Effects of body weight-supported treadmill training on heart rate variability and blood pressure variability in individuals with spinal cord injury

David S. Ditor, Mark V. Kamath, Maureen J. MacDonald, Joanne Bugaresti, Neil McCartney, and Audrey L. Hicks. Effects of body weight-supported treadmill training on heart rate variability and blood pressure variability in individuals with spinal cord injury. J Appl Physiol 98: 1519–1525, 2005. First published November 24, 2004; doi:10.1152/japplphysiol.01004.2004.—Individuals with spinal cord injury are prone to cardiovascular dysfunction and an increased risk of cardiovascular disease. Body weight-supported treadmill training (BWSTT) may enhance ambulation in individuals with incomplete spinal cord injury; however, its effects on cardiovascular regulation have not been investigated. The purpose of this study was to examine the effects of 6-mo of BWSTT on the autonomic regulation of heart rate (HR) and blood pressure (BP) in individuals with incomplete tetraplegia. Eight individuals [age 27.6 yr (SD 5.2)] with spinal cord injury [C4–C5; American Spinal Injury Association B-C; 9.6 yr (SD 7.5) postinjury] participated. Ten-minute HR and finger arterial pressure (Finapres) recordings were collected during (1) supine rest and (2) an orthostatic stress (60° head-up tilt) before and after 6 mo of BWSTT. Frequency domain measures of HR variability [low-frequency (LF) power, high-frequency (HF) power, and LF-HF ratio] and BP variability (systolic and diastolic LF power) were used as clinically valuable indexes of neurocardiac and neurovascular control, respectively. There was a significant reduction in HR [61.9 (SD 6.9) vs. 55.7 beats/min (SD 7.7); P = 0.05] and LF-HF ratio [1.23 (SD 0.47) vs. 0.99 (SD 0.40); P < 0.05] after BWSTT. There was a significant reduction in LF systolic BP [183.1 (SD 46.8) vs. 158.4 mmHg2 (SD 45.2); P < 0.01] but no change in BP. There were no significant effects of training on HR variability or BP variability during 60° head-up tilt. In conclusion, individuals with incomplete tetraplegia retain the ability to make positive changes in cardiovascular autonomic regulation with BWSTT without worsening orthostatic intolerance.

exercise training; neurovascular regulation; neurocardiac regulation; sympathetic decentralization; tetraplegia

THE INCIDENCE OF SPINAL CORD INJURY (SCI) in Canada and the United States has been estimated at 35/million and 40/million, respectively. Although these rates may seem relatively innocuous, they translate to ~1,000 newly injured Canadians and 12,000 newly injured Americans each year, and a combined prevalence of ~250,000 individuals (34). Roughly one-half of these individuals have incomplete injuries, and as such have retained some motor and/or sensory function below the level of injury (34).

In the last decade, body weight-supported treadmill training (BWSTT) has shown promise as a means of enhancing and restoring gait recovery in individuals with incomplete SCI (2, 31, 38–40). Improvements in ambulatory capacity after BWSTT have included a greater weight-bearing capacity, increases in walking speed and endurance, and an enhanced gait pattern during BWSTT (3), and, in some cases, an increased ability to walk over ground (39). To date, however, there are no published studies regarding the effects of BWSTT on the cardiovascular health and function of individuals with SCI, despite the fact that (1) cardiovascular health and function are major health issues in the SCI population and (2) BWSTT may hold particular promise as a means of improving such health issues.

Specifically, cervical SCI has been associated with an increased risk of mortality from several cardiovascular diseases, including both ischemic and nonischemic heart disease (9). However, the factors accounting for this increased risk are not fully understood, and, accordingly, there is much to be determined regarding the potential for cardiovascular improvement in individuals with SCI. BWSTT is an upright exercise that utilizes the large leg muscles and thus may provide a greater cardiovascular challenge than more traditional forms of aerobic training for individuals with SCI, such as arm ergometry. Furthermore, the supporting, or partial supporting, of one’s body weight allows a prolongation of exercise duration, which may be required to realize maximal cardiovascular benefit. Finally, although functional electrical stimulation (FES) has been shown to confer cardiovascular benefit in individuals with SCI (26), it may not be practical for individuals with incomplete injuries due to the pain associated with this technique (16).

