Gait Restoration by Functional Electrical Stimulation

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Abstract

For over 40 years, research labs have been developing gait assist systems that use electrical stimulation of muscle to restore function to limbs paralyzed as a result of spinal cord injury. The concept of functional electrical stimulation (FES) is simple, but realization is challenging. While there are some similarities between FES-aided gait and a bipedal robot walking machine, there are also significant differences in actuators (muscles versus motors), sensors, and control strategy. Hybrid approaches that combine FES with a mechanical orthosis show promise for overcoming some of the limitations of FES-aided gait.

Keywords: Walking, electrical stimulation, spinal cord injury, FES.

1 Basics of FES

Because the human nervous system is mediated by electrical events in the form of ionic currents, artificial application of electricity to the body can be used for many applications. For example, electrical stimulation is used for therapeutic purposes such as pain suppression, muscle conditioning or wound healing. The term "Functional electrical stimulation" or FES is used when the application of low level electrical excitation is for restoration or aiding of a function that is normally under central nervous system (CNS) control, but is missing or impaired because of disease, trauma, or developmental complications. There are many applications for FES. For example, nerves in the peritoneum can be stimulated to activate bladder sphincters to cure incontinence. Cochlear implants are small implanted devices that process sounds from an external microphone and stimulate the auditory nerve in the inner ear to restore rudimentary hearing. Visual prostheses take the form of an artificial retina that stimulates receptor cells at the rear of the eye or a matrix of electrodes that stimulate the visual cortex based on signals from an external camera. There has been an explosion of implantable stimulation products from medical device companies that target deep structures in the brain for curing movement disorders. The Medtronic Activa cite for tremor suppression in Parkinson's disease patients is one example. By far the largest FES application is cardiac rhythm management with hundreds of pacemakers and ICDs implanted worldwide every day.

The application of FES most closely related to mobile robots is restoring motion to limbs paralyzed following stroke or spinal cord injury (SCI). FES for paralyzed limb control was first proposed by Liberson [1] who in 1961 used a stimulator to correct hemiplegic drop foot, a common gait disability resulting from stroke. While there has been additional FES work for stroke, systems for individuals with SCI are far more advanced.

Spinal cord injury results from disease or trauma to the spinal cord. There are approximately 250,000 in the U.S. living with SCI and approximately 11,000 new cases each year [2]. One half of those with SCI have cervical injuries leading to partial or complete quadriplegia while the other half have thoracic or sacral injuries resulting in paraplegia. The leading causes of SCI are automobiles accidents, gunshot wounds, sporting accidents (particularly diving) and falls. Because of the active nature of the events that result in spinal trauma, the mean age at the time of SCI is 29 with most falling in the 16-30 age group.

SCI damages the communication pathway between the voluntary movement centers in the brain and the muscles. The machinery below the injury, including lower motor neurons and the muscles themselves, remains unaffected by the injury. In fact, those with SCI often have sensitized reflexes (spasticity) and can have massive withdrawal reflexes in both legs when the bottom of the foot is stroked.

The basis of FES for limb control is to activate the branches of the lower motor neurons by pulses of electricity passed through surface electrodes placed on the skin over the muscle, or through implanted electrodes placed in or on the muscle, or around the nerve that supplies the muscle, to cause muscle contraction (**Fig. 1**). A multi-channel stimulator connected to a controller that can read sensors, interpret voluntary commands, and output muscle activation strength results in a system that, in theory, can restore full function to the limb. For quadriplegics, hand and forearm muscles can be activated to restore rudimentary grasp [3, 4] while for paraplegics, leg muscles can be activated to restore rudimentary gait in the vicinity of a wheelchair. The remainder of this paper is limited to the latter application.

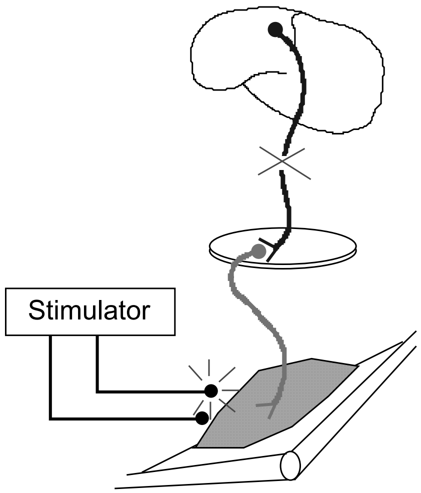

Fig. 1. Basics of FES. Spinal cord injury interrupts communication pathway between brain and muscles, but the lower motor neurons and muscles are intact. Application of current pulses through surface or implanted electrodes causes the muscle to contract and the paralyzed limb to move.

