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Disclosures:

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CASE SERIES

Effect of Dynamic Weight Bearing on Neuromuscular Activation After Spinal Cord Injury

ABSTRACT

Edwards LC, Layne CS: Effect of dynamic weight bearing on neuromuscular activation after spinal cord injury. Am J Phys Med Rehabil 2007;86:499–506.

Objective: To determine whether individuals who have a spinal cord injury have neuromuscular and physiologic responses to a personalized exercise program during dynamic weight bearing (DWB).

Design: Four subjects with spinal cord injuries (T6, T5–6, C2–5, and C5) completed a 12-wk exercise program that included DWB. Surface electromyography (EMG) was recorded from the right gastrocnemius, biceps femoris, rectus femoris, rectus abdominus, and external oblique. Heart rate (HR) and blood pressure (BP) were recorded throughout training. Descriptive statistics were used to analyze the data.

Results: The results of this study indicate that the subjects actively responded to exercise during DWB, as measured by EMG, HR, and BP.

Conclusions: The results suggest that exercise during DWB can induce physiologic and neuromuscular responses in individuals who have a spinal cord injury, and that exercise during DWB may serve as a preparatory program for more advanced rehabilitation.

Key Words: Spinal Cord Injury, Rehabilitation, Weight Bearing, Electromyography

Individuals who are paralyzed experience the paradox of needing to be physically active to regenerate their health and function, even though they are physically limited by their paralysis. Acute rehabilitation that follows the onset of paralysis from a spinal cord injury (SCI) or other disability is essential for preparing one for the dramatic changes in one's life. This initial aspect of rehabilitation averages 39 days[1] in the United States and focuses on preparation to handle the essential activities of daily living. However, limited long-term programs exist beyond acute rehabilitation. A survey of 590 paralyzed individuals who had completed their acute rehabilitation phase indicates that their first priority is to have access to programs that would help rebuild their health and function on a long-term basis.[2]

In recent years, healthcare investigators have sought to define appropriate ways in which programs directed at improving health and function could be implemented. One such program is active regeneration (AR), which combines the use of specialized equipment and training to help fulfill the regenerative potential of those paralyzed from SCI or other disability. AR is a means by which those who are paralyzed may be able to avert the known effects of inactivity while also being able to rebuild their health and function. The precepts of AR are driven by the research indicating that improvement in health and function can occur given an appropriate activity-dependent stimulus.[3–5] The premise of AR, therefore, is that the achievement of one's regenerative potential is dependent on active participation in AR on a continual basis, and that those with disabilities could benefit from participation in AR after the completion of the acute rehabilitation phase. The potential value of AR is further supported by evidence that stimulation of the central nervous system through physical activity results in activity-induced plasticity. Harkema[6] found increases in electromyographic (EMG) responses to increases in treadmill speed in subjects with an SCI, and Maegele et al.[7] found that more muscles were recruited in spinal cord–injured individuals who had to bear weight and perform movements *vs.* those who did not move while bearing weight. This implies that given the opportunity to participate in a portion of the AR program, namely, dynamic weight bearing (DWB) combined with voluntary movements, activity-induced plasticity could occur and might promote improvements in physiologic processes that underlie good health.

This paper focuses on one portion of AR: namely, DWB, an activity-dependent, weight-bearing intervention aimed at rebuilding the health and function of those who have an SCI. The overall objective of the study was to determine whether EMG, heart rate (HR), and blood pressure (BP) measures responded to DWB exercise in individuals who have an SCI. It was hypothesized that DWB exercise would induce increases in neuromuscular activation as evidenced by increases in EMG-activation levels relative to resting baseline measures. It was also hypothesized that HR would increase and that BP would stabilize to near-normal levels after 12 wks of DWB exercise. These measures were chosen because they are often used in physical training studies to provide an indication of neuro- and physiologic changes that occur as a result of exercise.[7–10]

METHODS

The training regime involved 12 wks, two times a week, of DWB exercise. Each training session lasted an hour. Generally, training consisted of various movements at different weight-bearing positions, whereby subjects were asked to provide as much voluntary effort as possible (see training protocol below). All training occurred in the Laboratory of Integrated Physiology at the University of Houston.