Recently developed methods may be particularly useful in evaluating the effects of BWSTT on the cardiovascular health and function in individuals with SCI. Specifically, power spectral analysis of heart rate (HR) variability (HRV) and blood pressure (BP) variability (BPV) have become commonly used, noninvasive methods used to quantify the autonomic control of the cardiovascular system (1, 17, 28, 29). With respect to HRV, successive R-R intervals obtained from ECG recordings have been shown to oscillate around two main frequencies. The high-frequency (HF) oscillation, centered at ~0.25 Hz (ranging between 0.15 and 0.40 Hz), corresponds to parasympathetic outflow to the heart via the vagus nerve (30),
whereas the low-frequency (LF) oscillation, centered at ~0.1 Hz (ranging between 0.04 and 0.15 Hz), has been shown to correspond to both the sympathetic and parasympathetic outflow to the heart, although it is much more indicative of the former (24, 30). Thus the LF-to-HF ratio of HRV has become an accepted measure of cardiac sympathovagal balance. Similarly, the LF oscillation of systolic (LFsBP) and diastolic (LFDsBP) BPV (0.04–0.15 Hz), also referred to as Mayer waves, has been shown to correspond to neurovascular control via the sympathetic nerves (28, 29). The HF oscillation of systolic and diastolic BPV (0.15–0.40 Hz) is not associated with neurovascular control, but rather it is thought to represent the mechanical effects of respiration that may act directly on the pressure gradients of the intrathoracic vessels (27). Finally, previous work from our laboratory has shown measures of HRV (10) and BPV (Ditor DS, unpublished observations) to be reproducible in individuals with SCI.

Measures of HRV and BPV have been found to have significant clinical value, as relative reductions in cardiac vagal predominance have been associated with an increased risk of cardiovascular mortality (19), and increased BPV and enhanced Mayer waves are associated with end-organ damage (11, 23). In the able-bodied population, exercise training has been shown to promote changes in HRV and BPV consistent with increases in cardiac vagal predominance and a general reduction of sympathetic outflow to the cardiovascular system (8, 35). It is currently unclear whether individuals with SCI are capable of experiencing the same exercise-induced enhancements in HRV and BPV or whether such changes are prevented by the unique autonomic disturbance that is often caused by the injury. Preliminary work from our laboratory (Ditor DS, unpublished observations) suggests that individuals with incomplete tetraplegia may experience increases in cardiac vagal predominance after an arm ergometry training protocol; however, that work did not include measures of BPV, and, as mentioned, autonomic adaptation may be more effectively examined via BWSTT. Furthermore, as individuals with cervical SCI are characterized by an inability to tolerate postural stress (15), it is of interest to determine what effects BWSTT may have on such orthostatic tolerance. There is some evidence that exercise training may confer an enhanced ability for individuals with SCI to respond to cardiovascular stress, as indicated by a relatively greater sympathetic response from rest to maximal arm-ergometry exercise after 6 mo of FES cycle training (4).

On the other hand, it is possible that potential training-induced reductions in sympathetic outflow, although beneficial to long-term cardiovascular health, may decrease the ability to tolerate postural stress, especially in light of the sympathetic decentralization that is characteristic of many with SCI.

The purpose of the present study was to determine the effects of a 6-mo BWSTT training regimen at a frequency of three times per week on measures of resting HRV and BPV in individuals with incomplete cervical SCI. A secondary purpose was to investigate the effects of the BWSTT regimen on the autonomic response to orthostatic stress in individuals with SCI, as determined by changes in HRV and BPV measures.

METHODS

Participants. Eight individuals [6 men, 2 women; age 27.6 yr (SD 5.2)] with chronic SCI [C4–C5; American Spinal Injury Association (ASIA) B–C; 9.6 yr (SD 7.5) postinjury] were included in the present investigation. The ASIA neurological examination was used to evaluate the level and severity of SCI. The resulting ASIA impairment scale is a five-point scale (ASIA A–E) based on sensory and motor function: ASIA A, no sensory or motor function is preserved in sacral segments S4–S5; ASIA B, sensory, but not motor, function is preserved below the neurological level of injury and extends through sacral segments S4–S5; ASIA C, motor function is preserved below the neurological level of injury but at least one-half of the key muscles below the neurological level have muscle grade of less than three (where grade 3 strength is defined as limb movement against gravity alone); ASIA D, motor function is preserved below the neurological level of injury and at least one-half of the key muscles below the neurological level have muscle grade greater than or equal to three; ASIA E, sensory and motor functions are normal. All eight individuals were recruited from an outpatient SCI clinic at Chedoke Hospital, Hamilton, Ontario, Canada, and were only included if they were at least 1 yr postinjury and were free of any coincident cardiac disease.

