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Effects of Stimulating Hip and Trunk Muscles on Seated Stability, Posture and Reach after Spinal Cord Injury

Ronald J. Triolo, PhD^{1,2}, Stephanie Nogan Bailey, BSE¹, Michael E. Miller, MS¹, Lisa M. Lombardo, MPT¹, and Musa L. Audu, PhD²

¹Louis Stokes Cleveland Department of Veterans Affairs Medical Center (Cleveland OH)

²Case Western Reserve University (Cleveland, OH)

Abstract

Objective—To determine the stimulated strength of the paralyzed gluteal and paraspinal muscles and their effects on the seated function of individuals with paralysis.

Design—Case series with subjects acting as their own concurrent controls.

Setting—Hospital-based clinical biomechanics laboratory.

Participants—Eight users of implanted neuroprostheses for lower extremity function with low-cervical or thoracic level injuries.

Interventions—Dynamometry and digital motion capture both with and without stimulation to the hip and trunk muscles.

Main Outcome Measure(s)—Isometric trunk extension moment at 0, 15 and 30 degrees of flexion; seated stability in terms of simulated isokinetic rowing; pelvic tilt, shoulder height, loaded and unloaded bimanual reaching to different heights, and subjective ratings of difficulty during unsupported sitting.

Results—Stimulation produced significant increases in mean trunk extension moment (9.2 ± 9.5 Nm, $p=0.0001$) and rowing force (27.4 ± 23.1 N, $p=0.0123$) over baseline volitional values. Similarly, stimulation induced positive changes in average pelvic tilt (16.7 ± 15.7 deg) and shoulder height (2.2 ± 2.5 cm) during quiet sitting and bimanual reaching, and increased mean reach distance

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Corresponding author: Ronald J. Triolo, Ph.D., Louis Stokes Cleveland Department of Veterans Affairs Medical Center, 10701 East Boulevard 151W/APT, Cleveland, OH 44106, Phone: 216-791-3800 x4138, Fax: 216-707-6420, Ronald.triolo@case.edu.

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(5.5±6.6cm) over all subjects, target heights and loading conditions. Subjects consistently rated tasks with stimulation easier than voluntary effort alone.

Conclusions—In spite of considerable inter-subject variability, stabilizing the paralyzed trunk with electrical stimulation can positively impact seated posture, extend forward reach and allow exertion of larger forces on objects in the environment.

Keywords

Neural Prostheses; Spinal Cord Injuries; Posture; Electrical Stimulation; Torso

Most individuals with motor complete SCI above the mid-thoracic level lack volitional control of core trunk and hip musculature, which can lead to spinal instability and increase risks of rotator cuff injuries and other chronic health problems [1,2]. Trunk instability can cause a posterior pelvic tilt that considerably flexes the thoraco-lumbar spine. This enlarges the base of support and can marginally improve balance or reduce the risk of falls. However, prolonged adoption of such kyphotic postures and other compensatory strategies can lead to pressure sores, skeletal deformities and back pain [3,4,5]. Belts, straps or custom seating adaptations are often the only alternatives for stabilizing the torso, preventing falls and maximizing seated function. The importance of controlling the torso was recently confirmed by a survey in which individuals with SCI consistently identified trunk stability as a high priority for motor recovery [6].

Prior studies utilizing anatomical and physiological appropriate biomechanical models of the pelvis, spine and pertinent musculature demonstrate that electrical stimulation of bilateral erector spinae, gluteus maximus, obliques and iliopsoas muscles could allow individuals with SCI to assume more than 50% of the stable able-bodied sitting postures and resist externally applied perturbations approaching 150N[7,8]. Continuous activation of the multifidus and abdominal muscles with surface stimulation has also been shown to increase gross mechanical efficiency of manual wheelchair propulsion in volunteers with SCI [9]. Although surface systems provide a convenient method to investigate the effects of stabilizing the paralyzed trunk with stimulation in the laboratory, implanted systems provide repeatable stimulated responses and access to deep neuromuscular structures without the complicating issues related to external componentry and adverse sensation from cutaneous sensory receptors. Previous case-studies suggest that stimulating the lumbar extensor muscles with electrodes implanted at the T12-L1 or L1-L2 spinal nerves can expand bimanual workspace, positively impact pelvic tilt and seated posture, facilitate forward reaching and active pulling, improve deep breathing and restore upright sitting [10,11]. No previous studies have quantified the effects of simultaneously controlling both pelvis and trunk with stimulation.