Subjects

Table 1 provides demographic information of the four male subjects who volunteered to participate in this study. Each subject reported his American Spinal Injury Association[11] impairment level according to his medical evaluation from immediately after his injury. Impairments associated with a particular American Spinal Injury Association scoring category may change over time in some individuals.[12] In our study, all four subjects were nonambulatory and exclusively used wheelchairs for daily mobility. It is unclear whether our subjects were able to regain voluntary control over their trunk or leg muscles. After local ethical approval, each subject provided written informed consent and a doctor's prescription stating that they were healthy enough to participate in a DWB program.

Because medications may have an impact on performance, a list of currently used medications was obtained from each subject. Medications primarily included antispasticity drugs (baclofen, diazepam, gabapentin, oxybutynin, toletrodine tartrate) and antidepressants (venlafaxin HCl, trazodone HCl, paroxetine HCl). Other medications that were used by the subjects included midodrine, alendronate sodium, zolpidim tartrate, famotidine, and nitrofurantoin macro/monohydrate. During the 12-wk period, subjects did not report any changes in medication.

At the time of the study, none of the subjects were involved in any individual or organized physical activity programs.

OrthoSYS Device

To achieve the various DWB positions used during training and testing, an OrthoSYS DWB device (OrthoSYS, IntelliGEN Foundation, Wichita

TABLE 1 Subject demographics

Subject	Age, yrs	TSI, yrs	Level of Injury	ASIA
1	27	3.5	C5	A
2	26	6	C2	A
3	33	3.5	T6	A
4	64	6	T5–6	A

TSI, time since injury; C, cervical; T, thoracic; ASIA, American Spinal Injury Association.

ASIA grade was self-reported and was based on time of initial injury.

Falls, TX) was used (Fig. 1). The OrthoSYS allows the subjects to perform specific DWB routines. The OrthoSYS enables individuals who have an SCI to be progressively raised from a seated position or lowered from a standing position in 1-cm increments while continuously bearing weight. This feature is in contrast to more traditional standing frames that generally constrain the individual to a back support, which results in passive weight bearing. In the current study, once various DWB positions were obtained, subjects performed unrestrained dynamic movements as allowed for by their abilities.

Training Protocol

Figure 2 represents examples of some of the DWB exercises performed during the training regime. Exercise sessions consisted of various "voluntary" movements while in the upright position, such as supported partial standing (Fig. 2a), standing spine flexion (Fig. 2b), standing back extension (Fig. 2c), partially elevated abdominal contraction, supported standing left and right lateral bends, tricep extensions from a flexed hip position, and tricep extension from a seated position.

The activities prescribed during each session were in accordance with each subject's capabilities; that is, some subjects could accomplish more from the various DWB positions than others. During the 12-wk training period, subject compliance was 100%; all subjects completed the training two times per week.