2 FES-aided gait

The inability to walk due to lower limb paralysis is a common result of thoracic level SCI. FES which uses electrical stimulation of motor nerves trigger muscle contractions, is one means for restoring rudimentary standing and limited mobility in the vicinity of a wheelchair to some individuals with SCI [5-11]. The user must have good trunk control and a strong upper body as considerable effort is required from the arms engaging parallel bars, walker or crutches for support. Despite these restrictions, successful FES users are able to ambulate for hundreds of meters with many years of use from their system [12, 13]. For example, the user shown in **Fig. 2** is T10 complete with total sensory and motor paralysis from the waist down. She is able to walk slowly, using parallel bars for support because her lower limb muscles are being activated with a rudimentary FES system [14, 15].

Fig. 2. User is paralyzed from the waist down following a T10 complete spinal cord injury. Rudimentary gait, using parallel bars for balance, is realized by electrical stimulation of the paralyzed muscles. This hybrid system combines the stimulation with a mechanical orthosis.

Several factors separate the performance of FES gait from normal gait under control of the central nervous system (CNS). First, while the CNS has access to all of the 60 lower limb muscles involved in gait, practical FES systems are limited to just a few channels of stimulation. Second, muscle activated by external electrical pulses fatigues far faster than muscle activated by the CNS. Third, artificial controllers must rely on a limited set of external sensors while the CNS has access to thousands of internal muscle stretch and tension sensors. Forth, the artificial system has no say over the upper body which remains entirely under voluntary control.

While FES-aided gait is similar in principle to a bipedal walking robot, there are many distinctions which separate the design and performance of FES systems from robot walking machines. Insufficient actuators and sensors is one difference, but more critical is the difference in actuators. Walking machines typically use DC servomotor actuators that have well-behaved, linear torque-current and torque-speed properties. In contrast, FES systems have muscle actuators. Muscles have exceedingly high strength-to-weight and power-to-weight characteristics, but are nonlinear, time-varying and saturate at a low peak force. The latter two properties are most critical during the rapid fatigue that greatly restricts the ability of the FES approach to restore meaningful gait for long periods. The former property means that, despite considerable efforts to model muscle input-output properties [16, 17], stimulated muscle output can be bounded but is never known with precision, making tight control of stepping motions challenging if not impossible.

To tackle the problem of fatigue that limits gait time and the problem of poor control that leads to non-repeatable stepping motions, several research groups have turned to hybrid systems that combine FES with a mechanical orthosis [18-33]. The FES system developed in our lab and shown in **Fig. 2** [14, 15] is one example of such a hybrid system. As illustrated in **Fig. 3**, the controlled brake orthosis (CBO) uses the stimulated muscle as a power source, but regulates swing phase limb motion by continuously controlling the action of orthosis-mounted magnetic particle brakes, much the same way as one controls the speed of a bicycle going downhill by manipulating the hand brakes. In addition, during the double-support phase of the gait cycle, the brace joints lock and the muscles can be turned off, delaying the time to fatigue. Users of the CBO are able to ambulate twice as far compared to when they have just the FES because of the reduced muscle stimulation [15].

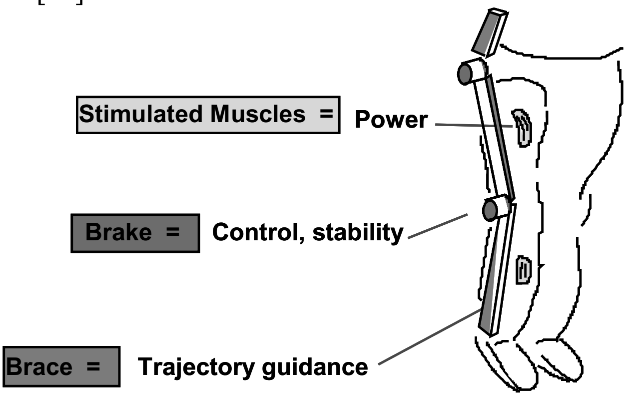

Fig. 3. The controlled brake orthosis (CBO) uses stimulated muscle for power and controls swing phase trajectory by modulating continuous brakes that act at the hip and knee. The brakes also lock the joints during double-support so that muscles are used less often thereby increasing usage time before fatigue sets in.