The purpose of this exploratory study was to determine if stabilizing both the pelvis and trunk with electrical stimulation can improve seated posture and reach, and to explore the impact of neurologic injury level on the outcome. It was designed to isolate the effects of activating the lumbar paraspinal and gluteal muscles on 1) trunk extension moment generating capacity, 2) sitting stability in the presence of internally generated perturbations,

3) unsupported sitting posture and bimanual reaching to different heights, and 4) subjective perceptions of relative ease or difficulty.

Methods

Subjects

Eight recipients of implanted neuroprostheses for standing after SCI participated. Subjects were predominantly male (6/8) and varied in injury level (C5-T10) and time-post-injury (11.5 ± 6.9 years), but all were long-term neuroprosthesis users (6.2 ± 3.9 years). Six were motor complete (ASIA A/B), but three had some preserved sensation. Two had neurologically incomplete injuries with some sensory and motor sparing (ASIA C). Three volunteers had low-cervical injuries (C5-C7) and five had mid- to low-thoracic (T5-T10) injuries. Clinical characteristics of study participants are summarized in Table 1.

Subjects either received 8-channel implanted receiver-stimulators [12] for standing transfer systems [13-15] or 16-channel implanted stimulator-telemeters [16] to study standing balance [17,18] or peripheral nerve cuffs [19-20]. All participants received IM stimulating electrodes [21] inserted bilaterally at L1-L2 spinal nerves to recruit lumbar erector mass for trunk extension [14,22,23]. All subjects also received IM or epimysial electrodes [24] to activate gluteus maximus bilaterally for hip extension [25]. Stimulation of semimembranosus was utilized in one volunteer (S7) with a non-functional gluteus maximus electrode, and two subjects (S1,S5) had IM electrodes at the spinal nerves of T12-L1 to activate quadratus lumborum for medial-lateral stability. Posterior portion of adductor magnus was stimulated in one subject (S8) to assist with hip extension and counteract external rotation of gluteus maximus. All procedures were approved separately from the original studies by the Institutional Review Board of the LSCDVAMC.

Stimulators delivered constant current, charge balanced biphasic waveforms with adjustable amplitude (2-20mA) and frequency (1-50Hz). Nominally 20mA and 20Hz were utilized for most electrodes, except in four instances where stimulus amplitudes were reduced to avoid activation of abdominal muscles that caused discomfort or interfered with breathing. Pulses were modulated independently (0-250µsec) on each channel and adjusted bilaterally to maintain sagittal alignment while achieving strongest tolerable contractions. Stimulated extension strength was tested with these patterns in a Biodex Pro System 3 dynamometer (Shirley NY). Because the maximal stimulation patterns could restrict mobility, a submaximal pattern was defined to permit comfortable wheelchair use and symmetric sitting without a back rest. This second pattern was utilized to test seated stability and the effects of stimulation on posture and bimanual reach during unsupported sitting. The order of the assessments described below varied from subject to subject with sufficient intervening rest to minimize any confounding effects of potentiation, fatigue or testing history.

Trunk Extension Strength

Isometric extension strength was assessed with subjects in the trunk extension attachment of the dynamometer at a hip/trunk angle of 0deg, corresponding to the nominal sitting posture

(Figure 1a). With arms folded, subjects pushed back as hard as possible for 5sec, alternating between eight repetitions of maximal volitional effort and maximal volitional effort with hip/trunk stimulation. Trials were separated by 25sec rest. The entire strength testing protocol was repeated at 15 and 30deg of flexion (Figures 1b, 1c). Data from these positions were assumed to correlate with ability to return to erect sitting from a forward-flexed position.

Active Seated Stability

Effects of stimulation on seated stability were assessed by recording the forces exerted by the upper extremities in a simulated rowing task in a manner similar to that described by Triolo *et al.* [11]. Subjects sat within comfortable reach of the closed-chain linear-motion attachment of the dynamometer. Subjects pulled the attachment toward their chests as hard as possible (Figure 2). A constant speed of 6cm/sec (30deg/sec rotary motion) was maintained while the exerted moment (and hence the applied force through the constant moment arm of the rotary attachment) was recorded. Test conditions alternated between 1) maximal voluntary effort alone and 2) submaximal hip/trunk stimulation with maximal voluntary effort. Each condition was repeated eight times separated by 2min rest to compute average forces.