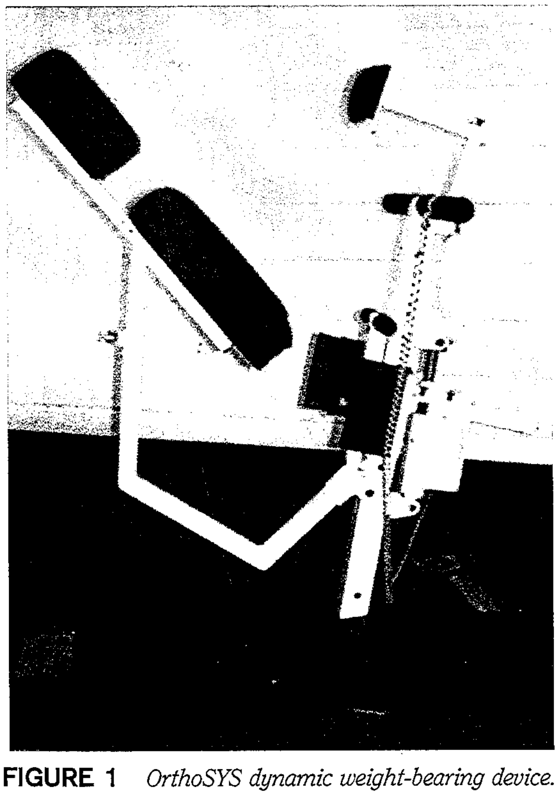

FIGURE 1 *OrthoSYS dynamic weight-bearing device.*

Data Collection Overview

When a subject arrived for a session, he was transferred from his wheelchair with the help of research assistants to a seated position on the OrthoSYS. The seat and kneepad height were initially adjusted so that when the subject was seated, his thighs were parallel to the ground. During testing and training, all subjects wore athletic shoes and comfortable, nonrestrictive clothing that allowed them to move freely. EMG, HR, and BP data were collected at week 1 (baseline), week 4, week 8, and week 12. HR and BP data were also collected during each training session (see Data Collection Procedures section below).

Before performing the testing protocol, subjects were prepared for EMG recording. The skin was shaved, and alcohol was applied to cleanse the area where the electrodes were placed. EMG recordings using silver–silver chloride preamplified surface electrodes (Therapeutics Unlimited, Iowa City, IA) were obtained from the right gastrocnemius, biceps femoris, rectus femoris, rectus abdominus, and external oblique. The EMG amplifier gain was set at 10,000 during recording. Root mean square (RMS) EMG was recorded using the Enhanced Graphics Acquisition and Analysis software (R.C. Electronics, Santa Barbara, CA) at a sample rate of 1000 Hz for 32 secs and was stored on a desktop computer for later analyses.

HR was monitored continually during each session, using a Polar HR monitor (Polar USA, Lake Success, NY). BP was measured using an electronic BP device (Omron HEM 712-C, Bannockburn, IL) before and during training. The testing protocol involved the subjects attempting to stand from various weight-bearing positions within the OrthoSYS. The EMG, HR, and BP measures were obtained during the testing protocol that occurred before their DWB exercise for that day. Table 2 describes the measures that were taken at each position.

Data Collection Procedures

Once seated in the OrthoSYS, the subjects laid against a back rest and relaxed so that resting measures of EMG, BP, and HR could be recorded. These were considered the *baseline seated* (BSST) measures. The subjects were then assisted by the research assistants to a supported seated position. Subjects were then instructed that on hearing a verbal *go*, they should attempt to stand unassisted by the research assistant, using whatever voluntary muscle control they possessed, including, in the cases of subjects 3 and 4, their trunk and arm musculature. This effort was labeled the *attempted stand* position. Coincident with the verbal *go*, an electronic signal activated the collection system, and the subjects had 32 secs to attempt to stand.

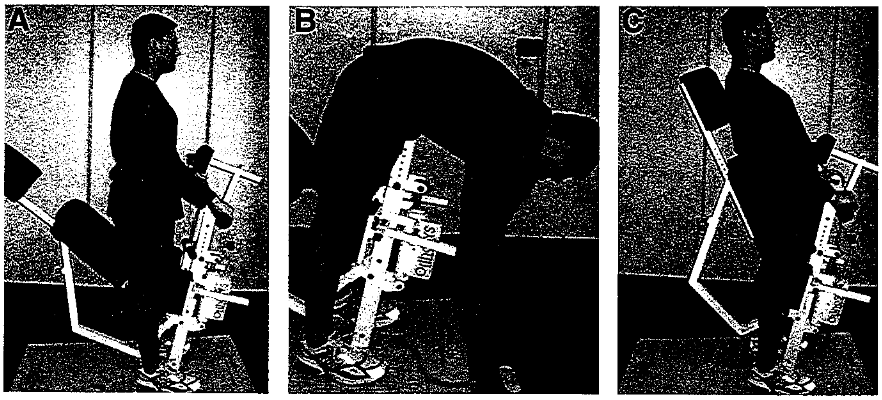

FIGURE 2 *A, Supported partial standing. B, Standing spine flexion. C, Standing back extension.*

TABLE 2 Descriptions of measures taken at each position

Position	Description	Measure	Description
BSST	Baseline seated	EMG, HR, BP	EMG taken for 32 secs while subject laid against the back rest; HR and BP taken immediately after EMG.
AS	Attempted stand	EMG, HR, BP	EMG taken for 32 secs; electric signal used to mark 3 secs of attempted stand within the 32-sec time frame.
BSS	Baseline standing	EMG, HR, BP	EMG taken for 32 secs during relaxed standing. In this position, subjects did not actually attempt to stand; rather, they were asked to relax as best they could.
P1–P6	Positions 1–6	EMG	EMG taken for 32 secs; electric signal used to mark 3 secs of attempted stand within the 32-sec time frame.