While the orthosis does increase function, it comes at the cost of requiring the user to don and doff a substantial piece of hardware. It is difficult to predict whether this shortcoming will ultimately be accepted by users and even more difficult to predict whether any form of FES gait assist technology will be sufficiently cost effective to merit reimbursement or individual payment.

Nevertheless, work continues on hybrid and other FES systems. For example, in our lab we are developing the energy storing orthosis (ESO) [34], another form of FES hybrid. Here, excess energy is extracted from the stimulated quadriceps muscle, stored, and piped to other joints for use later in the gait cycle (**Fig. 4**). The ESO is realized with a gas spring system to hold the leg in a flexed configuration at equilibrium, and a pneumatic system with air cylinders to convert excess extension energy at the knee to compressed air that is stored in a tubing accumulator then released into a second piston to actuate motion about the hip that is difficult to achieve with FES. The ESO makes possible a surface electrode FES gait system that uses just a single channel of muscle stimulation.

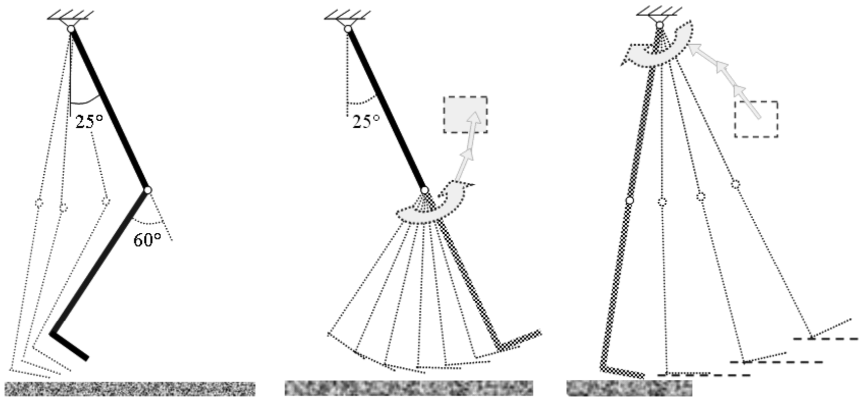

Fig. 4. The energy storing orthosis (ESO) captures and stores excess energy from quadriceps activation, and uses the stored energy to actuate hip motion later in the gait cycle.

References

1. Liberson, W.T., et al., Functional electrotherapy: stimulation of the peroneal nerve synchronized with the swing phase of the gait of hemiplegic patients. Arch Phys Med Rehabil, 1961. 42: p. 101-5.
2. SCIIN, Spinal cord injury: facts and figures at a glance - June 2005. 2005, Spinal Cord Injury Information Network.
3. Peckham, P.H., et al., Efficacy of an implanted neuroprosthesis for restoring hand grasp in tetraplegia: a multicenter study. Arch Phys Med Rehabil, 2001. 82(10): p. 1380-8.