Seated Posture and Bimanual Reach

Seated posture was determined in a similar manner to that described in Kukke *et al.* [10] and Triolo *et al.* [11]. Subjects sat without a back rest on an adjustable mat table within the measurement volume of a Vicon digital motion capture system (Vicon Inc., Oxford UK). Table height was adjusted to maintain the feet flat and femurs parallel to the floor with the knees at approximately 90deg. Reflective markers were placed on forehead, sternum, C7 and T6 spinal processes, a wand at mid-PSIS, and bilaterally on acromia, wrists, and inferior angles of the scapulae. Subjects sat quietly while 5sec of steady state data were collected to determine static posture. Pairs of static trials with and without stimulation were repeated five times separated by at least 5min.

Bimanual reaching was evaluated by having subjects grasp and hold handles affixed to a plastic container, move it as far forward as possible toward one of two targets for 5sec and return to starting position. Targets were located at heights of 30 and 48in, representing counter/table surfaces and high shelves, respectively [26]. Containers were either empty or filled with ballast equivalent to 20% of average maximal unilateral shoulder flexion strength measured with a handheld dynamometer (Lafayette Instruments, Lafayette IN). Loads ranged 1.2-3.0kg and averaged 1.9 ± 0.9 kg. Each combination of stimulation (on/off), target height (low/high) and load (empty/heavy) was repeated five times in random order. Maximal trunk angle (between vertical and line connecting C7 with derived location of true mid-PSIS) and pelvic angle (between mid-PSIS wand and horizontal) during the maneuver, and relative (C7 to wrists) and absolute (C7 during static non-stimulation trial to wrists) reach distances were computed for each combination of conditions.

Trunk angle and pelvic tilt indicate ability to alter posture from the nominal set point during task performance. Relative reach reflects the ability to extend elbows during forward

reaching, while absolute reach also incorporates a shift forward in workspace by repositioning the trunk in addition to any change in relative reach. Seven subjects participated, with one (S1) only able to complete unloaded reaching maneuvers. Subjective perception of effort to complete each reaching task was obtained by applying the URS [27,28], a 7-point ordinal scale ranging from “very difficult” (-3) to “very easy” (+3) after every trial.

Return to Erect Sitting

Utility of stimulation was assessed by having subjects return to upright sitting from a fully forward-flexed position, simulating retrieving objects from the floor bimanually. Subjects leaned forward in their wheelchairs with arms crossed until their chests rested on their thighs before volitionally attempting to return to erect. If volitional effort alone was insufficient, subjects were allowed to utilize any compensatory strategy except pushing or pulling their torsos upward with their arms. The maneuver was repeated with maximal stimulation for six subjects.

Statistical Analysis

Data were analyzed as a series of individual case studies with subjects acting as their own controls. Distributions of the collected data were checked with the Shapiro-Wilks test of normality. Statistical significance of changes in trunk extension strength, active seated stability in terms of the force applied to the dynamometer, and static seated postural variables (pelvic tilt, trunk angle and shoulder height) due to stimulation were determined by two-tailed Student-test ($p < 0.05$) for repeated measures from each individual [29-31]. For the dynamic bimanual reaching tasks, a MANOVA was performed to account for interactions with target height and object weight on maximum trunk and pelvic angles, and relative and absolute reach distances for each subject. Significant differences in subjective impressions of difficulty between stimulation-assisted and volitional reaching were determined with the non-parametric Wilcoxon Signed Rank Sum test applied to the ordinal URS scores. Within each subject, the same numbers of trials with and without stimulation were always collected (Table 2).

Results

Individual statistical results for trunk extension strength, seated stability and static unsupported seated posture are summarized in Table 3.

Trunk Extension Strength

Trunk extension moment increased significantly ($p < 0.002$) with stimulation over voluntary effort in 5/8 subjects at two or more of the positions tested (Figure 3, Table 3). Changes with stimulation approached 30Nm in some subjects. Both voluntary and stimulated extension moment tended to increase with hip/trunk angle. Stimulation tended to either move shoulders backward against the dynamometer (facilitating measurement of trunk extension strength) or upward by straightening the lumbar spine (which would fail to transmit moment to the dynamometer). Although the latter was observed in at least two subjects (S2,S5), mean isometric extension moment increased significantly ($p = 0.037$) with stimulation over

baseline maximal voluntary effort at all angles tested. On average, stimulation added 7Nm of extension moment at 0deg and at least 10Nm at other hip angles. These changes represent increases of 63%, 75% and 87% over baseline volitional values at 0, 15 and 30deg flexion, respectively.

