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Restoring standing capabilities with feedback control of functional neuromuscular stimulation following spinal cord injury

Raviraj Nataraj[a,c,d,*], Musa L. Audu[b,c], Ronald J. Triolo[a,b,c]

[a] Department of Orthopaedics, Case Western Reserve University, 10900 Euclid Avenue, Cleveland, OH, 44106, USA
[b] Department of Biomedical Engineering, Case Western Reserve University, 10900 Euclid Avenue, Cleveland, OH, 44106, USA
[c] Advanced Platform Technology Center, Louis Stokes Cleveland Veterans Affairs Medical Center, 10701 East Boulevard, Cleveland, OH, 44106, USA
[d] Department of Biomedical Engineering, Chemistry and Biological Sciences, Stevens Institute of Technology, 1 Castle Point Terrace, Hoboken, NJ 07030, USA

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ABSTRACT

This paper reviews the field of feedback control for neuroprosthesis systems that restore advanced standing function to individuals with spinal cord injury. Investigations into closed-loop control of standing by functional neuromuscular stimulation (FNS) have spanned three decades. The ultimate goal for FNS standing control systems is to facilitate hands free standing and enabling the user to perform manual functions at self-selected leaning positions. However, most clinical systems for home usage currently only provide basic upright standing using preprogrammed stimulation patterns. To date, online modulation of stimulation to produce advanced standing functions such as balance against postural disturbances or the ability to assume leaning postures have been limited to simulation and laboratory investigations. While great technological advances have been made in biomechanical sensing and interfaces for neuromuscular stimulation, further progress is still required for finer motor control by FNS. Another major challenge is the development of sophisticated control schemes that produce the necessary postural adjustments, adapt against accelerating muscle fatigue, and consider volitional actions of the intact upper-body of the user. Model-based development for novel control schemes are proven and sensible approaches to prototype and test the basic operating efficacy of potentially complex and multi-faceted control systems. The major considerations for further innovation of such systems are summarized in this paper prior to describing the evolution of closed-loop FNS control of standing from previous works. Finally, necessary emerging technologies to for implementing FNS feedback control systems for standing are identified. These technological advancements include novel electrodes that more completely and selectively activate paralyzed musculature and implantable sensors and stimulation modules for flexible neuroprosthesis system deployment.

1. Overview

1.1. Standing with functional neuromuscular stimulation after spinal cord injury

Injury to the spinal cord disrupts the natural communication pathways between the brain and body and can induce muscle paralysis that impairs the ability to perform standard daily motor tasks. The resulting immobility can compromise independence, productivity, and quality of life due to restrictions in engaging in certain work, social, and leisure activities. Complete thoracic-level spinal cord injury (SCI) results in significant motor and sensory loss at the lower extremities and trunk, but leaves the upper extremities largely unaffected. Individuals with paraplegia mainly utilize their arms to propel a wheelchair for basic mobility and may require assistance from caregivers to perform seated transfers. The inability to stand prevents individuals from performing activities of daily living (ADL) predicated on accessing elevated surfaces (e.g., high cabinets, cupboards, and shelving) otherwise unreachable from a seated position. Functional neuromuscular stimulation (FNS) is a proven rehabilitation solution to restoring standing function following paralysis [1–5]. Applying external electrical currents to the intact lower motor neurons innervating the paralyzed lower extremity musculature can generate powerful contractions of the knee, hip, and trunk extensors to facilitate the transition from a seated position to erect stance. This approach not only allows access to manipulate objects at elevated surfaces [3,6,7] and

* Corresponding author at: Department of Biomedical Engineering, Chemistry and Biological Sciences, Stevens Institute of Technology, 1 Castle Point Terrace, Hoboken, NJ 07030, USA.
E-mail address: raviraj.nataraj@gmail.com (R. Nataraj).

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significant assistance with seating transfers [3,4], it is also a mode of exercise that can offer significant therapeutic, physiological [8–10] and psychosocial benefits over wheelchair use alone [11].

Overall, current clinical FNS standing systems can readily produce the muscle forces and resultant joint moments to rise from a chair and assume an upright standing posture with stimulation applied in an open-loop manner. However, feedback control of stimulation to continually generate fine postural adjustments for leaning and maintaining balance while performing functional manual tasks in clinical settings remains a major challenge. Feedback control to achieve leaning postures would expand the reachable functional work volume while standing. Subsequent balance maintenance at these postures would then require stimulation-driven postural corrections to resist disturbances from, not only external sources, but those generated internally by the user during volitional reaching movements or other activities. *Automatic feedback control of standing posture during manual activity is the ultimate objective to improve functionality of lower extremity neuroprostheses.*

In the remainder of this paper, we review considerations for developing FNS systems for standing, describe previous major works, and outline the approaches and technology necessary to augment functionality of FNS standing. First, we re-evaluate the critical questions for the field originally posed in the review by Matjacic et al. [12]. Next, we summarize the evolution of closed-loop control of FNS for restoring standing function after SCI as detailed in previous studies. The summary includes methods developed in our laboratory that continue to evolve for facilitating translation of conceptual frameworks to laboratory demonstrations. Approaches from our laboratory typically include a rich simulation environment to initially develop and test novel feedback control structures. The modeling environment validates basic feasibility of these control structures and is a foundation for creating similar control systems to be deployed in the laboratory for specific users of our implantable FNS standing systems. Finally, we discuss the current and emerging technologies that will spearhead the development of future generations of standing neuroprostheses. These technological breakthroughs include advancements in muscle stimulation and recording techniques and sensor measurements of kinematic variables targeted for feedback control.

