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# Feedback Control of Upright Seating with Functional Neuromuscular Stimulation during a Functional Task after Spinal Cord Injury: A Case Study

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***Abstract*— Seated stability is a major concern of individuals with trunk paralysis. Trunk paralysis is commonly caused by spinal cord injuries (SCI) at or above the thoracic spine. Current methods to improve stability restrict the movement of the user by constraining their trunk to an upright position. Feedback control of functional neuromuscular stimulation (FNS) can help maintain seated stability while still allowing the user to perform movements to accomplish functional tasks. In this study, an individual with a SCI (C7, AIS B) and an implanted stimulator capable of recruiting trunk and hip musculature unilaterally moved a weighted jar on a countertop to and from three prescribed stations directly in front, laterally, and across midline. For comparison, the tasks were performed with constant baseline stimulation and with feedback modulated stimulation based on the tilt of the trunk obtained from an external accelerometer fed into two PID controllers; one for forward trunk pitch and the other for lateral roll. The trunk pitch and roll angles were obtained through motion capture cameras and various measures of postural sway (95% fitted ellipse area, root mean squared (RMS), path length) and the repeatability (coefficient of variation (CoV), variance ratio (VR)) were calculated. Feedback control significantly increased RMS of trunk movement along the major axis of the fitted ellipse, but decreased RMS values during bending along the minor axis of motion. As a result, the fitted ellipse area decreased when deploying the jar to one of the stations and increased with the other two. The CoV indicated reduced variation in the presence of feedback controlled stimulation for all stations, and VR showed higher repeatability in trunk pitch. Plots of the trunk pitch and roll revealed a faster return to upright motion due to feedback stimulation.**

***Clinical relevance*— Feedback control in combination with FNS is a viable method to improve seated stability while still allowing dynamic movements in individuals with a SCI, thus addressing a major concern of the population.**

## I. INTRODUCTION

Spinal cord injury (SCI) severely hampers the sensorimotor capabilities below the site of the injury resulting in a significantly reduced state of well-being [1]. Roughly 297,000 people in the United States currently live with SCI, increasing by 17,810 yearly [2]. Many individuals with SCI have difficulty of maintaining seated balance as the muscles of the trunk and hip are paralyzed in injuries at or above the thoracic level. This lack of seated stability has been rated the third highest priority for improvement by the population [3]. Current methods of restoring seated stability involve straps or pads that restrict range of trunk motion. While beneficial for actions that can be performed from a static upright posture, such methods restrict dynamic movements of the trunk and ultimately compromise work volume and the ability to reach and manipulate objects.

FNS has been successfully employed to restore or facilitate a multitude of functions to individuals with SCI, including walking [4], biking [5], grasping and reaching [6]. FNS applied to activate the lumbar paraspinals and pelvic muscles at constant levels has been shown to increase bimanual reach length, improve seated posture, and enhance resistance to minor destabilizing perturbations [7], [8]. Combining stimulation with a feedback control system allows for further improvements such as dynamic actions to compensate for external perturbations [9], [10] and return to an upright posture from a fully forward flexed position [11]. The ultimate goal of a neuroprosthesis for seated posture and balance is to allow users to accomplish activities of daily living (ADLs) while leaning or reaching in the presence of internally generated or externally applied perturbations, which requires feedback control of stimulation. Vanocini *et al.* tested both an optimal controller and a proportional, integral, derivative (PID) controller to maintain seated posture in individuals with SCI [9]. The PID controller was characterized by a faster recovery from the perturbations and reduced oscillations at the reference angle. Audu *et al.* similarly employed a PD controller to resist perturbations in the sagittal plane applied to the trunk by a linear actuator [10]. Feedback control of seated posture has yet to be implemented with regards to internal perturbations generated by voluntary movements of the upper extremities to acquire and relocate objects such as those encountered during many activities of daily living.

In this study, we implement two PID controllers to control both extension and lateral bending of the trunk. We hypothesize that implementation of feedback control of stimulation will increase the robustness of the system response to internal perturbations by increasing the consistency of trunk movements and reducing the postural sway of the user. The

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objectives of this study are twofold: 1) Demonstrate the effectiveness of a multi-directional FNS feedback controller during a functional task, and 2) Determine the impact of feedback control of stimulation on trunk movements compared to the same functional task performed with a constant level of stimulation.

