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Alternative foot placements for individuals with spinal cord injuries standing with the assistance of functional neuromuscular stimulation

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Abstract

This study investigated the effects of altering foot placement for two individuals with spinal cord injuries (SCI) that stood using functional neuromuscular stimulation (FNS) as compared to an able-bodied subject group. FNS-assisted standers used parallel bars as needed for support, while the able-bodied group stood hands-free. Three different foot placements were tested: side-by-side, wide, and modified tandem. For SCI subjects, the percentage of body weight loaded on the feet was not greatly affected by foot placement, which potentially could be altered to provide postural benefits during functional tasks. Anterior/posterior (A/P) center of pressure (COP) origins tended to be located more anterior in the base of support for SCI subjects as compared to able-bodied subjects. SCI subjects also tended to have medial/lateral (M/L) COP excursions that were larger than able-bodied subjects. The sacrum appeared to hold some promise as a sensor location for monitoring A/P postural sway, but movements in the M/L direction were inconsistent and will require additional study. General guidelines such as positioning the A/P COP more posterior in the base of support and feedback concerning excessive M/L COP displacements may be useful to improve standing performance for SCI subjects. In addition, the modified tandem placement was an effective alternative for making postural adjustments in one SCI subject who experienced excessive right knee flexion with other foot placements.

Keywords

Balance; center of pressure; functional neuromuscular stimulation; posture; spinal cord injury

Introduction

Complete spinal cord injuries (SCI) result in a loss of motor function and a loss of sensation below the level of injury. In the case of a complete thoracic-level injury, voluntary control of the lower extremities is absent, while voluntary control of the lower back musculature varies depending on the level of injury. Even though the lower extremities have been disconnected

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from the neural signals of the brain, the peripheral motor neuron circuitry may remain intact. Functional neuromuscular stimulation (FNS) systems consist of surface or implanted electrodes that are used to electrically activate intact peripheral motor nerves. In turn, the intact nerves activate muscle fibers, resulting in a muscular contraction. By producing muscular contractions in the lower extremities, FNS systems have provided individuals with spinal cord injury varying levels of standing capability [1–6]. One goal in the development of FNS standing systems is to allow the user to perform activities of daily living that otherwise would not be possible [7]. An example of this would be the ability to reach and manipulate objects at a counter. However, FNS system users maintain standing balance by applying forces to a support surface via the hands. This strategy is often ineffective during reaching since many FNS standers utilize a substantial amount of hand force and associated arm and trunk torques. Therefore, the FNS stander may not be able to safely release a hand from the support [8]–[9].

To ensure the safety of an FNS user as upper extremity support is reduced, balance and posture should be assessed during standing. Able-bodied postural control has been analyzed by monitoring changes in the center of pressure (COP) during quiet standing [10] and while introducing perturbations during quiet standing [11]–[15]. In addition, the response to perturbations has been examined in other populations, such as individuals with vestibular loss [16] and elderly individuals with a history of falling [17]. Investigating perturbations to arm-free standing for individuals with SCI requires additional safety precautions. For example, a combination of bracing and support ropes has been used to test feedback control of the ankle musculature [18,19]. As another example, a rotating frame was designed to provide adjustable ankle stiffness and bracing that limited the lower extremity range of motion to prevent falling [20]. Alternatively, FNS users can use their upper extremities as needed for support while the stimulated muscles provide bracing during standing [21]. Quiet standing using FNS with limited hand support is a prerequisite to arm-free standing and stable standing that can resist perturbations.

Previous studies have found that postural responses [10,22] and motor control strategies [23] were dependent upon foot placement. One likely explanation for these observed changes in balance is that the biomechanical constraints were altered as a function of foot placement. Biomechanical constraints include the size of the base of support and the stiffness of the muscles/tendons crossing the joints of the lower extremities. Theoretically, the COP must remain within a base of support defined by the outer points of contact between the feet and the floor. For example, a wider stance should increase the ability to shift the COP in the medial/lateral (M/L) direction. Similarly, moving one foot forward should increase the ability to shift the COP in the anterior/posterior (A/P) direction. Joint stiffness would also be expected to increase as muscles and tendons are stretched from their resting lengths while widening or deepening the base of support. Another potential explanation for observed changes in postural control may be that the coordination of joint rotations was altered as a function of foot placement. With a larger base of support, gross joint rotations may be adequate to maintain balance, while a smaller base of support may require a finer balance of joint rotations. With additional understanding of the effects on balance, foot placement may be a useful preparatory adjustment to achieve a more favorable base of support for activities of daily living.

The goals of this study were: a) to quantify the percentage of body weight loaded through the lower extremities during FNS quiet standing as a function of foot placement, and b) to compare postural parameters between able-bodied and FNS quiet standing. It is anticipated that the results of the study will be useful in designing standing strategies as well as training guidelines for FNS system users.