1.2. Considerations in developing FNS control systems for standing

In his review a little over a decade ago, Matjacic et al. [12] posed important questions on how best to approach improvements in the FNS control of posture. First*: How can the user be in continuous control of posture regulation?* To date, systems utilizing FNS to restore lower-extremity function are employed for individuals with SCI for whom volitional control of the upper-body is largely retained. Users of these systems can utilize their arms to balance themselves with upper-body support aids. Providing standing function to individuals with more severe deficits such that they have very little to no upper-body function is beyond current technical capabilities and represents an open area for future research work. Such an FNS system would need to recruit many muscle units from the shoulders and upper arms down to the ankles, and efficiently coordinate them to act cooperatively to grip an assistive device, help support body weight, and make the subtle postural corrections required to maintain standing balance. As such, a current objective to advancing FNS standing systems should involve integrating the capabilities of an intact upper-body under volitional user control with activation of the lower-body via FNS. This is still a complex, but necessary challenge to be overcome for meaningful advancements in the functionality and clinical utility of standing neuroprostheses. These issues can be further complicated in the case of incomplete spinal cord injury whereby the user still has some volitional control of the lower body and possibly compromised control of the upper body as well. For the purposes of this review, we presume the challenging case of complete spinal cord injury such that the lower-body is directly activated only by FNS.

The second question posed by Matjacic was: *What sensory feedback should be provided to the user and the artificial control system?* The importance of sensory feedback is well documented for normative standing function. Joint angle feedback is a highly prevalent mode of control in neuroprostheses and orthoses to restore standing and mobility, and can be thought of as the analogue of physiological proprioception [13]. Tactile sensation from the bottom of the feet can infer the location of center of pressure as individuals attempt to control their force interaction with the ground in order to dynamically maintain the total body center of mass within their base of support [14–17]. Head and trunk accelerations may induce vestibular feedback for the individual to produce anticipatory corrections to fast acting and potentially destabilizing postural disturbances [18,19]. Current commercial sensors measuring orientation, segmental accelerations, and point forces can provide surrogate measurements for all of these quantities. While center of pressure could be measured using force plates and force sensitive resistors, laboratory control systems for standing neuroprostheses have largely utilized potentiometers for joint angle feedback, and more recently, accelerometers for trunk or total body center of mass acceleration feedback [20,–22]. The typical neuroprosthesis user would have uncompromised visual feedback, but intact sensory feedback would be restricted to portions of the body innervated above the level of injury. Studies investigating cognitive feedback about whole-body leaning using electrocutaneous [23] and vibrotactile [24] stimulation to just the skin surface have shown improvement in balance performance. Such findings motivate the development of balance prostheses that augment sensory capabilities of the user such as touch and proprioception in relation to the lower extremities and facilitate the integration of that feedback for whole-body FNS standing control.

The third question from Matjacic asked: *What should be the role of the artificial control system in the whole control scheme?* The FNS control system is classically expected to actuate the system to correct deviations from a desired postural setpoint. It has been suggested that FNS control systems have the potential to regulate postural dynamics similarly to healthy individuals with intact CNS during quiet sway [25]. Considering only this controller design, adaptations for higher-order online performance are left to a "re-trained" upper-body wholly under control of the human user. For more natural and functional system performance, Matjacic postulated that the FNS control system should also achieve the secondary objectives of reducing stimulated muscle fatigue and minimizing effort of the user.

Finally, Matjacic asked: *Should the upper, non-paralyzed part of the body be "re-trained" to be able to regulate selected posture continuously?* If so, Matjacic further questioned what the training should be and how should the FNS control system operate to work in synergy with a re-trained user. The major challenge with restoring advanced standing function such that the human and FNS controllers are working in concert is negotiating the small magnitudes of operation in mechanical deviations and time periods from which to actuate control. Joint angle position errors of only a few degrees can shift the total center of mass near the boundary of the base of support, defined as the area under and between the feet. As such, control operation needs to respond to dynamic feedback of segmental velocities and accelerations predicting when disturbances will cause the projection of the center of mass to approach or exceed the base of support, and pro-actively minimize position errors before they are too large to prevent falling or to require a reactive step [26]. Both human and FNS control systems must also rely on dynamic feedback to overcome natural delays in neurophysiological processing that include pure human reaction time to balance