Active Seated Stability

Stimulation improved active sitting stability in terms of isokinetic force exerted during simulated rowing maneuvers in 6/8 subjects (Figure 4, Table 3). Mean changes with stimulation over baseline were significantly different than zero ($p<0.03$) and ranged from 14-62N in these subjects. The largest changes with stimulation occurred for subjects with highest injuries (S4,S7), while the smallest effects were observed in the subject with the lowest injury (S8). On average, stimulation improved the ability to withstand almost 30N more force than voluntary effort alone, representing a net increase of 58% over baseline.

Seated Posture and Bimanual Reach

Figure 5 illustrates static, unsupported sitting with (Figure 5b) and without (Figure 5a) stimulation. Stimulation caused a positive, statistically significant ($p<0.013$) change in shoulder height of 1-6cm for 4/7 subjects. Across all subjects, shoulder height increased 2.2 ± 2.5 cm.

Stimulation significantly ($p<0.001$) improved anterior pelvic tilt up to 42deg during quiet sitting for 5/7 subjects (Figure 6a), with a mean change of 16.7 ± 15.7 deg across all subjects. Trunk angle statistically ($p<0.003$) increased with stimulation (Figure 6b) up to 7deg in 2/7 subjects.

Figure 7 shows maximal unsupported bimanual reach distances to low (bottom) and high (top) targets without (left) and with (right) stimulation. During reaching, pelvic tilt changed significantly ($p<0.008$) with stimulation regardless of target height or weight in 4/6 subjects. Similarly, trunk angle changed significantly ($p<0.007$) with stimulation during reaching to the low, unweighted target for the same four subjects. Over all reaching conditions, 2/6 subjects exhibited significant ($p<0.001$) improvements in trunk angle, with changes ranging 6-10deg.

Relative reach changed significantly ($p<0.008$) with stimulation for all target and loading conditions for one subject due to increased ability to extend the elbows resulting from better core trunk stability (Figure 7). Stimulation produced a significant ($p<0.031$) change of 12-17cm in absolute reach regardless of target height in two subjects. No consistent changes were observed in other subjects.

According to the MANOVA, stimulation had significant ($p<0.001$) positive effects on average change in trunk angle (3.3 ± 5.0 deg), pelvic tilt (14.3 ± 15.8 deg) and absolute reach (5.7 ± 7.4 cm), but not relative reach ($p=0.348$). Increased load significantly ($p<0.01$) decreased the changes in trunk angle, relative and absolute reach, but not pelvic tilt ($p=0.130$) with stimulation over unloaded conditions. Target height had no effect on any of the outcomes ($p=0.499$).

To further investigate effects of stimulation on reach, stimulated trunk extension strength and injury level were included as covariates. Subjects were classified as weak (S2,S6,S8) or strong (S1,S3,S5,S7) based on changes to baseline volitional trunk extension moment with stimulation. Subjects were also stratified into low (T5-10: S1,S2,S3,S6,S8) or high (C6-C7: S5,S7) injury groups. The MANOVA revealed a significant ($p<0.003$) interaction of trunk strength on pelvic angle, relative and absolute reach, but not trunk angle ($p=0.948$). Stronger subjects had an average of 20deg greater pelvic tilt with stimulation, along with almost 4cm of increased relative and absolute reach. Injury level also had significant ($p<0.017$) interactions with all parameters. The high injury group exhibited greater improvements with stimulation, averaging almost 2deg more trunk angle, 26deg more pelvic tilt, and 6-8cm more relative and absolute reach than the low injury group. S5 and S7 belonged to both the high strength and high injury groups, making it impossible to examine the interactions between the covariates.

Two of the six subjects attempting all four reaching maneuvers consistently perceived them to be easier with stimulation. Positive changes in URS scores approached or exceeded three intervals on the 7-point scale, with the largest changes in the heavy load carrying conditions regardless of target height. The Wilcoxon Signed Rank Sum test showed a significant ($p<0.001$) difference in URS between volitional and stimulated trials across all reaching conditions and subjects, indicating a net positive effect on perceived effort.

