Published in final edited form as:

Med Eng Phys. 2017 April ; 42: 13–25. doi:10.1016/j.medengphy.2017.01.023.

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

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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

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Ethical approval: The research was approved by VA IRB #2008-027.

Conflict of interest: None

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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 [Agarwal, Triolo et al. 1, Davis, Triolo et al. 2, Rohde, Bonder et al. 3, Triolo, Bailey et al. 4, Ho, Triolo et al. 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 [Rohde, Bonder et al. 3, Moynahan, Mullin et al. 6, Triolo, Bevelheimer et al. 7] and significant assistance with seating transfers [Rohde, Bonder et al. 3, Triolo, Bailey et al. 4], it is also a mode of exercise that can offer significant therapeutic, physiological [Jaeger 8, Kobetic, Triolo et al. 9, Marsolais and Kobetic 10] and psychosocial benefits over wheelchair use alone [Andrews and Wheeler 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 [Matjacic, Hunt 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 [Matjacic, Hunt 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 [Fitzpatrick, Gorman et al. 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 [Benda, Riley et al. 14, Winter 15, Winter, Patla et al. 16, Krishnamoorthy, Goodman et al. 17]. Head and trunk accelerations may induce vestibular feedback for the individual to produce anticipatory

corrections to fast acting and potentially destabilizing postural disturbances [Allum and Honegger 18, Runge, Shupert et al. 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 [Nataraj, Audu et al. 20, Nataraj, Audu et al. 21, Nataraj, Audu et al. 22]. The typical neuroprosthesis user would have uncompromised visual feedback, but in tact 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 [Matjacic, Jensen et al. 23] and vibrotactile [Kadkade, Benda et al. 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 [Vette, Masani et al. 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 “retrained” 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 [Pai and Patton 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 perturbations [Liston and Brouwer 27] and coupling dynamics between neural excitation to muscle force activation [Zajac 28]. It is also important to address the biomechanical delay in torque generation subsequent to muscle activation [Masani, Vette et al. 29]. Such processing and actuation delays can be a destabilizing factor in sensorimotor control of standing and

must be considered accordingly. While wholly actuating bipedal balance control without real human input as with an autonomous humanoid robot [Sakagami, Watanabe et al. 30] has been reported, integrating automatic FNS control processes in parallel with a partial human operator that still responds to cognitive and perceptual cues for complex standing control [Balasubramaniam and Wing 31] has not yet been well realized. In order to continue making progress to this end, effective control strategies need to be formulated and vetted to consider the constraints of the system at hand and provide pathways for the human and FNS controllers to work synergistically.

1.3 Objectives for Whole-body FNS Standing Systems

Each body, upper and lower, control system has an independent command center where the user volitionally governs upper-body actions according to natural sensory channels while the FNS feedback controller modulates the stimulation levels across the trunk and lower extremities based on feedback from body-mounted sensors (FIGURE 1). The human central nervous system receives physiological feedbacks that include proprioceptive, tactile, and visual information to maintain posture via the intact upper body. The FNS control system relies on externally-worn sensor measurements to estimate dynamic variables of interest such as orientations, positions, velocities, and accelerations. External forces to the system typically include ground reactions at the feet and hand reactions applied against an assistive device or support surface. There may also be forces acting as external disturbances. Since both upper and lower body systems are mechanically coupled, successful approaches thus far to integrate actions of the distinct controllers have simply assumed both systems share a common objective to maintain a similar postural setpoint. *Given the presence of two distinct control systems acting in parallel to maintain posture, it is important to consider to what extent these systems may operate upon similar principles, objectives, and state information.*

Roles of Intact Upper-body and Activated Lower-body—For governing the upper-body, the human CNS may be specifically utilizing sensory channels to estimate dynamic mechanical variables that include proprioception for body orientation and position [Allum, Honegger et al. 32, Allum and Honegger 33], vision for postural configuration relative to the environment, tactile sensation at the hands for support or sense of balance against a support surface or assistive device [Kouzaki and Masani 34, Suzuki, Mito et al. 35], and vestibular feedback for sensitivity to head and upper-trunk accelerations [Mayagoitia, Lotters et al. 36, Moe-Nilssen and Helbostad 37, Nashner, Shupert et al. 38, Nashner, Woollacott et al. 39]. The standing neuroprosthesis recipient likely utilizes these feedbacks and representative information to exert volitional control of their upper-body muscles towards some postural objective such as maintaining the trunk position or head orientation in a stable manner. While the user has intact sensory representation of upper-body posture, sense of the lower-body is indirect and may be largely treated as external stimuli to which the user must also respond and adapt even if the lower body is acting towards a similar setpoint.

The basic role of FNS systems has been to provide the propulsion and support to assume and maintain a standing posture for individuals with spinal cord injury. For standing balance and rejection of postural disturbances, sensor-based feedback provides estimates of postural states upon which control laws take actions by distributing muscle activation commands to

drive state errors to zero. The postural setpoint is prescribed as a controller design parameter, and the estimate of postural state deviations away from the setpoint are predicated upon sensible transduction of postural variables from raw sensor signals. Joint angle variables measured by potentiometers must assume that the joint center of rotation is well identified to sufficiently coincide with the sensor point of measurement. To avoid errors due to misalignment of such sensors with the anatomical joint centers, relative angles between adjacent segments can be better inferred from relative three-dimensional orientations derived from inertial motion units in real time [Roetenberg, Baten et al. 40]. However, some alignment procedure to match the long-axes of the segments relative to primary measurement axes of the sensors according to anatomical landmarks would still be required.