EMG, electromyography; HR, heart rate; BP, blood pressure.

On the basis of visual inspection of the subject, the initiation of all attempts to stand within the 32-sec window were electronically marked by a switch controlled by the investigator. After the subjects attempted to stand from the attempted stand position, the OrthoSYS was raised until the subjects were in a supported standing position, labeled the *baseline standing position* (BSS). In the BSS position, subjects did not actually attempt to stand; instead, they were asked to relax as best they could, and EMG, BP, and HR were again obtained. After the BSS measures were obtained, the subjects again attempted to stand using whatever voluntary muscle control they possessed; this was labeled *position 6*. The OrthoSYS was then lowered 1 cm, and the subjects again attempted to stand. Each 1-cm lowering of the OrthoSYS constituted a new position from which the subjects attempted to stand. There were six of these positions, and EMG was obtained for each attempted stand from each position. The process of lowering continued either until a subject was unable to stand or the subject was able to stand from a seated position. Note that HR and BP data were only obtained during BSST and BSS, whereas EMG was collected during all conditions. Subjects 1 and 2 were not able to complete all of the positions. Position 1 and *attempted stand* were ultimately the same position; the only difference was that position 1 was attempted after all other positions. As noted above, once data collection had been completed, the subjects performed their DWB exercises, during which HR was continuously monitored.

Data Analysis

The four subjects included in this investigation constituted a small, nonhomogenous group of individuals displaying a wide range of abilities, which is consistent with the population of those with SCIs. Primarily for this reason, but also because our sample violated many assumptions required for the use of techniques designed to assess potential differences between means, we chose to focus on individualized responses. Therefore, descriptive statistics are used to report the data. RMS was used to assess the power of the signal and was calculated as the sum of the 3-sec analysis window. Three seconds of EMG resting baseline data were obtained in the BSST position before any attempt to stand. The first 3 secs of an attempted stand from various positions within the OrthoSYS were analyzed to obtain a sum of RMS electrical activity. A percent-change score of summed RMS activity relative to baseline was chosen as the dependent variable. In rare cases, some of the subjects attempted to stand multiple times within the 32-sec collection epoch. When this occurred, the data were visually inspected, and the 3-sec window associated with a given stand attempt that had the greatest amount of RMS activity across all muscles was selected for data analysis. EMG data for weeks 1, 4, 8, and 12 were converted to percent-change scores relative to each week's BSST data. Examination of the data associated with each attempted stand position revealed there were no consistent trends related to position. Therefore, the percent-change scores were collapsed over position. The resulting scores represent the average percentage of change for each muscle, for each subject, for each week. This procedure enabled us to determine whether there were systematic differences in EMG activation for different muscles across testing periods. Average HR and BP for the 12-wk period during the BSST and BSS conditions were obtained and evaluated to identify any changes that might have occurred as a result of DWB.

RESULTS

The primary goal of this study was to assess whether increases in neuromuscular activation occurred in individuals with an SCI who participated in DWB exercise. Furthermore, HR and BP responses were assessed to determine whether changes in circulatory responses occurred as a result of DWB exercise. Consistent increases in neuromuscular activation and HR, and normalization of BP, would indicate that DWB exercise could be an effective exercise program in the spinal cord–injured population and that it might enable general improvements in overall functional status.[8–10]

EMG Results

We assessed whether there were increases in neuromuscular activation associated with exercising during DWB, and whether 12 wks of training systematically influenced the magnitude of EMG responses.