Return to Erect Sitting

Stimulation improved ability to return to erect sitting either by enabling independent performance, or reducing need for compensatory strategies. Five of the six subjects attempting to return from a forward-flexed position were able to do so with stimulation. Stimulation enabled four subjects to complete the maneuvers who were otherwise unable to do so volitionally. These subjects would have had to use their arms to push or pull themselves back to the upright position, thus compromising the ability to hold or carry objects. S8 was able to complete the maneuver without stimulation only by utilizing compensatory strategies such as rapidly extending the head/neck and retracting the arms. Stimulation obviated need for such compensation and enabled him to return to erect sitting with arms folded and head in a comfortable neutral position. One subject with a cervical level injury (S7) was unable to sit up either voluntarily or with stimulation despite compensatory strategies involving upper extremity and head motion.

Discussion

Isometric trunk extension moments elicited by stimulation are modest compared to able-bodied values, which can exceed 200Nm for males and 100Nm for females [32-37]. This is likely due to the segmental innervation of the paraspinal muscles. A single electrode at L1-L2 would be incapable of completely recruiting the entirety of erector spinae, resulting in less output than the maximal moment generating capacity of the muscles. Similarly, a single electrode cannot be expected to fully recruit gluteus maximus since the inferior gluteal nerve arborizes into multiple motor points as it enters the muscle. Stimulated responses were highly variable from subject to subject depending on individual anatomy and specific

relationship between electrode and target nerve. In spite of these factors, trunk extension moments produced by stimulation were sufficient to enhance active seated stability assessed by simulated rowing maneuvers. Along with improvements in bimanual reaching, this indicates enhanced ability to interact with the environment by stabilizing the torso. Effects of stimulation on the ability to resist externally applied disturbances and maintain seated balance remain to be determined.

The most consistent effect of trunk stimulation was on pelvic tilt. While pelvic tilt during quiet sitting is nominally 28deg in able-bodied individuals [38], subjects uniformly adopted more posterior tilt without stimulation. With activation of hip and trunk extensors, pelvic tilt consistently became less negative, which is likely to shift seated pressures away from the sacrum and other bony prominences, relieve pressures on internal organs and provide room for diaphragm and intercostal muscles to move larger lung volumes.

While effective at improving static, unsupported posture, outcomes from constantly activating the hip and trunk extensors during dynamic reaching tasks were mixed. The primary effect of constant stimulation appears to be a more favorable posture for reaching forward (absolute reach) rather than the stability required to further extend the arms (relative reach). Methods to dynamically modulate stimulation during a task need to be developed, beginning with a better understanding of active and passive mechanical properties of pelvic and spinal muscles. Future evaluation of continuous stimulation on reaching may be more functionally relevant if performed in the user's own wheelchair.

The extent of preserved sensation and motor control in subjects with neurologically incomplete injuries may play a role in the ability to maintain balance with or without stimulation. Individuals in the lower level injury group (T5-10) were either motor and sensory complete (ASIA A) or exhibited some sensory sparing with complete loss of motor function (ASIA B), while most participants (2/3) in the higher injury group (C5-C7) were both motor and sensory incomplete (ASIA C). The higher injury group exhibited greater improvement with stimulation than the lower injury group, although the samples are too small to draw definitive conclusions about these interactions. None of the individuals with sensory incomplete injuries complained of adverse sensation due to the implanted stimulation. Although individuals with injury levels above T6 are susceptible to episodes of AD, hemodynamic responses to electrical stimulation of the paraspinal and gluteal muscles are unremarkable [39]. No signs of elevated blood pressure or other symptoms of AD were observed during the course of these experiments, or during prior exercise, standing, transfers or stepping with the implanted systems.

Results of this study are consistent with those previously reported for five subjects with paraplegia [10] and one individual with high tetraplegia [11]. In particular, the observed effects of stimulation on static sitting posture, and in particular pelvic tilt, coincide with observations from both [10] and [11]. The simulated rowing results at a single constant velocity in this study are consistent with those reported for multiple velocities in [11], and the sagittal reaching performance with stimulation coincides with changes observed in the three dimensional workspace with stimulation reported in [10].