Methods

Experimental protocol

Two individuals with thoracic-level spinal cord injuries participated in this study. SCI subject one (SCI-1) was a 38 year-old male with a T6-level spinal cord injury (ASIA-A), and SCI subject two (SCI-2) was a 32 year-old male with a T4/T5-level spinal cord injury (ASIA-A). In addition, eighteen able-bodied subjects (9 males/9 females, age 32.0 ± 5.2 years) with no history of neuromuscular disorders participated in the study. The Office of Research Integrity at the University of Kentucky and the Office of Research Assurances at Iowa State University approved the protocol. All subjects provided informed consent prior to testing.

SCI-1 utilized surface electrodes to bilaterally stimulate the gluteal, hamstring, and quadriceps muscles. An Octostim Stimulator (Freiler, Santa Cruz, CA) delivered current-regulated electrical pulses with 68 mA maximum amplitude, 360 μ s pulse width, and 20 Hz frequency. The hamstring and gluteal muscles were stimulated between 68–80% of the maximum amplitude, while the quadriceps muscles were stimulated at successively increased levels from 56–100% to account for fatigue. SCI-2 used an implanted CWRU/VA neuroprosthesis (Case Western Reserve University, Cleveland, OH) that bilaterally stimulated the gluteus maximus, posterior adductor, vastus lateralis, and erector spinae muscles. A preset pattern of current-regulated stimulation with 20 mA amplitude, 100–200 μ s pulse width, and 20 Hz frequency was activated using an external control box. Surgical positioning of the electrodes in closer proximity to the motor point allowed for lower current amplitudes and pulse widths with the implanted system. Each muscle group demonstrated a 5/5 manual muscle test (MMT) with stimulation, except the right quadriceps, which demonstrated a 3/5 MMT. Both SCI subjects had previous experience standing with FNS.

SCI subjects used parallel bars for hand support as needed and stood quietly for 20 seconds using three different foot placements: side-by-side, wide [22] and modified tandem [10]. The length of standing time allowed both SCI subjects to complete six trials without significant increases in arm support. For the side-by-side placement, the feet were placed at a width equal to the distance between the anterior superior iliac spines, while the wide placement was at twice this width. The modified tandem placement was at side-by-side width, but with the leg on the side of the dominant arm shifted a foot length in the anterior direction. The modified tandem placement was of interest because of advantages with this posture while reaching [24].

On four separate days, each SCI subject stood six times (three foot placements x two repetitions) for a total of 24 trials. SCI subjects stood with each foot on a separate force platform (Bertec Corp., Columbus, OH), while reflective markers placed on the feet, calves, thighs, pelvis, and torso were tracked using a six-camera Motion Analysis (Santa Rosa, CA) system. Similarly, able-bodied subjects stood quietly for thirty seconds without any hand support for nine trials (three foot placements x three repetitions) on a single experimental day. Each foot was placed on a separate force platform (AMTI, Watertown, MA), and reflective markers were tracked by an eight-camera Peak Performance (Centennial, CO) system.

Biomechanical analysis

Vertical ground reactions were measured during the SCI standing trials to give an indication of the upper extremity support required to maintain balance. The vertical ground reactions were divided by the subject's body weight to give a percentage of weight loaded on the feet (FEET %). The mean COP was calculated to give an indication of where the subject's weight was centered within the base of support (COP origin). The absolute value of the M/L COP origin was used to indicate the degree of asymmetry for statistical purposes. COP excursions were

determined for each trial by finding the difference between the maximum and minimum COP values in the A/P and M/L directions.

Dynamic and reconstructed marker positions were combined to designate calf and thigh coordinate axes [25]. Three successive Euler rotations (flexion/extension, abduction/adduction, and internal/external rotation) were used to define the knee joint angles [26]. Knee flexion angles were used to give an indication of inadequate knee joint stiffness. Postural correlation coefficients were calculated between sacral position, cervicale position, and COP in the A/P and M/L directions. A marker triad positioned at the L5/S1 intervertebral disc was used to define sacral position, and a marker triad placed over the seventh cervical vertebrae was used to define cervicale position. These correlations were used to evaluate possible sensor locations and to provide insight into postural coordination.

Statistical analysis

The SCI data were averaged across trials and able-bodied data across trials and subjects as a function of foot placement. Averages for each SCI subject are reported as case study comparisons with the able-bodied data. For the able-bodied data, multivariate ANOVA (SAS, Cary, NC) was carried out to test the dependence of the A/P COP origin, M/L COP origin, A/P COP excursion, and M/L excursion on foot placement. If the multivariate ANOVA showed significant dependence upon foot placement ($p < 0.01$), then pair-wise comparisons were used to test for significant differences ($p < 0.01$). Able-bodied data are often used as a baseline in FNS system design [15,19,20] with the goal of mimicking intact standing.