Estimating Postural States across Whole Body—Whole body variables such as total body center of mass dynamics cannot be directly measured, but must be sensibly estimated from a surrogate quantity derived according to well established anthropometric assumptions. These assumptions include center of mass location of individual limb segments from respective segment endpoints [Winter, Patla et al. 16, Dempster 41]. A sensor system to estimate such whole-body variables needs to have an architecture that is distributed across the body and broadly captures dynamics of individual body segments. Body segments that contribute more to the functional motion of interest may require additional instrumentation. For standing postural responses, the torso, pelvis, and thighs are body segments with notable mass and relatively large changes in motion thereby having greater contributions to center of mass dynamics [Nataraj 42, Nataraj, Audu et al. 43]. As such, accurately characterizing the kinematics of these segments is paramount and additional instrumentation may be required for robust feedback. Furthermore, whole-body kinematics would require identification of a common reference frame from which to describe and sum the effects across all segments. To this end, real-time global orientation can be derived from inertial motion units. However, dynamic orientation estimation requires algorithms to fuse multiple signals across various sensor types, including accelerometers, goniometers, and magnetometers [Roetenberg, Baten et al. 40].

It is still unclear how similar the explicit postural estimates obtained from physical sensor measurements to drive FNS feedback control of the trunk and lower extremities are to those perceived by the intact human CNS. Synergistic activation of paralyzed muscles through electrical stimulation is accomplished by identifying the necessary outputs to drive state error inputs to zero as prescribed by a priori controller design with system identification techniques [Scheerer, Liao et al. 44, Hunt, Stone et al. 45, Vette, Masani et al. 46]. For example, an artificial neural network may relate desired changes in sensor outputs, such as total body center of mass acceleration, to the changes in stimulation levels from a presumed postural setpoint whereby positional deviations are assumed to be small [Nataraj, Audu et al. 20, Nataraj, Audu et al. 21]. However, whether the actions of these activated paralyzed muscles are also productively synergistic with those of the volitional upper body relies on having a similar control objective of restoring posture to a similar setpoint.

Coordinating the Actions of Upper- and Lower-Body—Significant mismatch in objective and setpoint can result in discordant parallel actions whereby the FNS controller

and the human operator are at cross purposes and interpret each other's actions as external disturbances. Earlier investigations for FNS feedback control of standing largely avoided this consideration by reducing the joint degrees-of-freedom and/or limiting the influence of user control with elaborate experimental set-ups involving systematic bracing and support apparatuses. More recent simulation [Nataraj, Audu et al. 20, Nataraj, Audu et al. 43, Nataraj, Audu et al. 47] and laboratory [Nataraj, Audu et al. 21, Nataraj, Audu et al. 22] investigations have employed paradigms with greater potential for clinical translation by removing bracing and allowing for free three-dimensional movements of the user against disturbances during upright stance. The inherent assumption in the controller design of these studies was that the FNS control system for the lower trunk and extremities had the same postural setpoint as the user. While the validity of this assumption was not explicitly established, the subsequent design, tuning, and testing of the controller produced a significant reduction in upper-extremity loading required by the subject to reject systematic postural disturbances. This suggests that the basic assumption is sufficient to achieve improved performance, but that even greater improvements may be attainable. Furthermore, subjects may also positively adapt to FNS controller performance with repeated use and appropriate tuning [Nataraj, Audu et al. 22, Nataraj, Audu et al. 48]. The maintenance of a particular posture setpoint may be an objective that readily allows the user to naturally find cooperative actions with the FNS feedback controller. Positional deviations with typical standing neuroprosthesis usage are typically small, and utilizing dynamic sensor feedbacks such as accelerations are most valuable in largely rejecting fast-acting perturbations, but the return to a natural position setpoint can be left more to the user.

Utilizing FNS of the torso and lower-body to assist the user to attain leaning postures should likely involve more user input in driving the system. Simulation studies have suggested that effective posture shifting [Audu, Nataraj et al. 49] and maintenance [Nataraj, Audu et al. 50] at leaning postures are feasible with stimulation of muscles that produce lower forces as typical following paralysis. In simulation, it has also been shown that a presumed user-driven system to initiate shifting with their upper-body to leaning postures can also be developed [Audu, Gartman et al. 51]. Specifically, a controller that modulates activation levels of target paralyzed muscles according to the neuroprosthesis user driving total body center of mass to a desired location reduces the effort the user may exert to do so when compared to constant activation of those muscles. Allowing the user to drive neuroprosthesis operation is a direct approach to synchronizing voluntary actions with those of the FNS control system. This user-driven control can be done according to sensor-based measurements to estimate surrogate postural variables such as total body center of mass [Nataraj, Audu et al. 50], or detecting user intent from applied loads on handles [Donaldson and Yu 52] or electromyography [Graue 53, Hefftner, Zucchini et al. 54].

Minimize Usage Fatigue and Facilitate Hands-free Standing—During FNS standing, both the upper and lower bodies adapt in response to fatigue. Continually reduced force output from stimulated muscles will compromise the support capabilities of the lower body. To compensate, the upper body will be more greatly recruited towards supportive actions for standing maintenance. It is fatigue across upper and lower bodies that combine to limit the ability to maintain upright posture and restrict standing time. Alternatively

activating distinct muscle groups to switch postures [Kralj, Bajd et al. 55] or adaptive techniques to generate cyclic contractions [Abbas and Chizeck 56, Riess and Abbas 57] have been investigated to mitigate the issue of FNS-generated muscle fatigue. Recent investigations utilizing newer FNS systems with channels of implantable stimulation [Triolo, Bailey et al. 4, Fisher, Miller et al. 58] have reported several cases of excellent standing times (> 20 minutes). In these cases, individuals achieve excellent upright posture and use upper-body loading on an assistive device largely for balance. Presumably these gains were achieved with additional channels and applying stimulation more directly to the biological interface through the implantable electrodes. Thus, significant progress in basic standing maintenance against stimulation-induced muscle fatigue has been shown. It is still unclear how time-varying changes in muscle force output produce specific limits on feedback control applications to improve reaching functionality.