The specific set of muscles stimulated was allowed to vary based on the available implanted electrodes, and could therefore have influenced the results. Since all subjects received electrodes in the hip and trunk extensor muscles, the primary effect of stimulation was consistent across the entire cohort and tended to stabilize sitting in the sagittal plane. No evaluations that challenged lateral or axial motion were included, thus minimizing the potential for confounding effects of muscles such as the quadratus lumborum. Substituting hamstrings or posterior portion of adductor magnus for the gluteus maximus would have extended the hip in a similar fashion, thus only marginally affecting the results. Future studies need to examine the potential for stabilizing the spine in lateral bending and axial rotation, as well as to determine the potential influence of height and other anthropometric parameters on forward and lateral reach.

Study Limitations

Limitations include a relatively small sample size that compromises rigorous exploration of inter-subject differences and interactions with injury level, preserved sensation or motor function. Other variables such as time-post-injury and exercise history with electrical stimulation were not controlled and may have influenced the outcomes. Larger scale studies are needed to thoroughly understand the segment of SCI population that would most benefit from the intervention. Additionally, the implanted systems utilized were all optimized for functions other than seated posture and balance. The implanted systems were installed by several different surgical teams, and variations in stimulated responses from differences in electrode insertion techniques could have affected the results. There is also the potential for selection bias because only individuals who had satisfied the rigorous inclusion criteria for other investigations and were well exercised and experienced users of the implanted stimulation systems were able to participate.

Conclusions

Electrical stimulation can produce clinically relevant increases in trunk extension moments over baseline volitional effort that can improve seated stability, alter seated posture, enhance bimanual reach, and enable performance of new functions or reduce reliance on compensatory strategies. Seated posture can be modulated by activating the hip and trunk extensor musculature, resulting in positive changes in skeletal alignment and resumption of more normal lumbar curvature. Individual results may be related to injury level and magnitude of voluntary and stimulated muscle strength.

Supramaximal stimulation of hip and trunk extensors is effective in restoring upright seated posture from a fully forward-flexed position. This could be an important adjunct to custom seating systems and eventually eliminate the need for belts or straps and enable users to retrieve objects from the ground independently.

In spite of high inter-subject variability, stimulation may be most beneficial to individuals with mid-thoracic or higher level injuries. Effects of stimulation on activities of daily living including manual wheelchair propulsion, transfers, bed turning, and pressure relief maneuvers still need to be determined. Yet, this study demonstrates that electrical stimulation has potential to be an important new intervention to improve the functional

capacity, daily functioning, community participation and quality of life of individuals with SCI.

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Abbreviations

ASIA	American Spinal Injury Association
AD	autonomic dysreflexia
IM	intramuscular
MANOVA	multivariate analysis of variance
LSCDVAMC	Louis Stokes Cleveland Department of Veterans Affairs Medical Center
PSIS	posterior superior iliac spine
SCI	spinal cord injury
URS	Usability Rating Scale

Figure 1. Isometric trunk extension strength testing in neutral sitting (a), 15deg (b) and 30deg (c) of forward trunk flexion. Dynamometer trunk extension attachment was aligned with the anterior superior iliac spine to provide a generalized measure of hip/trunk extension strength.

Figure 2. Simulated rowing test of active trunk stability during dynamic voluntary upper extremity loads. The rotary-to-linear motion dynamometer attachment was positioned chest high and arm's length from the subject who was instructed to pull it towards him at a maximal and steady effort. Isokinetic motion was constrained to be at a constant 6 cm/sec (30 deg/sec).

Figure 3.

Baseline volitional and change in trunk extension moment generated with stimulation during volitional movements for each subject and mean values (M) averaged across all subjects at three flexion angles.

Figure 4.

Average ($\pm$ SD) change in active force exerted with stimulation over baseline volitional output for each subject and overall mean value (M) during simulated rowing maneuvers.

Figure 5. Static sitting posture without (a) and with (b) activation of the hip and trunk extensor musculature. Reflective markers placed on bony prominences quantified skeletal alignment and effects of stimulation on pelvic tilt, trunk lean and shoulder height.

Figure 6.

Average ($\pm$ SD) change in quiet unsupported sitting posture with stimulation of the trunk and hip extensors in terms of pelvic tilt (a) and trunk lean (b) for each subject and overall mean value (M).

Figure 7. Effects of trunk and hip stimulation on unsupported bimanual reach. Maximal forward reach to low (bottom) and high (top) targets without stimulation (left) and with stimulation (right).