Results

FEET%

For SCI-1, FEET% values were within one standard deviation when comparing different foot placements (Figure 1). For SCI-2, FEET% was slightly greater than one standard deviation higher when using the modified tandem placement as compared to the side-by-side placement. When comparing subjects, SCI-2 ($89.5 \pm 5.7\%$) stood with consistently higher FEET% values than did SCI-1 ($78.9 \pm 8.0\%$).

Centers of pressure

For able-bodied subjects, A/P COP origins were located significantly more posterior ($p < 0.01$) in the base of support when using the modified tandem placement as compared to the side-by-side and wide placements (Figure 2). SCI-1 had A/P COP origins greater than one standard deviation anterior of able-bodied for the side-by-side and modified tandem placements. SCI-2 had A/P COP origins greater than one standard deviation anterior of able-bodied subjects for the side-by-side placement only. In contrast, M/L COP origins did not show statistical dependency upon foot placement for able-bodied subjects. Both SCI subjects also had M/L COP origins that were within one standard deviation of able-bodied subjects.

A/P COP excursions were not significantly dependent upon foot placement for able-bodied subjects (Figure 3). In addition, A/P COP excursions for SCI-1 were within one standard deviation of able-bodied subjects for all foot placements. For SCI-2, A/P COP excursions were outside one standard deviation compared to able-bodied for the modified tandem placement. M/L COP excursions were significantly dependent upon foot placement for able-bodied subjects, with significantly larger excursions for the modified tandem placement than the side-by-side or wide placements ($p < 0.01$). SCI-1 had M/L COP excursions more than one standard deviation greater than able-bodied subjects with the wide placement, while SCI-2 had M/L COP excursions more than one standard deviation greater than able-bodied subjects for all of the foot placements.

Knee flexion

For SCI-1, right and left knee flexion angles were within one standard deviation for all foot placements (Figure 4). In contrast, right knee flexion angles for SCI-2 were greater than one standard deviation larger when using the side-by-side and wide placements as compared to the modified tandem placement. Left knee flexion angles for SCI-2 differed by less than one standard deviation when comparing foot placements.

Postural correlations

Postural correlations for A/P sacral position – A/P COP, A/P sacral position – A/P cervicale position, and M/L cervicale position – M/L COP were greater than 0.8 for all foot placements with able-bodied subjects (Table 1). In addition, all postural correlations were greater than 0.8 for the modified tandem placement with able-bodied subjects. None of the postural correlations were greater than 0.8 for the SCI subjects. For SCI-1, the A/P sacral position – A/P COP correlation was greater than 0.7 with the modified tandem placement. For SCI-2, the A/P sacral – A/P COP and M/L sacral position – M/L cervicale position correlations were greater than 0.7 for the side-by-side and modified tandem placements.

Discussion

The amount of loading on the lower extremities did not change substantially with different foot placements, which was consistent with expectations. This is a promising result toward the use of preparatory adjustments for functional tasks, since any alternative foot placements must first prove to be stable during quiet standing. Factors such as subject experience/confidence, electrode placement, and stimulated muscle strength may prove to be more critical than foot placement for minimizing hand support. A goal is to have an FNS stander place at least ninety percent of his/her body weight on the lower extremities. At this level, the FNS stander should be able to safely release a hand for functional use. SCI-2 was able to achieve this target level, while SCI-1 was about ten percent below this level.

Able-bodied subjects tended to center their body weight more posterior in their base of support as compared to the SCI subjects. The exception was SCI-2 when using the modified tandem placement, which also corresponded to the highest FEET% values. Interestingly, the most posterior COP origins for SCI-1 were observed with the wide placement, which also had the highest FEET% for this subject. Thus, individuals with SCI may be able to reduce their need for upper extremity support by making an effort to shift their body weight in the posterior direction. However, a fear of falling backward may prevent some individuals with SCI from shifting their body weight as far back as able-bodied individuals. The results were less distinct for COP origins in the M/L direction.

When comparing COP excursions, the most striking differences between SCI and able-bodied subjects were in the M/L direction. A potential explanation is that the stimulated muscles primarily developed torques in the sagittal plane and reasonably mimicked able-bodied stiffness. In contrast, a lack of stimulated muscular torques in the frontal plane left the upper extremity to less effectively make M/L postural adjustments. Comparing SCI and able-bodied subjects, the ratios of A/P to M/L COP excursions were most similar for the modified tandem placement. When using the modified tandem placement, the midline of the base of support was approximately 45° to the A/P and M/L directions. Thus, muscle torques in the sagittal plane had effects both parallel and perpendicular to the base of support.

