform the phase resetting process with online tuning of the weights of the spinal afferents as the input drives of CPG, when the external disturbance is exerted. The results show that the fuzzy controller has had an effective roll in reduction of the transient time, the value of maximum overshoot, and the absolute value of minimum undershoot of joint angle change during the phase resetting process. Because controlling the weight of afferents can be performed using the microstimulation of the spinal afferents, it can be concluded that the proposed fuzzy controller can be inherently capable of being utilized for movement stabilization based on intraspinal microstimulation.

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None.

Conflicts of interest

There are no conflicts of interest.

References

1. Barbeau H, McCrea DA, O'Donovan MJ, Rossignol S, Grill WM, Lemay MA. Tapping into spinal circuits to restore motor function. Brain Res Rev 1999;30:27-51.
2. Rossignol S, Bouyer D, Barthelemy C, Langlet H. Recovery of locomotion in the cat following spinal cord lesions. Brain Res Rev 2002;40:257-66.
3. Roy RR, Harkema SJ, Edgerton VR. Basic concepts of activity-based interventions for improved recovery of motor function after spinal cord injury. Arch Phys Med Rehabil 2012;93:1487-97.
4. Marsh BC, Astill SL, Utley A, Ichiyama RM. Movement rehabilitation after spinal cord injuries: Emerging concepts and future directions, Brain Res Bull 2011;84:327-36.
5. Harkema S, Gerasimenko Y, Hodes J, Burdick J, Angeli C, Chen Y, *et al.* Effect of epidural stimulation of the lumbosacral spinal cord on voluntary movement, standing, and assisted stepping after motor complete paraplegia: A case study. Lancet 2011;377:1938-47.
6. van den Brand R, Heutschi J, Barraud Q, DiGiovanna J, Bartholdi K, Huerlimann M, *et al.* Restoring voluntary control of locomotion after paralyzing spinal cord injury. Science 2012;336;1182-5.
7. Holinski BJ, Everaert DG, Mushahwar VK, Stein RB. Real-time control of walking using recordings from dorsal root ganglia. J Neural Eng 2013;10:056008.
8. Capogrosso M, Wenger N, Raspopovic S, Musienko P, Beauparlant J, Bassi Luciani L, *et al.* A computational model for epidural electrical stimulation of spinal sensorimotor circuits., J Neurosci 2013;33:19326-40.
9. Gad P, Lavrov I, Shah P, Zhong H, Roy RR, Edgerton VR, *et al.* Neuromodulation of motor-evoked potentials during stepping in spinal rats. J Neurophysiol 2013;110:1311-22.
10. Lavrov I, Dy CJ, Fong AJ, Gerasimenko Y, Courtine G, Zhong H, *et al*. Epidural stimulation induced modulation of spinal locomotor networks in adult spinal rats. J Neurosci 2008;28:6022-9.
11. Lozano M, Lipsman N. Probing and regulating dysfunctional circuits using deep brain stimulation. Neuron 2013;406-24.
12. Borton D, Micera S, Millán Jdel R, Courtine G. Personalized neuroprosthetics. Sci Transl Med 2013;5:210-2.
13. Minassian K, Jilge B, Rattay F, Pinter MM, Binder H, Gerstenbrand F, *et al.* Stepping-like movements in humans with complete spinal cord injury induced by epidural stimulation of the lumbar cord: Electromyographic study of compound muscle action potentials. Spinal Cord 2004;42:401-16.
14. Lyalka VF, Hsu LJ, Karayannidou A, Zelenin PV, Orlovsky GN, Deliagina TG. Facilitation of postural limb reflexes in spinal rabbits by serotonergic agonist administration, epidural electrical stimulation, and postural training. J Neurophysiol 2011;106:1341-54.
15. Wenger N, Moraud EM, Raspopovic S, Bonizzato M, DiGiovanna J, Musienko P, *et al.* Closed-loop neuromodulation of spinal sensorimotor circuits controls refined locomotion after complete spinal cord injury. Sci Transl Med 2014;6:255ra133.
16. Quevedo J, Stecina K, Gosgnach S, McCrea DA. Stumbling corrective reaction during fictive locomotion in the cat. J Neurophysiol 2005;94:2045-52.
17. Conway BA, Hultborn H, Kiehn O. Proprioceptive input resets central locomotor rhythm in the spinal cat. Exp Brain Res 1987;68:643-56.
18. Schomburg ED, Petersen N, Barajon I, Hultborn H. Flexor reflex afferents reset the step cycle during fictive locomotion in the cat. Exp Brain Res 1998;122:339-50.
19. Duysens J. Fluctuations in sensitivity to rhythm resetting effects during the cat's step cycle. Brain Res 1977;133:190-5.

20. Funato T, Yamamoto Y, Aoi S, Imai T, Aoyagi T, Tomita N, *et al.* Evaluation of the phase-dependent rhythm control of human walking using phase response curves. PLoS Comput Biol 2016;12:e1004950.
21. Quevedo J, Stecina K, McCrea DA. Intracellular analysis of reflex pathways underlying the stumbling corrective reaction during fictive locomotion in the cat. J Neurophys 2005;94:2053-62.
22. Nashner LM. Balance and posture control. In R.S. Larry, ed., Encyclopedia of neuroscience, Academic Press, Oxford 2009; 2010. p. 21-9.
23. Kawato M. Transient and steady state phase response curves of limit cycle oscillators. J Math Biol 1981;12:13-30.
24. Nomura T, Kawa K, Suzuki Y, Nakanishi M. Dynamic stability and phase resetting during biped gait. Chaos 2009;19:026103.
25. Markin SN, Klishko AN, Shevtsova NA, Lemay MA, Prilutsky BI, Rybak IA. Afferent control of locomotor CPG: Insights from a simple neuro-mechanical model. In: Fetcho J, Hochman S, McDermott A, Stein P, Ziskind-Conhaim L, editors. Cellular and Network Functions in the Spinal Cord. Annals of the New York Academy of Sciences. New York Academy of Sciences; 2010.