Hands-free standing is the ultimate objective of a standing neuroprosthesis. Approaches that identify optimal control structures according to current technological capabilities with specific user actions will advance the current state of the art. Implementation of hands-free FNS control systems have been shown to be plausible with elegant dynamic modeling and laboratory implementation of systems with constrained degrees-of freedom [Vette, Masani et al. 59, Kim, Mills et al. 60, Vette, Kim et al. 61]. Although integrating the actions of the volitional upper-body with the FNS-controlled lower-body poses challenges from a control perspective, novel strategies that enable these two systems to better operate together are needed to facilitate more natural standing function. The user must continually be further relieved from the task of stabilizing posture so as to more actively focus on manipulation tasks. The FNS system should facilitate not only basic standing but support the functional intentions of the user. *Therefore, the main objective for closed-loop FNS control to augment the user's functional capabilities while standing is to work in concert with the upper-body and minimize user efforts for postural stabilization.*

2 - PREVIOUS STUDIES

2.1 Restoration of Basic Standing

Seminal investigations have demonstrated that basic standing following paraplegia is possible with as few as two to six channels of surface stimulation [Jaeger 8, Jaeger, Yarkony et al. 62, Bajd, Kralj et al. 63, Scheiner, Polando et al. 64]. Pre-programmed patterns of stimulation first facilitate a sit-to-stand maneuver for the user and then continuous supramaximal stimulation is applied to maintain erect standing. Continuous stimulation to the knee, hip, and trunk muscles provides sufficient anti-gravity support to allow for transfers, standing, and swing-to ambulation with walking aids. Percutaneous approaches have allowed generation of more complex movements than with surface stimulation alone [Scheiner, Polando et al. 64, Marsolais and Kobetic 65]. However, more recent clinical deployments have utilized surgically implantable stimulation systems that include intramuscular electrodes [Memberg, Stage et al. 66] and radiofrequency transmission for wireless power and communication [Bhadra, Kilgore et al. 67]. First-generation implanted standing neuroprostheses via epimysial or intramuscular electrodes [Akers, Peckham et al. 68] have undergone successful clinical testing. Implantable systems require surgery and the

typical risks of invasive procedures. But they also offer their recipients the advantages of ease-of-use with minimal donning and doffing of external equipment and improved cosmesis compared to either surface or percutaneous systems. Furthermore, implantable stimulation techniques can provide superior functional performance with greater selectivity and reliable recruitment of target muscle fibers over surface stimulation, which is prone to spillover and producing variable stimulated responses pending session-to-session electrode placement. Increasing the number of stimulation channels facilitates the targeting of additional musculature about the hips, knees, and ankles to increase long-term standing performance in terms of times to fatigue [Triolo, Bailey et al. 4] and to investigate additional functions beyond basic standing; such as stepping [Kobetic, To et al. 69], improved wheelchair propulsion [Triolo, Bailey et al. 70] and seated stability [Triolo, Bailey et al. 71]. Technological innovations at the stimulation interface such as nerve cuff electrodes are continually being developed to improve elicited muscle outputs in terms of recruitment and selectivity [Fisher, Miller et al. 72, Schiefer, Triolo et al. 73]. Such technical advancements should expand the range of neuroprosthesis capabilities and yield further improvements in long-term functional standing performance.

2.2 Feedback Control of Standing Posture and Balance

Despite major progress in stimulation capabilities that readily facilitate erect standing postures and prolonged standing times, the major objective of home use of a neuroprosthesis with closed-loop control for automatic balance capabilities has yet to be realized. Previous studies employing closed-loop control of FNS in simulation and laboratory experiments have demonstrated the feasibility of achieving and maintaining standing postures and minimizing upper-body support against *systematic* postural disturbances [Nataraj 42, Nataraj, Audu et al. 43, Nataraj, Audu et al. 47, Vette, Masani et al. 59, Kim, Mills et al. 60, Vette, Kim et al. 61, Nataraj, Audu et al. 74, Jaeger 75, Jaime, Matjacic et al. 76, Matjacic and Bajd 77, Matjacic and Bajd 78, Tan, Masani et al. 79]. However, clinical implementation of FNS for basic standing is still largely deployed in an open-loop manner. Classically, the main drawback with this approach of constant supramaximal stimulation to maintain standing has been accelerated fatigue of the targeted muscles which inherently minimizes the ability to stand for extended durations. In order to rely on stimulated muscle outputs for prolonged basic standing maintenance, stimulation duty cycles may be enacted that allows certain stimulated muscles to sufficiently rest and recover for discrete periods of time. This presumes that an energy-efficient posture can be achieved by activating the remaining muscles and exploiting user volitional upper-body effort. To enact this type of control actuation, schemes have been previously developed with some success including posture-switching, PID control at the knees, and artificial reflex controllers as reviewed by Matjacic [Matjacic, Hunt et al. 12]. However, newer generations of implantable systems have allowed users who regularly engage in stimulation-driven exercise to recondition the paralyzed muscles sufficiently to achieve quiet standing at times for over an hour with minimal additional support effort [Triolo, Bailey et al. 4]. Given such extended standing times, the major current limitations with constant stimulation approaches involve restricted user capabilities to assume various leaning postures and resist postural disturbances so as to easily perform manual functions while standing.