## II. METHODS

### A. Participant and Neuroprosthesis

One 48-year-old female with a C7 AIS B (motor complete paralysis with some sensory sparing) spinal cord injury was recruited for this initial study. At the time of testing, the participant was 167.6cm tall, weighed 58.5kg, 22 years post injury, and 21 years post implantation of a motor system neuroprosthesis. The volunteer had been previously received the neuroprosthesis for other studies of standing and stepping after paralysis that required activation of the muscles that controlled the hip and trunk via intramuscular or epimysial electrodes. In this series of experiments, stimulation was applied to the nerves innervating the lumbar erector spinae (ES), the quadratus lumborum (QL), the posterior portion of the adductor magnus (PA), the gluteus maximus (GX), the gluteus medius (GM), and the hamstring semimembranosus (HS). The electrodes connect to an implanted stimulator-telemeter developed at Case Western Reserve University that is powered by an external control unit that modulates stimulus parameters via an inductive communication channel [12], [13]. The subject signed a consent form approved by the local institutional review board before participation (IRB: VA Northeast Ohio Healthcare System, Protocol Number: 07101-H36, Approval Date: 9/7/2010).

### B. Feedback Control System

The control system was composed of an tri-axis accelerometer (CMA3000- D01, VTI Technologies, Vantaa, Finland) as a sensor to measure trunk tilt, an external controller, and the implanted stimulator (Fig. 1a) to excite the trunk and hip muscles which served as the actuators. The feedback signal was obtained from the accelerometer (sampled at 40Hz) placed on the sternum. The corresponding accelerometer tilt angle was computed with the same method from Audu *et al.* [10]. Briefly, the accelerometer predominately measures acceleration due to gravity. Changes in the tilt of the tri-axis accelerometer due to trunk movement results in measurable changes in the relative position of the gravity vector. Changes in the x axis value were related to changes in lateral bending of the trunk, while changes in the z value were related to trunk flexion angle. Baseline x and z values were set at the beginning of each trial while the subject was in an upright seated position. The error signal for the PID controller was calculated as the difference between the measured and baseline tilt manually set at the beginning of each trial. Two PID controllers were simultaneously employed for flexion and lateral bending. The flexion PID controller modulated activation of the ES, PA, HS, GX, GM with the gain applied to both the left and right sides of the body equally. The lateral bending PID controller modulated activation of the ES and QL. In this controller, if the error signal was negative the gain was applied to the stimulus channels on the left side of the body, if the error signal was positive the gain was applied to the stimulus channels on the right side of the body. The resulting controller gain was then used to calculate the stimulation level to each muscle via Equation 1.

$$p^i_{applied} = p^i_{min} + C \cdot (p^i_{max} - p^i_{min}) \qquad (1)$$

Where $p^i_{applied}$ was the pulse width (PW) setting for the $i^{th}$ electrode, $p^i_{max}$ was the maximum allowable PW, and $p^i_{min}$ was the minimum PW value showing a visible contraction of the muscle. C was the controller gain. The new stimulation levels ($p^i_{applied}$) were delivered to the subject's FNS external control unit to elicit changes to the trunk position. In the constant stimulation condition the $p^i_{applied}$ was equal only to the $p^i_{min}$. All calculations were conducted in a MATLAB/Simulink (MathWorks Inc., USA) model running on the xPC Host-Target real-time environment.

The minimum and maximum pulse width (PW) levels of stimulation for each muscle are specific to the subject and were determined prior to the experimental session. The minimum value was the minimum amount of stimulation that results in visible contraction of the muscle. The maximum stimulation value was set as the maximum value comfortable to the subject, did not recruit any additional muscle force, or as dictated by the hardware limit (250 µsec). The control system modulated PW values as the stimulator has a higher resolution in PW modulation than in amplitude modulation. Stimulation frequency was fixed at 20Hz and amplitude set at 20mA. The PID control parameters were tuned online before the experiment while the subject was completing practice reaching.

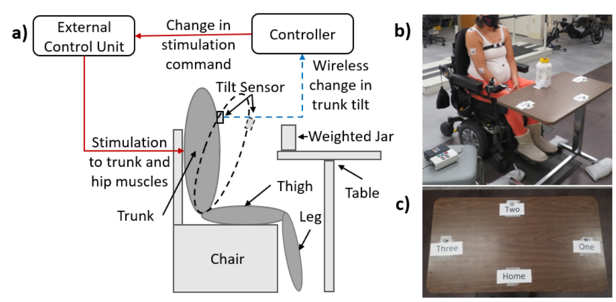


Fig. 1. a) Schematic of the trunk feedback control system. An external computer reads in the position of the trunk from a tilt sensor in real-time. The computer determines the level of stimulation necessary and according to the PID control laws sends the information to an external control unit capable of communicating with the implanted stimulator. b) A subject was seated in front of a table with adjustable height. c) Locations were labeled on the table as home, one (across midline), two (forward), and three (lateral).