Modification of Amplitude

The data reveal that when collapsed over attempted stand positions, 71 of the 79* resulting percent-change measures reflect increases in EMG activity above baseline (71/79; 89.9%) (Table 3). Although there was a wide range of percentage changes (range, 1524; −41.8%), there was a clear tendency for EMG-activation amplitude to increase relative to baseline measures during attempted stands.

TABLE 3 Percent change of root mean square relative to seated baseline, collapsed over positions

	Week 1	Week 4	Week 8	Week 12
Subject 1				
GA	37.0	442.0	64.7	9.3
BF	61.1	102.3	96.8	27.1
RF	0.6	55.8	11.9	62.6
RA		209.2	128.2	23.2
EO	151.1	446.7	306.1	192.8
Subject 2				
GA	59.5	76.3	11.3	17.1
BF	84.9	63.1	4.0	4.0
RF	52.5	88.7	8.5	5.1
RA	31.2	72.3	6.7	12.3
EO	18.2	12.9	6.6	15.5
Subject 3				
GA	22.2	14.0	16.7	38.6
BF	−34.0	64.6	12.2	15.2
RF	−21.0	−20.2	23.3	16.8
RA	−28.5	−41.8	17.0	20.5
EO	158.0	206.4	130.4	135.8
Subject 4				
GAS	2.8	21.4	14.1	20.2
BF	20.8	39.9	4.4	338.1
RF	−9.5	−8.8	43.4	-36.5
RA	378.1	1190.7	618.5	453.7
EO	1524.4	497.9	170.2	617.3

All 19 of subject 1's EMG measures displayed increases in EMG during attempted standing (100%). Subject 2 increased activation in all 20 of his measures, whereas subject 3 displayed increases in 15 of his 20 measures. Finally, subject 4 displayed increases in 17 of 20 measures. Figure 3 provides exemplary EMG activity during the attempted stand for subjects 3 and 4.

HR and BP Results

The results indicate that all subjects experienced increases in HR as a result of physical effort. BP changes also occurred as a result of effort. In particular, two subjects experienced increases in systolic BP, and two subjects experienced decreases in systolic BP. Diastolic BP remained relatively stable during rest and DWB.

DISCUSSION

The overall purpose of the present research was to study the effects of a portion of the IntelliGEN AR program that centered on the use of DWB during a personalized exercise program. In particular, we were interested in determining whether

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*On testing day 1, subject 1's rectus abdominus electrode experienced technical difficulty that prevented data collection. Therefore, there are only 79 EMG measures collapsed over positions rather than 80 (five muscles, four subjects).