Excessive knee flexion is often a limiting factor for how much weight can be accepted by the lower extremities during FNS assisted standing. For example, SCI-2 experienced much lower right knee flexion when using the modified tandem placement. SCI-2 had muscular weakness

in his right quadriceps, a leg length discrepancy, and right thoracic scoliosis. All of these factors contributed to excessive right knee flexion when the legs were loaded symmetrically. However, SCI-2 was able to preferentially load his left leg with the modified tandem placement by shifting his weight along an expanded A/P base of support, which resulted in reduced right knee flexion. The forward position of the right leg also allowed the line of gravity to fall behind the right knee, which aided in maintaining knee extension.

Able-bodied subjects had high correlation coefficients between the sacral and cervicale positions and the A/P and M/L COP when using the side-by-side and modified tandem placements. This was consistent with the body moving like a single inverted pendulum. Correlations for SCI subjects tended to be much lower, with the highest correlations occurring between the A/P sacral position and the A/P COP with the modified tandem placement. Sensor placement on the sacrum may provide effective feedback of A/P postural sway (especially for SCI-2), but further study is needed before an appropriate sensor location for M/L postural sway is determined. Hand support forces that constrained or even controlled postural sway was a probable explanation for the lower correlation coefficients in SCI subjects.

The main limitation of this study is that only two SCI subjects were assessed. Additional subjects will need to be analyzed before generalized conclusions can be drawn, although individualized standing protocols may be most appropriate. Another limitation of this project was the short time periods that the subjects SCI quietly stood. Future studies should monitor quiet standing with additional SCI subjects over periods of one minute or more, which is a more practical time frame for completing functional tasks. If stable standing is achieved for longer durations, the SCI subject may then practice FNS standing with a single hand for support. The goal is then to move from single-hand support while standing to single-hand support while reaching and manipulating an object at a counter.

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Fig. 1. FEET% as a function of foot placement. Standard deviations are shown as extensions of the bar graphs. The goal of ninety percent of body weight loaded on the feet is also displayed (see Discussion).

Fig. 2.

COP origins. Able-bodied subjects had A/P origins that were significantly posterior when using the modified tandem as compared to other placements ($p < 0.01$). Compared to able-bodied subjects, SCI-1 had A/P COP origins located more anterior for the side-by-side and modified tandem placements, while SCI-2 was located more anterior for the side-by-side placement. The origin of these graphs represents the midline of the base of support. The length of the bars originating from the mean values indicates standard deviations in the A/P and M/L directions.

Fig. 3.

COP excursions. M/L COP excursions were significantly greater when using the modified tandem placement as compared to the side-by-side and wide placements for able-bodied subjects ($p < 0.01$). SCI-1 had greater M/L COP excursions than able-bodied subjects with the wide placement. SCI-2 had greater A/P COP excursions than able-bodied subjects with the modified tandem placement and greater M/L COP excursions with all foot placements. The black lines illustrate the average COP excursions in each direction, while the gray lines illustrate the standard deviations.

Fig. 4.

Knee flexion angles. Right and left knee flexion angles for SCI-1 differed by less than one standard deviation when comparing foot placements. Right knee flexion angles for SCI-2 were greater when using the side-by-side and wide foot placements as compared to the modified tandem foot placement. Averages and standard deviations are displayed in the figure.

Table 1

Postural correlation coefficients. Postural correlation coefficients for the A/P sacral position – A/P COP, A/P sacral position – A/P cervicale position, and M/L cervicale position – M/L COP were above 0.8 for the able-bodied subjects. None of the postural correlation coefficients were above 0.8 for the SCI subjects

Correlated Variables	Foot Placement	Correlation Coefficient		
		SCI #1	SCI #2	Able-Bodied
A/P Sacral position - A/P COP	Side-by-side	0.46	0.70	0.94
	Wide	0.56	0.67	0.93
	Modified tandem	0.72	0.79	0.91
A/P Cervicale position - A/P COP	Side-by-side	0.30	0.15	0.82
	Wide	0.45	0.24	0.47
	Modified tandem	0.32	0.27	0.91
A/P Sacral position - A/P Cervicale position	Side-by-side	0.37	0.36	0.93
	Wide	0.53	0.28	0.91
	Modified tandem	0.35	0.38	0.88
M/L Sacral position- M/L COP	Side-by-side	0.10	0.57	0.79
	Wide	-0.01	0.05	0.60
	Modified tandem	0.33	0.23	0.91
M/L Cervicale position - M/L COP	Side-by-side	0.01	0.45	0.91
	Wide	0.13	0.65	0.88
	Modified tandem	0.24	0.45	0.89
M/L Sacral position - M/L Cervicale position	Side-by-side	0.59	0.77	0.76
	Wide	0.59	0.26	0.36
	Modified tandem	0.56	0.70	0.93