4. Snoek, G.J., et al., Use of the NESS handmaster to restore handfunction in tetraplegia: clinical experiences in ten patients. Spinal Cord, 2000. 38(4): p. 244-9.
5. Marsolais, E.B. and R. Kobetic, Functional electrical stimulation for walking in paraplegia. J Bone Joint Surg Am., 1987. 69A: p. 728-733.
6. Kobetic, R., R.J. Triolo, and E.B. Marsolais, Muscle selection and walking performance of multichannel FES systems for ambulation in paraplegia. IEEE Trans Rehabil Eng, 1997. 5(1): p. 23-29.
7. Cybulski, G., R. Penn, and R. Jaeger, Lower extremity functional neuromuscular stimulation in cases of spinal cord injury. Neurosurgery, 1984. 15(1): p. 132-146.
8. Graupe, D. and K. Kohn, Functional Electrical Stimulation for Ambulation by Paraplegics. 1994: Krieger.
9. Kralj, A. and T. Bajd, Functional Electrical Stimulation: Standing and Walking After Spinal Cord Injury. 1989: CRC Press.
10. Marsolais, E.B. and R. Kobetic, Functional walking in paralyzed patients by means of electrical stimulation. Clin Orthop, 1983. 175(30-36).
11. Creasey, G.H., et al., Clinical applications of electrical stimulation after spinal cord injury. J Spinal Cord Med, 2004. 27(4): p. 365-75.
12. Kobetic, R., et al., Implanted functional electrical stimulation system for mobility in paraplegia: a follow-up case report. IEEE Trans Rehabil Eng, 1999. 7(4): p. 390-8.
13. Kralj, A., T. Bajd, and R. Turk, Enhancement of gait restoration in spinal injured patients by functional electrical stimulation. Clin Orthop Relat Res, 1988(233): p. 34-43.
14. Goldfarb, M. and W.K. Durfee, Design of a controlled-brake orthosis for FES-aided gait. IEEE Trans Rehabil Eng, 1996. 4(1): p. 13-24.
15. Goldfarb, M., et al., Preliminary evaluation of a controlled-brake orthosis for FES-aided gait. IEEE Trans Neural Syst Rehabil Eng, 2003. 11(3): p. 241-8.
16. Durfee, W.K., Muscle model identification in neural prosthesis systems, in Neural Prostheses: Replacing Motor Function After Disease or Disability, R. Stein and H. Peckham, Editors. 1992, Oxford University Press.
17. Durfee, W.K. and K.I. Palmer, Estimation of force-activation, force-length, and force-velocity properties in isolated, electrically stimulated muscle. IEEE Trans Biomed Eng, 1994. 41(3): p. 205-16.
18. Andrews, B., et al., Hybrid FES orthosis incorporating closed loop control and sensory feedback. J Biomed Eng, 1988. 10: p. 189-195.
19. Ferguson, K.A., et al., Walking with a hybrid orthosis system. Spinal Cord, 1999. 37(11): p. 800-4.
20. Kobetic, R., et al., Development of a hybrid gait orthosis: a case report. J Spinal Cord Med, 2003. 26(3): p. 254-8.
21. Major, R., J. Stallard, and G. Rose, The dynamics of walking using the hip guidance orthosis (HGO) with crutches. Prosthet Orthot Int, 1981. 5(1): p. 19-22.
22. Marsolais, E.B., et al., The Case Western Reserve University hybrid gait orthosis. J Spinal Cord Med, 2000. 23(2): p. 100-8.

23. McClelland, M., et al., Augmentation of the Oswestry Parawalker orthosis by means of surface electrical stimulation: gait analysis of three patients. Paraplegia, 1987. 25: p. 32-38.
24. Nene, A. and S. Jennings, Hybrid paraplegic locomotion with the Parawalker using intramuscular stimulation: a single subject study. Paraplegia, 1989. 27: p. 125-132.
25. Petrofsky, J. and J. Smith, Physiologic costs of computer-controlled walking in persons with paraplegia using a reciprocating-gait orthosis. Arch Phys Med Rehabil, 1991. 72(11): p. 890-896.
26. Popovic, D., Dynamics of the self-fitting modular orthosis. IEEE Trans Robotics Automat, 1990. 6(2): p. 200-207.
27. Popovic, D., R. Tomovic, and L. Schwirtlich, Hybrid assistive system - the motor neuroprosthesis. IEEE Trans Biomed Eng, 1989. 36(7): p. 729-737.
28. Solomonow, M., et al., Reciprocating gait orthosis powered with electrical muscle stimulation(RGO II). Part I: performance evaluation of 70 paraplegic patients. Orthopedics, 1997. 20(4): p. 315-324.
29. Solomonow, M., et al., The RGO generation II: muscle stimulation powered orthosis as a practical walking system for thoracic paraplegics. Orthopedics, 1989. 12(10): p. 1309-1315.
30. Stallard, J., R. Major, and J. Patrick, A review of the fundamental design problems of providing ambulation for paraplegic patients. Paraplegia, 1989. 27: p. 70-75.
31. Tomovic, R., M. Vukobrativic, and L. Vodovnik, Hybrid actuators for orthotic systems: hybrid assistive systems, in Adv. External Contr. Human Extremities IV. 1973. p. 73-80.
32. Yang, L., et al., Further development of hybrid functional electrical stimulation orthoses. Artif Organs, 1997. 21(3): p. 183-7.
33. Butler, P., R. Major, and J. Patrick, The technique of reciprocal walking using the hip guidance orthosis (HGO) with crutches. Prosthet Orthot Int, 1984. 8(1): p. 33-38.
34. Durfee, W.K. and A. Rivard. Preliminary design and simulation of a pneumatic, stored-energy, hybrid orthosis for gait restoration. 2004.