Participants were also required to be free of any musculoskeletal condition that would contraindicate exercise training, and although each participant was attending regular physiotherapy sessions at the time of study inclusion, no participant was involved in any other form of regular progressive exercise during the BWSTT protocol. Finally, participants were not asked to discontinue their regular physiotherapy sessions during this study with the exception of those days that coincided with HRV and BPV testing. This investigation was approved by the McMaster Research Ethics Board, and all participants provided written, informed consent in accordance to McMaster Research Ethics Board guidelines. Characteristics of the exercising participants are summarized in Table 1.

ECG and BP data acquisition. Continuous recordings of HR and BP data were obtained from each participant at baseline and after 6 mo of BWSTT. In general, testing sessions occurred between 12:30 PM and 7:00 PM; however, for any given participant, the time of day for pre- and posttesting sessions never deviated by >1.5 h. Participants were instructed to abstain from caffeine and cigarette smoking for at least 12 h before testing, and they were 2 h postprandial. All posttraining testing sessions were conducted at least 24 h after the last bout of exercise to ensure a true resting condition during data acquisition. Medications were not interrupted during the study; however, medications and dosages were identical at all testing sessions for each participant. In addition, only four of our eight participants were taking any medication, and of those four, the only medications that may reasonably have affected our measures were baclofen and ditropan, which were taken for their antispastic properties. Furthermore, the incidence of cardiovascular side effects associated with these medications are very low, usually transient, and only associated with the start of treatment (7).

On entering the laboratory, each participant was asked to empty his or her urine bag and then was transferred onto a table and fitted with a Polar HR monitor and a finger plethysmograph (Finapres) cuff (Ohmeda 2300, Madison, WI). In an attempt to achieve steady-state resting conditions, participants lay quietly in a dark, quiet room for 10

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ASIA, American Spinal Injury Association; M, male; F, female.
min before the start of data collection. The testing protocol consisted of a 10-min period of supine rest, a 5-min period of 20° head-up tilt (HUT), a 5-min period of 40° HUT, and finally a 10-min period of 60° HUT. HR and BP data were only recorded during the 10-min supine and the 10-min 60° HUT conditions. An adjustable arm rest was attached to the tilt table such that participants could keep their hand at heart level during 60° HUT for Finapres BP recording. Participants were asked not to sleep during data collection, and although they were not disturbed during the testing sessions, none had any problems remaining awake. Data were recorded during spontaneous breathing, and antiembolic stockings and abdominal binders were not worn by any of our participants during the testing sessions.

HR and BP signals were sampled at 500 Hz using a 12-bit analog-to-digital converter (CODAS, DATAQ, Akron, OH). The signals were continuously and simultaneously displayed on an IBM computer using WINDAQ data acquisition software (Dataq Instruments). The HR and BP recordings were saved on the computer hard drive and transferred to a separate computer equipped for HRV and BPV analysis.

Computation of HRV and BPV. A customized software program (MATLAB) (18) was used to identify a stable and noise-independent fiducial point on all R-waves for each recording, as well as beat-to-beat values of systolic (SBP) and diastolic BP (DBP). An R-R-interval tachogram, as well as separate SBP and DBP tachograms, were then generated from the continuous HR and BP data, respectively. All tachograms were then inspected for ectopic beats, which were subsequently removed using a linear interpolation algorithm (18). When files were found to contain excessive ectopic beats (>5 beats/min), the investigator visually inspected the tachogram for a sufficiently long period of relatively ectopic-free segments of HR and BP data for further analysis. Beat-to-beat HRV and BPV signals were then computed and resampled at 2 Hz using linear interpolation to obtain equally sampled time series. For each data set, four record lengths of 256 points were selected automatically for power spectral analysis. The mean value of the HR and BP were removed, and the equally sampled HRV and BPV signals were fed through a second-order high-pass Butterworth filter with a cutoff of 0.02 Hz. Power spectra were then computed from the filtered HRV and BPV signals using previously described software (18). Final frequency domain measures represent the average of all accepted record lengths. Oscillations ranging between 0.04 and 0.15 Hz were designated as LF, whereas oscillations between 0.15 and 0.40 Hz were designated as HF. The power of the LF and HF peaks, which sometimes, albeit rarely, occurred during spontaneous breathing. Peak values of the LF and HF components were identified from the HRV and BPV power spectra and were expressed as (beats/min)²/Hz and (mmHg)²/Hz, respectively. The power of the LF and HF components were calculated via integrating the area under each curve and expressed as (beats/min)² and mmHg². LF-to-HF ratios and mean HR were also calculated by the MATLAB program. SBP and DBP were determined by auscultation over the left brachial artery at heart level and mean arterial pressure (MAP) was subsequently calculated [MAP = (SBP + 2DBP)/3].