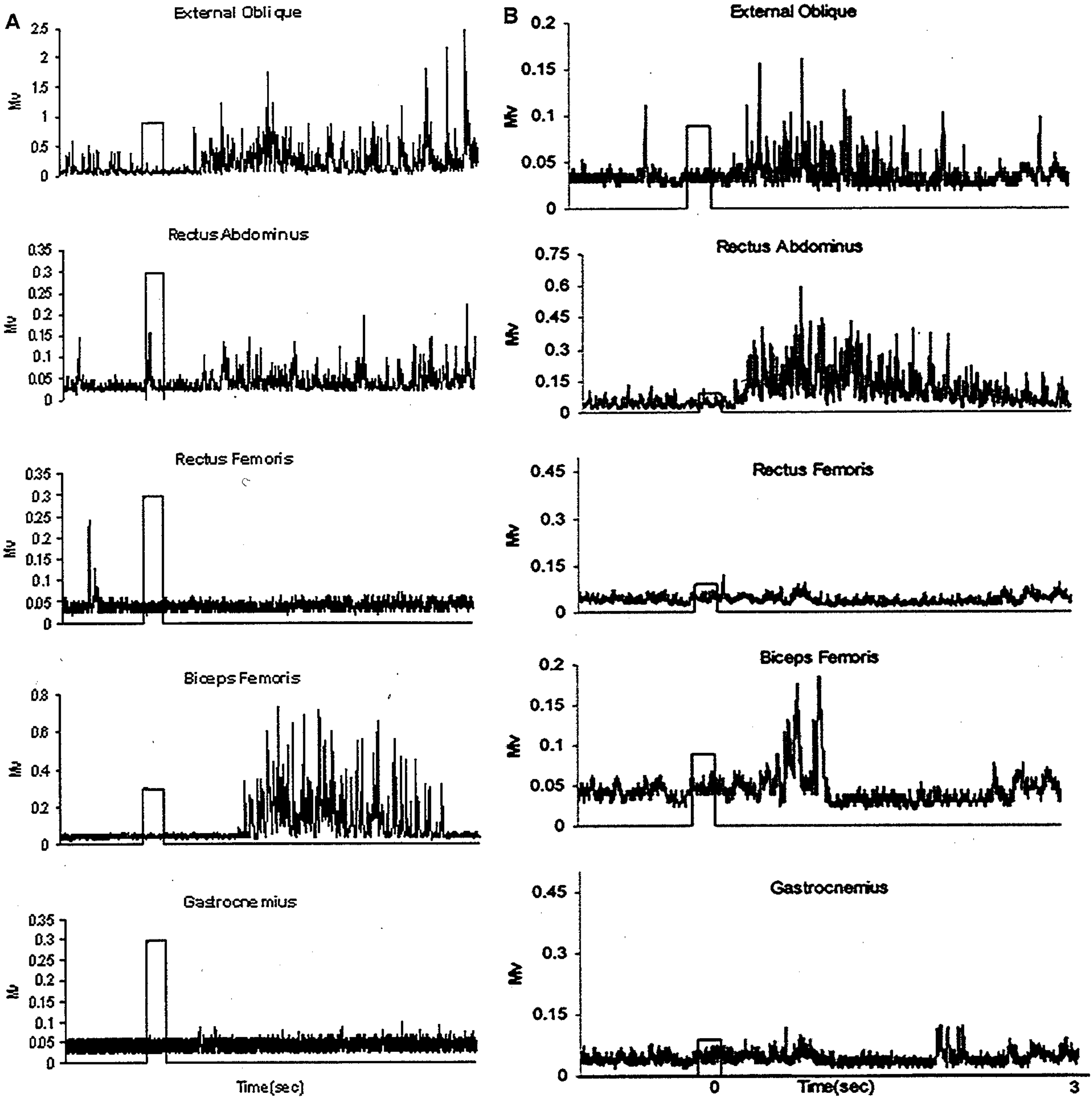

FIGURE 3 *A, EMG of subject 4 during attempted stand. Note the sustained increase in the activation levels of the trunk and biceps femoris. B, EMG of subject 3 during attempted stand.*

individuals with an SCI would respond to DWB training, as measured by EMG, HR, and BP.

The results suggest that the four individuals who participated in the DWB exercise regime consistently responded during the course of the 12-wk training period. Edgerton et al.[13] have determined that retraining the spinal cord requires extensive training and is context dependent. The results of this study indicate that the spinal cord can be responsive to specific activities designed to stimulate the central nervous system, and an AR program that incorporates DWB with exercise may allow an individual to stimulate his or her postinjury central nervous system in ways that may have been overlooked during the initial years of recovery. In particular, subject 3 was able to raise both his arms above his head and still maintain his balance in his wheelchair—something he could not do before training. DWB exercise also may have contributed to the ability of subjects 3 and 4 to go from a seated to a standing position after the 12-wk period. At the start of the training neither subject was able to complete this task successfully. These anecdotes suggest not only improvements in muscle function but also improvements in overall sensory motor integration. Sensory motor integration can be facilitated through practice, and the subjects in our study may have been able to more fully integrate their current levels of function to bring about changes in performance. For instance, increased arm strength may have contributed to the ability to go from a seated to a standing position in subjects 3 and 4. Furthermore, during the 12-wk period, subjects 3 and 4 may have been able to "learn" the most efficient way to go from a seated to a standing position within the constraints of their functional levels.