With open-loop stimulation, the user is left to volitionally stabilize against dynamic postural disturbances with his or her upper-extremities and apply balancing loads upon a nearby surface or an assistive device, such as a walker (FIGURE 2). This added functional burden compromises the user's abilities to utilize the arms during activities of daily living such as reaching and manipulating objects [Triolo, Bevelheimer et al. 7]. While the magnitudes of these corrective forces can be small for quiet standing, these loads increase during dynamic activities necessitating support from at least one upper limb to free the contralateral hand and perform reaching and manipulation tasks [Ho, Triolo et al. 80]. The continual reliance on an assistive device for support over time while performing functional manual tasks can accelerate upper body fatigue and limits the scope of activities and environments for which the neuroprosthesis can be effectively utilized. Regardless of quiet or active standing conditions, prolonged usage and fatigue of the upper-extremities for support will ultimately limit standing times [Uhlir, Triolo et al. 81].

Investigations into closed-loop approaches for FNS standing with disturbance-rejection at individual joints have previously examined isolated control at the knees [Jaeger 75, Moynahan and Chizeck 82], hips [Abbas and Chizeck 83, Chizeck, Kobetic et al. 84], and ankles [Jaime, Matjacic et al. 76, Hunt, Gollee et al. 85]. The objectives in these studies were monitoring the position of the target joints and selectively applying stimulation proportional to deviations away from setpoint values. In so doing, whether joint errors could be reduced while simultaneously minimizing the stimulation delivered to paralyzed muscles was examined. Typically, measures of improved performance were observed on both counts, but required significant instrumentation or bracing at the remaining joints as part of the experimental controls.

Similar constraints were applied again in the next generation of studies that sought to apply feedback control assuming standing function was restricted to the sagittal plane of motion [Matjacic and Bajd 77, Matjacic and Bajd 78]. In these instances, hands-free standing was achievable with feedback control responding to focal joint-disturbances in concert with volitional swaying of the trunk. The model of stance was simplified with fewer degrees-of-freedom and implemented experimentally by extensively restricting multiple joints across the lower-body and torso, including those at the arms. If assuming quiet standing, variations of an inverted pendulum are reasonable approximations, and controller designs acting only at the ankles can be somewhat effective [Winter 86]. FNS system testing apparatuses have been created with such approximations specifically in mind [Tan, Masani et al. 79]. These platforms provide a strong foundation to explore the feasibility of FNS control assuming this approximation, but clinical standing with complex balance and reaching patterns representing more functional activities will ultimately require an expansion of the system beyond the sagittal plane. Time-varying changes in the contractile capabilities of stimulated paralyzed musculature including atrophy, fatigue, and inconsistent recruitment, can further invalidate *a priori* design of a hands-free controller upon a simplified system when applied to the unconstrained system in the laboratory.

Alternatively, there have been studies investigating the feasibility of using upper body loading as a controller input. Several groups have investigated handle reaction forces to control the sit-to-stand maneuver to mediate lower-extremity actions while minimizing

upper-body loading [Donaldson and Yu 52]. However, all of these approaches simplify the musculoskeletal system and typically do not take the three dimensional actions of multi-articulate musculature and coupling joints into account. While these studies established the potential of applying feedback control for FNS standing applications, progressing towards clinical solutions still requires considering the three-dimensional and synergistic nature of standing. To this end, three-dimensional musculoskeletal models have been valuable in formulating FNS control solutions for standing balance.

2.3 Model-based Development of FNS Controllers for Standing

Utilizing a three-dimensional model of standing (FIGURE 3) that includes the lower-extremities [Zhao, Kirsch et al. 87] and trunk [Lambrecht, Audu et al. 88, Wilkenfeld, Audu et al. 89], and then adjusted for the passive joint properties and moment generating capacities with stimulation after SCI [Nataraj, Audu et al. 47], FNS feedback control systems for postural balance have been created and initially evaluated in simulation [Nataraj, Audu et al. 20, Nataraj, Audu et al. 43, Audu, Nataraj et al. 49, Nataraj, Audu et al. 50, Audu, Gartman et al. 51, Nataraj, Audu et al. 74]. Our group has observed that FNS standing users under external perturbations with walker support demonstrate minimal changes in posture including the arms such that the support loads at the hands can be effectively assumed to be equivalently applied at the shoulder joints to the torso [Nataraj, Audu et al. 22, Nataraj 42, Nataraj, Audu et al. 47]. Various feedback control signals indicating perturbed states of standing were evaluated including total-body center of mass (CoM) acceleration in addition to conventional joint kinematics. While standard joint feedback has been demonstrated to reduce position errors during standing, there would be limitations in the ability to reject fast-acting perturbations given non-linear and time-delayed muscle activation dynamics [Zajac 28]. While derivative joint feedback may mitigate this limitation, we postulated that the feedback signal of center of mass acceleration may offer advantages unique to joint-based control such as better representing fast-changing dynamics across the entire system and be estimable using fewer sensors [Nataraj, Audu et al. 43, Nataraj, Audu et al. 50].

The same model environment utilized for initially conceiving various feedback control structures also assisted in planning and formulating the approach implemented during experiments with SCI subjects. Specifically, feedback control approaches were not only evaluated according to optimal performance, but also performance in the presence of feedback errors that are typical of inertial motion-sensing units (IMUs) [Nataraj, Audu et al. 50]. With ideal sensor measurements, comprehensive joint-based feedback control produced a mean reduction of 51% in upper-extremity loading needed to stabilize against various postural disturbances compared to the clinical standard of constant stimulation. However, in the presence of typical sensor errors reported for IMUs [Roetenberg, Baten et al. 40, Roetenberg, Luinge et al. 90, Roetenberg, Slycke et al. 91], almost 86% of the functional gains observed with comprehensive joint feedback control was lost. While a control structure utilizing feedback of total-body CoM acceleration produced a lower mean reduction (43%) in upper-extremity loading compared to comprehensive joint feedback, the former was more robust against typical sensor errors. With sensor error, the functional performance of the CoM acceleration controller only degraded by 35%. Therefore, an

experimental paradigm for CoM acceleration feedback control was developed for an individual with SCI in the laboratory while minimizing the number of accelerometers needed to obtain a robust estimate of CoM acceleration [Nataraj, Audu et al. 21, Nataraj, Audu et al. 22]. A controller utilizing CoM acceleration feedback was constructed according to similar principles as those in simulation for a user of a 16-channel standing neuroprosthesis. This controller successfully reduced the upper extremity loading compared to the clinical standard of constant maximal stimulation in the presence of external and internal perturbations [Nataraj, Audu et al. 21, Nataraj, Audu et al. 22] by 33% and 27%, respectively. External force perturbations were applied systematically utilizing linear electromotor actuators connected to a user of an FNS feedback control system bracing against postural disturbances using an instrumented support device that measures handle forces (FIGURE 4).