### C. Experimental Setup

A weighted jar was placed on a table with a labeled 'home' station and three stations (one, two, and three) located radially from the home station as shown in Fig. 1. The height of the table was adjusted to allow the subject to move the jar to the various stations comfortably. An upper body motion capture marker set was applied to the subject, including markers on the sacrum and C7 vertebrae. Additionally, markers were taped to the weighted jar and at the target stations. Motion capture of the subject's movement was obtained with a 16 camera Vicon system (Vicon Motion Systems Ltd., Oxford, UK) at a sampling rate of 100Hz.

### D. Functional Task Procedure

The functional task was to move the weighted jar from the center (home) station to the radial stations. The subject remained seated in their wheelchair for the duration of the experiment (Fig. 1b). They were instructed to move the jar to one of the three target stations (Fig. 1c), leave the jar at that station, then reacquire the jar and return it to the original home station upon receipt of a second cue. The subject used their left hand to perform all reaching actions. In each trial, the jar was deployed to and returned from each station three times in a random order. Four trials were done with constant stimulation and four trials were done with stimulation modulated by the feedback controller. These were alternated with breaks between trials to reduce fatigue. This resulted in 12 total movements to each target station for both conditions.

### E. Experiment Data Analysis and Statistics

Real time feedback of trunk pitch (extension and flexion movements) and trunk roll (lateral bending movements) was determined by measuring the gravity vector with a tri-axis accelerometer. All offline data analysis of trunk pitch and roll angles were calculated from the motion capture data as the angle of the line between the C7 and sacrum markers measured from its reference position with the subject in an erect seated posture [14]. These pitch and roll angles were filtered offline with a 4th order zero-phase Butterworth filter with a low-pass cutoff of 10 Hz [15]. The trunk angles from each trial were separated by target station (one, two, three). The movements were then normalized by time to a cycle percentage (100 time points). The cycle beginning was set as 1.25s before the weighted jar reached 10% of its maximum velocity and 1.25s after the movement of the weighted jar dropped below 10% of its maximum velocity. These values were chosen qualitatively to include the vast majority of the trunk movement while eliminating starting and stopping transients. The first 50% of the cycle is the deployment of the jar to the target station, the second 50% is the return of the jar to the home station.

To characterize the postural sway of the subject, the pitch angle was plotted against the roll angle during each movement. An ellipse was fitted to these data to encompass 95% of the data following the prediction method described in [16] for each movement. The root mean square (RMS) was calculated along both the primary and secondary ellipse axes, hence referred to as the major and minor axis of trunk motion. Finally, path length was also determined from the motion capture data. These results were compared between the constant stimulation and feedback stimulation conditions with a student's t-test ($\alpha = 0.95$, $n = 12$), p-values under 0.05 were considered significant.

Time series analysis was also performed to compare constant stimulation to feedback control during the internally generated perturbations. The coefficient of variation (CoV), modified for a time series [17], was calculated to compare the variation in the movement of the trunk in each condition. The variance ratio (VR) was also calculated using established methods described in [18]. VR is a measure of the repeatability of the movement, with values closer to 0 indicating increased repeatability and values close to 1 showing little repeatability.

## III. RESULTS

Table I shows the kinematic variance measures with respect to each targeted station. Bold values show significance. Fitted ellipse area was significantly changed by the feedback controller in all three stations, however the direction of change was not consistent, with a decrease in area in Station One and an increase for both Stations Two and Three. Every station showed a significant change in the major axis RMS with increasing values from feedback control. Only Station One showed a significant decrease in the minor axis motion with feedback controlled stimulation. The path length showed a significant increase in Station Three with feedback control and no difference in the other stations. The CoV was lower with feedback control for all target stations in both trunk pitch and roll. The VR was lower for every station in trunk pitch movements and lower for Station Two in roll. The VR increased in Station One and Three in trunk roll. Fig. 2 shows the trunk pitch and roll while deploying and returning the jar to station two. The feedback control condition was characterized by a faster return to erect extension movement and increased lateral bending.

## IV. DISCUSSION

The feedback control system drastically impacted the trunk movement in completion of the functional task. The major axis of trunk movement saw significantly increased magnitude while secondary directional movements decreased. This led to an inconsistent effect on the ellipse area with a significant reduction in area during movement of the jar to Station One and a significant increase when moving to Stations Two and Three. It is possible that the compensatory strategies employed by the subject varied depending on

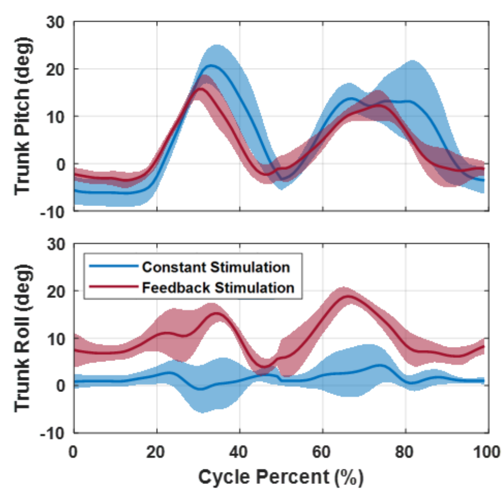


Fig. 2. Trunk pitch and roll plotted against the cycle percent for station two. Shaded colored areas are standard deviation (n=12).