BWSTT apparatus. The Woodway Loco-system (Woodway, Foster, CT) is a specialized treadmill with a built-in weight-supporting system. Participants were fitted with a harness while seated in their wheelchairs and then wheeled up a ramp to the treadmill. Cables were then attached to the harness, and a pulley system was used to hoist participants into the standing position over the treadmill. Once upright, a second set of cables was used to connect participants to weight stacks located at the front of the treadmill. Weight could be added to the stacks in 8-kg increments (4 kg/stack), and when finer increments were needed, hand weights were added to the stacks. The hoisting cables were loosened once body weight had been counterbalanced but remained attached to the harness at all times for safety reasons; i.e., in case of a fall, the hoisting cables would “catch” the participant almost immediately. The Woodway Loco-system allows for a range of speeds between 0.1 and 5.0 km/h, and speed may be adjusted by 0.1-km/h increments. Treadmill speed, as well as distance and time ambulated, are displayed on a computer control panel at the side of treadmill within view of the exerciser. Handrails are attached to the treadmill, and participants were allowed to use these rails for balance but were discouraged from using them to assist in weight support. Two assistants sat at either side of the tread and assisted participants in the gait cycle, while a third assistant stood behind the participant and aided in weight shifting, balance, and general safety. All assistants were trained to detect signs of autonomic dysreflexia and to respond accordingly; however, no episodes of autonomic dysreflexia were evoked during the training sessions.

Training protocol. Participants exercised at a frequency of three times per week for 6 mo. During the first training session, an appropriate amount of body weight support was chosen for each participant, such that he or she could just stand on the treadmill without buckling at the knees. Body weight support was decreased as individually tolerated over the course of the study. For the sake of safety, initial treadmill speed was arbitrarily chosen at 0.5 km/h and the duration of ambulation at 15 min (3 bouts of 5 min). Speed and duration were also increased as individually tolerated over the course of the study. However, time constraints dictated a maximum duration of 60 min, and increases in speed were only allowed if proper gait mechanics could be maintained. When decreases in body weight support were made, it was not unusual for a participant to require brief periods of decreased speed or duration until he or she became more comfortable with the new weight. Likewise, increases in speed were sometimes accompanied by periods of decreased weight support and duration. The distance ambulated per session was obtained from each participant’s training log and used as an index of exercise progression over time. Daily training HRs were recorded in each participant’s training log, from which an average training HR could be determined over the course of the 6-mo training period.

Statistical analysis. The means of resting HRV and BPV measures at baseline and after 6 mo of BWSTT were compared by one-way ANOVA. One-way ANOVAs were also used to make comparisons between the first 3 mo of training and the last 3 mo of training regarding mean distance ambulated per session, speed of ambulation, and mean HR during BWSTT. Two-way ANOVAs (condition × time) were used to determine exercise training-induced changes in HRV and BPV in response to orthostatic stress. Tukey’s honestly significant difference post hoc analyses were used as required to determine specific differences between means. Statistical significance was set at P ≤ 0.05, and throughout the text and figures data are presented as means with SD in parentheses.

RESULTS

Program compliance. All eight participants successfully completed the 6-mo BWSTT protocol. The compliance rate, calculated as (number of sessions completed/number of scheduled sessions) × 100, was 83.6% (SD 9.1). There were no episodes of autonomic dysreflexia, musculoskeletal injury, or pressure sore development in any participant during the course of the training program.

Distance ambulated per BWSTT session. There was a significant increase in distance ambulated per session when comparing the first 3 mo of the BWSTT program to the last 3 mo, indicating that the training protocol was indeed progressive. The increase in distance was due to an increased speed of ambulation [0.79 (SD 0.32) vs. 1.08 km/h (SD 0.31); P = 0.0001] rather than duration of ambulation per session [29.6 (SD 12.0) vs. 32.9 min/session (SD 9.7); P = 0.09]. In addition, the mean HR during BWSTT was 128.8 beats/min

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significant decrease compared with supine baseline values (P = 0.05). However, there were no significant changes in resting SBP, DBP, or MAP (Table 2).