3 - NECESSARY ADVANCEMENTS

3.1 Minimize Tuning of Controller Parameters

Previous studies have demonstrated that coordinated three-dimensional synergistic actions can be produced from a FNS feedback control structure for effectively assisting standing balance. Despite this finding, additional measures still must be taken to continue advancing FNS feedback control to improve and extend the functionality of standing with neuroprostheses. The procedures outlined previously [Nataraj, Audu et al. 21, Nataraj, Audu et al. 22, Nataraj, Audu et al. 48] involved extensive data collections for developing, tuning, and testing subject-specific FNS controllers. This approach was appropriate for scientific and proof-of-concept investigation, but it may prove cumbersome as standard operating procedure in a clinical setting. Since standing is a weight-bearing functional activity, reducing the need to collect additional data trials for controller development is important to avoid exhaustive time and effort costs for the user. *Therefore, methodologies that streamline the development of FNS control systems that are subject-specific and minimize experimental tuning are imperative.*

3.2 Enhance Quality of Force Output from Muscle Stimulation

Augmenting the force-output features (increased magnitude, decreased variability, compensating for fatigue) observed in stimulation-induced contractions of paralyzed muscles will always provide a source for improved task-performance with FNS. In simulation [Nataraj 42], the capacity for a CoM acceleration feedback controller to reject disturbances was reduced by 72% when the force-generating capabilities of the stimulated muscles were modified to reflect paralysis. This basic limitation in generating joint moments from stimulated muscle contractions after SCI cannot be wholly circumvented by the control structure itself. Advances in neural technology such as stimulators with high numbers of output channels and complete activation of paralyzed muscles via direct nerve contact [Fisher, Miller et al. 72, Schiefer, Triolo et al. 73, Fisher, Miller et al. 92] are continually being developed to address this end. These advancements provide novel and effective means by which to not only augment recruitment, but also provide options such as systematic cycling between stimulation channels to switch postural support strategies and continually adapt and compensate against muscle fatigue [Krajl, Bajd et al. 55]. In deed, stimulation

cycling with a spatially-distributed stimulation interface can delay fatigue in the quadriceps [Maneski, Malesevic et al. 93].

For standing function, quickly generating larger forces at musculature about the ankle such as the tibialis anterior and gastrocnemius would be especially valuable for continual modulation during quiet standing [Winter, Patla et al. 94] and facilitating ankle-hip strategies [Horak and Nashner 95] for balance against fast-acting perturbations in the sagittal plane. Methods to generate such force impulses may entail high-frequency, short-burst of stimulation pulses to generate rapid force increases while still mitigating muscle fatigue [Karu, Durfee et al. 96]. Being able to more fully recruit additional hip abductor and adductor muscles (e.g., gluteus medius, adductor magnus) expands the control space from which to find and execute optimal responses to stabilize within the coronal plane. Strategies developed for technological advances such as multi-contact nerve stimulation could better facilitate cyclic stimulation across musculature with redundant functional roles in standing [Fisher, Tyler et al. 97]. For example, varying activation levels across the quadriceps heads for providing stable knee extension may further extend standing times.

3.3 Improve Accuracy of Postural State Measurements for Feedback

Sensor-based feedback for closed-loop control of a neuroprosthesis must consider the error inherent to the sensors being utilized when attempting to optimize functional performance that is inextricably sensitive to that feedback. Work from Nataraj et al., [Nataraj, Audu et al. 43] indicated the dependence of feedback controller performance of standing neuroprostheses on error-types and error-magnitudes typical of IMU's of that time. Conclusions from that study assisted in the guidance of the selection of control strategy to employ during laboratory experimentation with neuroprosthetic users. Continued advancements in the quality of sensor components have led to the promising miniature, lower-power inertial sensors that can be part of implantable motion capture systems [Lambrecht and Kirsch 98]. Furthermore, algorithms that consider stereotypical features inherent to the desired movement can optimize the information acquired from networks of multiple body-mounted sensors by incorporating data related to their locations to provide robust estimates of feedback variables of interest [Nataraj, Audu et al. 21]. Future developments of sensor feedback systems for FNS standing should focally consider ways to generate better estimates for ankle angle and torso acceleration given their high relative contributions to estimating total-body center of mass position and acceleration, respectively [Nataraj, Audu et al. 43].

3.4 Create Controller Modules that Add Standing Functionality

While previous FNS studies have focused on restoring basic standing function and maintaining bipedal postural balance, continuing to advance standing functionality would involve restoring additional standing capabilities to the neuroprosthesis user. Truly functional neuroprostheses should enable users to manipulate objects while standing to facilitate a larger reachable workspace. While improved postural balance at the basic erect standing position can augment resistance to systematic disturbances constrained to a single plane [Nataraj, Audu et al. 21, Nataraj, Audu et al. 48], facilitating neuroprosthesis users' abilities to change their setpoint to leaning postures would further improve their reaching

capabilities. Simulation studies demonstrate that forward and side leaning attitudes can be assumed with FNS while minimizing the upper extremity loading exerted while shifting standing posture [Audu, Nataraj et al. 49, Audu, Gartman et al. 51]. To augment margins of safety while using a standing neuroprosthesis, enacting reactive-stepping [Pai, Rogers et al. 99] strategy could also be pursued to protect against unusually large postural disturbances and minimize the likelihood of falling.