TABLE I

KINEMATIC VARIANCE MEASURES (MEAN ± SD) OF THE SUBJECT BOTH WITH AND WITHOUT STIMULATION FOR EACH TARGETED POSITION. A STUDENT'S T-TEST CALCULATED THE P-VALUE (N = 12). BOLD VALUES HIGHLIGHT SIGNIFICANCE.

| | Station One | | | Station Two | | | Station Three | | |
|---|---|---|---|---|---|---|---|---|---|
| | Constant | Feedback | p-value | Constant | Feedback | p-value | Constant | Feedback | p-value |
| Ellipse Area (deg) | 366.6 ± 131.8 | 160.6 ± 36.7 | **0.000** | 277.9 ± 70.2 | 347.1 ± 60.6 | **0.013** | 78.1 ± 18.7 | 120.1 ± 46.2 | **0.008** |
| Major Axis RMS (deg) | 10.3 ± 0.74 | 11.7 ± 1.8 | **0.020** | 9.5 ± 0.83 | 12.3 ± 1.8 | **0.000** | 4.5 ± 0.6 | 7.3 ± 1.6 | **0.000** |
| Minor Axis RMS (deg) | 4.5 ± 1 | 2 ± 0.75 | **0.000** | 5.8 ± 2.8 | 4.4 ± 1.2 | 0.132 | 2.7 ± 1.2 | 2.3 ± 0.55 | 0.402 |
| Path Length (deg) | 97.6 ± 9.7 | 92.6 ± 7.3 | 0.165 | 107.2 ± 10.2 | 113 ± 7.6 | 0.125 | 60.4 ± 11.75 | 75.55 ± 12 | **0.005** |
| Pitch CoV (%) | 115.1 | 71.9 | | 55.4 | 46.8 | | 86 | 83.9 | |
| Roll CoV (%) | 31.4 | 24.8 | | 186 | 28.9 | | 85.7 | 36 | |
| Pitch VR | 0.55 | 0.31 | | 0.23 | 0.15 | | 0.39 | 0.37 | |
| Roll VR | 0.12 | 0.22 | | 0.96 | 0.35 | | 0.62 | 0.75 | |

the stimulation condition. Due to the nature of stimulation it is difficult to blind the subject to which condition is being applied as the different stimulation paradigms have obvious and immediate effects on seated posture. As a result, the subject employed more ballistic compensatory strategies when feedback stimulation was applied, as is evident in the increased magnitudes in the primary direction of motion (Table I). The increased major axis movements are possibly due to the confidence of knowing an increase of stimulation will occur to help return the user upright. Contrarily, during constant stimulation the subject employed a different strategy that involved greater motion in the secondary direction.

The altered movements/strategies that emerged in the feedback controlled stimulation condition were also more consistent than those with constant stimulation. The CoV was lower when feedback control was applied for all target stations and the pitch angle VR was lower for all stations. Both these measures indicate that feedback control resulted in more consistent and repeatable trunk movements. Goal directed reaching strategies are optimized in the nervous system based on multiple objectives including the smoothness of the trajectory, accuracy of the terminal extremity, and metabolic energy costs [19]. In a seated scenario the trunk serves as a base of support for the actions of the upper extremities, and as such the consistency of the trunk movements directly impact the smoothness and accuracy of the upper extremities. The feedback control system in this study has shown greater reliability of movements thus providing a stable base and possibly improving goal directed reaching. Additionally, Fig. 2 suggests that feedback resulted in a faster return to erect than constant stimulation. This observation will need to be confirmed in additional subjects; however, it is feasible that the controller is capable of improving the return to upright motion by decreasing response time to internal perturbations through modulated activation of the trunk and hip muscles.

This work will need to replicated to more subjects to see whether the trends observed here extend to multiple users of various injury levels, or if controller performance is highly subject specific since each neuroprosthesis implementation has characteristics unique to each recipient [20]. Additionally, the impact of fatigue on controller performance should be explored as fatigue will have a greater effect with prolonged use. As the eventual objective of the FNS system is to converge to movements similar to that of the intact trunk, a repeat of the functional task with able bodied subjects will provide further insights for future modifications to the control system.

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