Table 1
Summary of clinical characteristics of individual study participants

Subject	Age ¹ (years)	Gender	Height (cm)	Weight (kg)	Injury Level	ASIA Class ²	Time Post Injury ¹ (years)	Time Post Implant ¹ (years)	Muscles Stimulated ³
1	45	M	177.8	97.5	T5	B	26.5	9.6	ES, GM, QL
2	56	F	167.6	67.7	T5-6	B	6.6	2.3	ES, GM
3	58	M	174.0	80.9	T6	A	11.8	10.6	ES, GM
4	46	M	177.8	89.5	C5-6	C	14.1	3.8	ES, GM
5	40	F	167.6	57.3	C7	C	13.0	11.4	ES, GM, QL
6	50	M	185.4	97.7	T6	B	7.8	6.4	ES, GM
7	26	M	165.1	63.2	C6	A	6.3	4.7	ES, GM, SM
8	47	M	181.6	65.5	T10	A	5.8	0.9	ES, GM, AM

¹ At time of initial enrollment and testing

² A = motor and sensory complete; B = motor complete with sensory sparing; C = motor and sensory incomplete

³ ES = Erector Spinae; GM = Gluteus Maximus; QL = Quadratus Lumborum; SM = Semimembranosus; AM = Posterior portion of Adductor Magnus

Table 2
Number of repeated trials with and without stimulation for each outcome measure

Subject	Trunk Extension Strength ¹	Active Stability	Static Posture ²	Dynamic Posture ³	Sagittal Reach ⁴
1*	0 deg: 7 15 deg: 8 30 deg: 8	8	5	Low/No Load: 5 High/No Load: 5	Low/No Load: 5 High/No Load: 5
2	0 deg: 8 15 deg: 8 30 deg: 8	8	5	Low/No Load: 5 High/No Load: 5 Low/Loaded: 5 High/Loaded: 5	Low/No Load: 5 High/No Load: 5 Low/Loaded: 5 High/Loaded: 5
3	0 deg: 7 15 deg: 8 30 deg: 8	5	5	Low/No Load: 5 High/No Load: 5 Low/Loaded: 5 High/Loaded: 5	Low/No Load: 5 High/No Load: 5 Low/Loaded: 5 High/Loaded: 5
4*	0 deg: 8 15 deg: 8 30 deg: 8	8	5	N/A	N/A
5	0 deg: 8 15 deg: 8 30 deg: 8	8	5	Low/No Load: 5 High/No Load: 5 Low/Loaded: 5 High/Loaded: 5	Low/No Load: 5 High/No Load: 5 Low/Loaded: 5 High/Loaded: 5
6	0 deg: 8 15 deg: 8 30 deg: 8	8	5	Low/No Load: 5 High/No Load: 5 Low/Loaded: 5 High/Loaded: 5	Low/No Load: 5 High/No Load: 5 Low/Loaded: 5 High/Loaded: 5
7	0 deg: 8 15 deg: 8 30 deg: 8	8	5	Low/No Load: 5 High/No Load: 5 Low/Loaded: 5 High/Loaded: 5	Low/No Load: 5 High/No Load: 5 Low/Loaded: 5 High/Loaded: 5
8	0 deg: 8 15 deg: 8 30 deg: 8	8	5	Low/No Load: 5 High/No Load: 5 Low/Loaded: 5 High/Loaded: 5	Low/No Load: 5 High/No Load: 5 Low/Loaded: 5 High/Loaded: 5

Number of trials with and without stimulation were always equal

¹ Mean moment over middle 3 sec of maneuver (average of 300 samples per trial)

² Mean steady-state pelvic angle, trunk angle, and shoulder height over 1 sec (100 samples)

³ Dynamic change in pelvic angle, trunk angle, and shoulder height while reaching

⁴ Absolute and relative reach distances; Usability Rating Scale

* - Unable to complete all reaching tasks due to rotator cuff tear or other upper extremity impairment

Table 3

Individual statistical results of each outcome assessment for each subject. Statistically significant differences ($p<0.05$) between stimulation-assisted and baseline voluntary outcomes are shaded.

Subject	Trunk Extension Moment*	Seated Stability	Static Shoulder Height	Static Pelvic Tilt	Static Trunk Angle
1					
2					
3					
4			N/A	N/A	N/A
5					
6					
7					
8					

* Statistically significant results for at least 2 out of 3 flexion angles
N/A – Not attempted