4 - ONGOING DEVELOPMENTS AND FUTURE OPPORTUNITIES

4.1 Nerve-based Electrode Stimulation for Muscle Activation

As reviewed in Ho et al., [Ho, Triolo et al. 5], functional stimulation technology has been rapidly advancing with novel techniques for activating the neuromuscular interface. Commercially available surface stimulators with reduced channel counts can generate limited lower extremity function. However, implantable systems with epimysial and intramuscular electrodes to activate only the knee, hip, and trunk extensor muscles can reliably power the sit-to-stand maneuver and maintain basic standing. Increasing the number of intramuscular stimulation sites [Bhadra, Kilgore et al. 67] to activate ankle muscles and hip ab/adductors has facilitated the use of sensor-based feedback control to automate maintenance of standing balance [Nataraj, Audu et al. 22]. Electrodes designed to wrap around individual nerves with various geometries [Agnew, McCreery et al. 100, Naples, Mortimer et al. 101, Tyler and Durand 102] are being employed to selectively target smaller groups of axons within a nerve and access particular fibers not readily accessible from the surface or with intramuscular electrodes. Neuron pools may also be activated directly in the spinal cord with intraspinal microstimulation [Bamford and Mushahwar 103] and via epidural stimulation at the lumbosacral spinal cord [Harkema, Gerasimenko et al. 104].

Standing performance and functionality may be significantly improved with nerve-based electrodes to augment recruitment of target muscles via efferent pathways. Continuous stimulation of the femoral nerve with a multi-contact cuff electrode was shown to increase standing time and accelerate the reconditioning rehabilitation of the target muscles to mitigate atrophy and facilitate strengthening [Fisher, Miller et al. 58, McDonnall, Clark et al. 105, Yoshida and Horch 106] (FIGURE 5A). Multi-contact nerve stimulation electrodes place a high density of contacts around or in peripheral nerves to independently activate multiple fascicles and motor units [Fisher, Miller et al. 58, McDonnall, Clark et al. 105, Yoshida and Horch 106]. Such approaches also offer the potential to delay the effects of fatigue by alternating activation of independent motor unit pools between synergistic muscles or within a single muscle via high contact density nerve cuffs or multiple independent nerve- or muscle-based electrodes [Fisher, Tyler et al. 97]. Direct contact with the electrode exposes the nerve to potential damage and more complicated revision surgeries. As such, nerve-based electrodes [Fisher, Miller et al. 58, Schiefer, Polasek et al. 107] with novel designs are being developed that minimize physical pressure and mechanical insult to mitigate the associated risks. Independent motor unit pool activation can also facilitate the reduction in the required number of implantation sites, thus improving surgical efficiency, provide better control of multiple movements with a single electrode, and recruiting of populations of agonist motor units to facilitate multiple new functions such as

enabling stepping as well as standing [Schiefer, Polasek et al. 107, Fisher, Tyler et al. 108]. For even the singular task of standing balance, multiple coordinated movements may need to be available to be invoked for optimal standing performance. Pending the nature of the postural configuration and available feedbacks, varying hip and ankle strategies may be employed to best resist the effects of particular postural perturbations [Horak and Nashner 95, Friedli, Cohen et al. 109, Horak, Diener et al. 110]. Improved selectivity in stimulating target musculature, enhanced fiber recruitment and complete activation of the target muscles, and the ability to activate smaller motor units first may all enhance neuroprosthesis function through the application of nerve-based stimulation technologies. This would effectively increase the operating range of control and facilitate motor function capabilities that require either more precision or greater strength.

Further innovations in these nerve-based electrodes are being investigated to offer even greater potential for improving standing function with neuroprostheses. Since many nerves are not circular in cross section, the flat interface nerve electrode (FINE) was created to be more congruent with nerves having oblong cross sections (FIGURE 5B). In so doing, the FINE can recruit muscles more selectively than a spiral or other nerve cuffs with circular cross sections without penetrating the epineurium. Greater recruitment selectivity from a single multi-contact electrode offers greater possibilities for generating coordinated contractions of several muscles innervated by the same nerve trunk. For example, the CWRU spiral nerve cuff electrode has been shown to be capable of generating joint moments from functionally synergistic muscle groups [Fisher, Tyler et al. 97], but the FINE can better increase the scope of finer control with more selective activation of individual muscles [Schiefer, Freeberg et al. 111]. While greater and more selective activation of additional muscle groups may allow for development of FNS balance control systems that better resist postural disturbances, nerve-based electrodes may also facilitate additional balance functionality such as stepping strategies to prevent falling when disturbances are too large to reject [Pai and Patton 26, Pai, Rogers et al. 99].

Nerve electrode applications have also been developed for stimulating afferent pathways to restore sensation to paralyzed individuals. Restoring tactile feedback following nervous system trauma may offer opportunities to develop feedback control systems that provide user a more natural interface with their prostheses. While the FNS control system could rely directly on sensor-based feedback, user actions may be positively modified for better functional performance by providing the tactile sensation to which able-bodied individuals have access. Users of standing neuroprostheses primarily rely on natural physiological feedbacks of vision, proprioception of their upper body posture and tactile feedback at their hands when using a support device. The user typically has little to no direct sense of their lower extremities and must simply react following disturbances and FNS-induced motions of the lower body. Work is ongoing for applications to improve task performance of upper-extremity prostheses by restoring sensation [Tan, Schiefer et al. 112, Tan, Schiefer et al. 113] to provide the user spatial information about the objects being manipulated. Tactile sensation ultimately provides important cues for maintaining postural balance during normative standing as well. Individuals ultimately gain representation of their standing center of pressure (CoP) according to location of the ground contact forces applied to the bottom of their feet. Several studies have postulated that differentials between standing CoP versus the

individuals total-body CoM provides the fundamental basis of standing control [Winter 15]. How individuals with SCI would effectively integrate restored sensation of the lower body to modulate their upper-body actions when using a standing neuroprosthesis has yet to be examined.