The effort required during DWB to recruit muscles below the level of lesion may have resulted in spared neuronal fibers being used more actively than normal for their activities of daily living. Dimitrijevic et al.[14] found that SCI subjects were able to activate or suppress motor activity below the level of lesion, suggesting that some individuals who have sustained an SCI have some suprasegmental neuromuscular "control." The possible use of spared fibers below the lesion may be partially responsible for the increases in neuromuscular activation we observed throughout the training regime. Also, Sherwood et al.[15] have found that when individuals with an SCI completed a specified protocol of both passive and attempted voluntary movements in a supine position, more motor activity was observed during attempted voluntary movements. This is similar to the results of the current study in that the greatest increases in neuromuscular activation were seen as a result of increased physical effort. We suggest that our protocol was particularly valuable to our subjects because they were exercising in a weight-bearing position. The demands placed on the subjects during this study were far greater than was expected of them on a daily basis. All of our subjects exclusively used wheelchairs for daily mobility, and none participated in programs that placed significant physical demands on them.

With the exception of subject 3, the subjects in this study displayed greater increases in neuromuscular activation when placed in weight-bearing positions *vs.* the seated baseline position. This suggests that afferent input that results from loading the lower limbs may stimulate an increase in neuromuscular activation. This suggestion is consistent with the findings of Sinkjaer et al.,[16] who report that up to 50% of soleus muscle activity during the stance phase in walking in healthy individuals is attributable to afferent feedback. They found that when the ankles were unloaded, a reduction of approximately 50% in soleus EMG activity was observed during walking. Increasing sensory feedback may also contribute to the improvements seen in individuals with an SCI who participate in supported treadmill training.[17,18] Afferent feedback that increases muscle activity in the lower limbs suggests that loading the lower limbs may be an important physiologic need and may facilitate the access of the remaining sensory and motor neural functioning fibers below the level of lesion.

It should be noted that in this study, there were several instances of decreased neuromuscular activation relative to baseline measures during voluntary efforts. These decreases may be associated with decreases in muscle spasticity.[19] Although spasticity was not directly measured, some subjects reported spasticity, and in some cases spasticity was evidenced during the training sessions. However, all analyzed EMG data were free of any evidence of spasticity-related activation. A decrease in spasticity can result in improvements in activities of daily living by allowing individuals to move freely and unhindered. It is also possible that muscle-specific fatigue may have resulted in less use of particular muscles during a particular attempt to stand.

As part of this study, we also examined any changes in HR and BP. As in able-bodied individuals, increases in effort during a task will result in increases in HR and BP. The subjects in our study all experienced increases in HR as a result of effort during training sessions. Also, systolic BP increased in two of the subjects, whereas diastolic BP remained relatively stable during the 12-wk period in all subjects. The maintenance of stable BP during DWB training is essential if an individual is to attain his or her rehabilitation goals. Also, the ability to assimilate to an upright, weight-bearing position as a result of DWB could be a prerequisite for progression in the AR program. These results suggest that the nervous system is trainable if it is given an appropriate stimulus, which DWB seems to be.

The results of this study suggest that practical functional gains and physiologic changes in spinal cord–injured individuals can occur as a result of participating in a DWB exercise regime. Furthermore, the results suggest that an individual with an SCI may have a latent regenerative potential that has yet to be fulfilled.

Limitations of the study include the small sample size and the lack of information regarding the subjects' neurological status. We have presumed that the EMG we consistently observed throughout the training was the result of muscular activity coupled to spared neuronal fibers. However, without accurate knowledge of our subjects' neurological status, we are unable to determine whether our training protocol would be of any benefit to complete patients. Therefore, future research should include complete as well as incomplete injured individuals to assess whether the effects of DWB differ between the groups. Additional investigations of the short-term effects on a larger sample size would provide more conclusive results. Further study also is needed to demonstrate the long-term effects of DWB exercise, especially in conjunction with other aspects of AR that were not included in our protocol. Additional investigations are needed to assess the possible effects of AR in other individuals who have conditions such as cerebral palsy, multiple sclerosis, brain injury, Parkinson disease, or other neurological conditions.

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Erratum

In the article by Miyoshi et al., published in the August 2005 issue of the *American Journal of Physical Medicine & Rehabilitation*, on page 615, under Data Analysis and Statistics, the first sentence should read as follows:

To compare the data between two groups, the independent sample *t* test and chi-square test with tabulations were used.

The authors regret the error.

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