4.2 Sensing for Postural State Feedback

FNS standing feedback control has typically relied on measurements from externally worn sensors such as potentiometers for estimating joint angles [Jaeger 75, Matjacic and Bajd 77, Chizek, Kobetic et al. 84, Hunt, Gollee et al. 85, Hunt, Gollee et al. 114, Gollee, Hunt et al. 115] and more recently accelerometers for total body CoM accelerations [Nataraj, Audu et al. 21, Nataraj, Audu et al. 22]. Inertial motion units include components of gyroscopes, magnetometers, and accelerometers from which the real-time estimates of three-dimensional changes in orientation during functional activities can be derived [Roetenberg, Baten et al. 40, Roetenberg, Slycke et al. 91]. Miniature lower-power inertial sensors are being evaluated for implantable motion capture systems [Lambrecht and Kirsch 98]. Recent advances at CWRU [Krames, Peckham et al. 116] have led to the development of implanted modules that can remotely communicate through radio-frequency signaling and include within each module both stimulation and sensing capabilities as part of a networked neuroprosthesis system (NNPS). To investigate the potential of employing such a system in the laboratory, methodology was developed and tested in simulation that estimates desired feedback variables of total body center of mass position and acceleration for a possible architecture of the NNPS that restores erect and leaning standing function (FIGURE 6) [Nataraj, Audu et al. 50]. The tested architecture was constrained to only include accelerometer sensors with each module which is consistent with the planned implementation of the first-generation NNPS. The simulation strategy assumed that each accelerometer signal would either represent segmental tilt or segmental acceleration depending if the system was in either balance mode at a particular setpoint posture or was actively shifting to another leaning posture. CoM acceleration and CoM position were the feedback variables of interest for balance maintenance and posture shifting, respectively. The strategy employed in simulation demonstrated that both CoM acceleration and position could be approximated to within 20 % of the maximum respective value measured. Furthermore, strong correlations ($R > 0.9$) were observed between values estimated by the proposed method and the true values derived from model dynamics. Utilizing the estimated feedback values for control still significantly reduced ($p < 0.001$) the maximum upper extremity loading observed against postural perturbations compared to conventionally applying constant and maximal stimulation. Thus, while an accelerometer-only sensor scheme has potential feasibility, a scheme that considers real-time orientation under dynamic conditions offers more comprehensive characterization of system states and greater reductions in upper extremity stabilization loading [Nataraj, Audu et al. 43]. Furthermore, no parsing between shifting and setpoint maintenance modes would be necessary.

5 – RECOMMENDATIONS FOR MODEL-BASED CONTROL OF FNS STANDING

Continued progress in augmenting the performance and capabilities of standing neuroprostheses is predicated on not only technological advancements in modes of stimulation and the sensors being implemented, but also on intelligent control methodology to optimize the technical aspects of the employed system with the specific user. *The musculoskeletal modeling environment can provide a test-bed for these types of control structures from which to create simulation data mapping feedback kinematics to muscle excitation levels specific to the user.* These maps can be reliably represented by artificial neural networks and then driven as part of a servo-control structure for neuroprosthetic operation of standing function [Nataraj, Audu et al. 20, Nataraj, Audu et al. 21, Nataraj, Audu et al. 47]. The control structures themselves may utilize gain values to be optimally tuned towards minimizing the potential contributions of an upper-extremity control system that is essentially independent of the FNS control structure, but similarly acts to stabilize system operation. This fundamental approach provides a basis from which to tune the actions of the FNS system to those of the volitional control system when maintaining standing balance or assuming new standing postures.

Thus far, the musculoskeletal modeling environment has been used to test the conceptual feasibility of novel control structures for standing neuroprostheses. *In the future, to reduce the onus on laboratory experimentation with subjects to identify and tune control structures, musculoskeletal models reflecting anatomical features and force-generation capabilities of the user can then be utilized.* This approach may be used to better initially identify subject-specific control structures which potentially require minimal online tuning. Furthermore, simulation can provide the basis from which to identify which sources of sensor feedback are most needed for clinical intervention in designing and constructing more efficient control solutions. While comprehensive control of a system or task is ideally desirable, clinical acceptance is typically predicated on factors such as ease-of-use, reliability, robust and predictable operation, and of course, functionality [Batavia and Hammer 117, Phillips and Zhao 118]. Therefore, prostheses and paradigms may be optimized according to well-founded functional specifications identified in simulation for minimizing the number of sensors utilized or gain-optimizing the control structures in the presence of expected levels of sensor error. Enhancing methods for creating subject-specific musculoskeletal models are increasingly prevalent [Bolsterlee, Veeger et al. 119, Cleather and Bull 120, Fregly, Besier et al. 121, Gerus, Rao et al. 122] with the ultimate objective of utilizing them for producing clinical solutions. Given the variable nature of SCI and need for customizing interventions to specific individuals, musculoskeletal modeling may be especially valuable in neuroprosthetic development.

Finally, the modeling environment provides the platform to test various controller paradigms. *Specifically, one can evaluate mechanical performance of the system according to different bases of neural control.* The user and upper-body can be modeled as a human operator system acting against automated control of the FNS system [Parasuraman, Sheridan et al. 123]. Cooperative control approaches for advanced human machines interfaces [Cao,

Fukunaga et al. 124, Hoc 125, Goodrich and Schultz 126] could be readily employed and tested in simulation to evaluate the potential for synergistic actions between the user upper-body system and that of the FNS system acting directly upon the torso and lower-extremities. Feedbacks can be varied to consider different sensor locations [Nataraj, Audu et al. 50], typical sensor errors [Nataraj, Audu et al. 43], or novel sensor signals such as nerve electrode recordings [Cogan 127]. These signals would need to be represented mathematically according to known signal features such as frequency content including noise, presence of bias, and possible online tracking inaccuracies. For novel controllers designed to better bridge operation between the user and the neuroprosthesis, additional signals may be included and modeled accordingly. These signals may indicate user intent such as force loading or electromyography activity, or provide novel feedback to the user such as nerve stimulation for restoring tactile sensation. In any case, the musculoskeletal modeling environment provides the basis to observe potential mechanical effects to these various control structures being tested against specified environmental or user-created postural disturbances.

For model-based development of FNS controllers for standing, we recommend the following:

1. Creating subject-specific models: Given the variation in height, weight, and force-generating capabilities of muscles activated by stimulation across users, controller design parameters such as gains cannot be universally identified and must be customized for each individual accordingly. Creating platforms to rapidly and accurately identify these parameters in simulation prior to experimental testing in the laboratory can produce major gains in controller development efficiency.
2. Identify the human operator module of the control system: The volitional actions of the user should be characterized to identify an operating point about which to reliably tune parameters of the FNS system in simulation. Previous studies have typically assumed approximate general behavior of the user to demonstrate proof-of-concept potential of FNS feedback control. In the laboratory, investigations for feedback control have relied upon the user in part to adapt to the actions of the FNS control system online. Ideally, the basic human operator model of the user for a particular functional task related to FNS standing, such as stabilizing against perturbations or initiating leaning movements for reaching, can be identified using human factors approaches [McMillan, Beevis et al. 128] prior to FNS parameter tuning in simulation.
3. Develop real-time modeling environments to adaptively optimize controllers online: Instead of using bulk data collections for offline optimization done in batch with the musculoskeletal model, parameters for the control system should be continually adapted with each trial presentation of new data. Such an advanced environment would also be able to identify and consider variations in sensor measurements, biomechanical changes due to stimulation from a desired reference point, and uncertainties in the human operator when identifying new controller parameters. Adaptive FNS algorithms have been developed based on

input-output estimation to eliminate model identification [Brend, Freeman et al. 129], but mechanistically defining a real-time model that includes definitions for the muscles targeted for FNS provides a more comprehensive and transparent basis for controller development. Real-time modeling applications could utilize subject-specific musculoskeletal models from imaging methods [Fernandez and Pandy 130] or custom modifications of models specifically designed to be tractable for standing and walking control applications [Ferrarin, Palazzo et al. 131, Popovic, Radulovic et al. 132].

6 - CONCLUDING REMARKS

The ultimate achievement in a standing neuroprosthesis would be to allow the user to assume various stable postures and have both arms fully available for manipulation activities and not rely upon them for active postural stabilization using an assistive device or support surface. Challenges to this end involve responding to the inherent instability of the bipedal standing system, enacting complex control synergies, and attaining accurate system identification. Normative standing postural control may be empirically described by simplified control principles [Winter, Patla et al. 16], but highly evolved sensorimotor systems may be coordinating multiple sources of sensory feedback to perform the necessary finer and more complex motor control adaptations [Kawato 133]. Replicating such systems with artificial sensing and actuation presents large technical challenges. Continued progress in advanced stimulation technology, better performance and integration of inertial sensors, and recording and stimulation techniques of natural sensory channels are serving to address these issues. These considerations are best examined initially in simulation to identify variability in user operation, sensitivity of performance to different sensor-based feedbacks, and the mechanical consequences of having a user volitionally-controlled upper body and an FNS-driven lower body.

Acknowledgments

The prevalent research described that was performed by the authors was supported by Grant Number R01NS040547 from NINDS/NIH, and T32AR00750525 from NIAMS/NIH. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of NIH. The research described here was supported in part by the Department of Veterans Affairs, Veterans Health Administration, Rehabilitation Research and Development Service—Award No. A9259-L.

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Highlights

- Review current status of functional neuromuscular stimulation control of standing
- Discussion of computer simulation as platform for evaluating controller performance
- Detailing necessary technological developments in sensing and stimulation

FIGURE 1.

Two distinct control systems present during operation of neuroprosthesis to restore standing function: (1) Volitional control of user upper-body governed by human CNS, (2) FNS feedback controller electrically activating lower-extremities and lower trunk according to sensor-based feedback. An important underlying consideration for overall postural control is whether the setpoint and estimated postural state are similar for both control systems.

FIGURE 2.

Eight-channel implant recipient (T9 AIS A) releases one hand from walker or surface for manual tasks and overhead reaching activities while standing with the neuroprosthesis.

FIGURE 3.

Three-dimensional (3-D) musculoskeletal model of human bipedal stance adjusted to reflect effects of spinal cord injury (SCI) while under feedback control of functional neuromuscular stimulation (FNS) with user upper-extremity support on an assistive device.

FIGURE 4.

Experimental set-up for FNS feedback control during bipedal standing against external perturbations has user applying support loads upon stable instrumented handles.

FIGURE 5.
(A) The CWRU spiral nerve-cuff stimulation electrode, (B) The C-FINE stimulation electrode developed at the Cleveland APT Center

FIGURE 6.

LEFT – Implantable components utilized with networked neuroprosthetic system (NNPS) developed at Cleveland FES Center, RIGHT – Possible architecture for implantable modules used with NNPS for restoring standing function (Nataraj et al., 2015)