Effects of exercise training on resting HR and BP. There was a significant decrease in resting HR after 6 mo of BWSTT (P = 0.05). However, there were no significant changes in resting SBP, DBP, or MAP (Table 2).

Effects of exercise training on resting HRV and BPV measures. There was a significant reduction in the resting LF-to-HF ratio after 6 mo of BWSTT (P = 0.01) (Table 3). The reduction in the resting LF-to-HF ratio was due to the significant reduction in resting LF power (P = 0.009), as changes in resting HF power were not significant (P = 0.63) (Table 3).

Regarding BPV, there was a significant decrease in resting LF$_{\text{SBP}}$ after 6 mo of BWSTT (P = 0.007) (Table 4). In contrast, there was only a nonsignificant reduction in LF$_{\text{DBP}}$ after the training program (P = 0.13) (Table 4).

Effects of exercise training on resting HR and BP during orthostatic stress. There was a significant increase in HR on 60° HUT (P = 0.001) but no significant changes in SBP, DBP, or MAP, indicating a maintenance of BP on postural stress. There was no effect of training on the HR or BP response to 60° HUT (Table 2).

Effects of exercise training on HRV and BPV measures during orthostatic stress. There was a significant increase in the LF-to-HF ratio on 60° HUT (P = 0.005), but there was no training effect on this response (P = 0.50). The increase in the LF-to-HF ratio on postural stress was due to a significant increase and decrease in LF power (P = 0.03) and HF power (P = 0.004), respectively. There was a trend (P = 0.09) for a condition × time interaction for LF power, suggesting an enhanced sympathetic response to 60° HUT after training (Table 3). There were no effects of 60° HUT on measures of BPV and no condition × time interaction (Table 4).

DISCUSSION

The main findings of this study have both physiological and practical relevance. From a physiological perspective, our results demonstrate that individuals with incomplete cervical SCI retain the ability to make positive changes to the autonomic regulation of the cardiovascular system with exercise training. Specifically, this study is the first to show favorable exercise-induced changes in CVR in individuals with SCI, and furthermore, the present findings help to confirm preliminary findings (Ditor DS, unpublished observations) from our laboratory regarding positive changes in HRV measures after exercise training in individuals with incomplete tetraplegia. From a practical perspective, this study is the first to demonstrate the effectiveness of BWSTT as a means of improving cardiovascular health and regulation in individuals with incomplete SCI.

Clinically, the changes observed in this study are important because lower LF-to-HF ratios and LF$_{\text{SBP}}$ have been associated with a decreased risk of cardiovascular mortality and end-organ damage, respectively (11, 21). Furthermore, since SCI has been shown to result in an increased risk of mortality from various cardiovascular diseases (9), favorable changes in HRV and BPV may be of particular interest to the SCI population.

Although concurrent reductions were observed in the resting LF-to-HF ratio and resting HR, the reduction that was observed in resting LF$_{\text{SBP}}$ was not accompanied by a similar decline in resting SBP or MAP. Although the lack of a change in resting BP may seem to detract from the clinical implications of the present study, it is important to note that reductions in BPV may confer a protective effect against cardiovascular disease independently of BP. For example, in previous work (11), BPV was determined in 73 hypertensive patients who were divided into quartiles based on their 24-h MAP. Measures of end-organ damage were subsequently determined at follow-up, ~7 yr later. The results showed that, for any given quartile of MAP, those patients with lower values of BPV determined at the initial examination had a lower severity of end-organ damage at follow-up. Furthermore, this relationship held true even at the lowest quartile of MAP, which was ~80–85 mmHg. In addition, animal work using the sinoaortic-denervated rat model has provided evidence that lower BPV may confer cardiovascular benefit independently of BP. In the sinoaortic-denervated model, rats are subject to surgical destruction of the carotid and aortic baroreceptor afferents and in the chronic

| Table 2. Measures of HR and BP during supine rest and orthostatic stress before and after 6 mo of BWSTT |
|-------------------------------------------------|---------------------------------|-----------------|-----------------|
| | Supine | Baseline | HR,‡ beats/min | 61.9 (6.9) | 90.2 (21.4) | 55.7 (7.7)* | 80.0 (15.7) | 69.3 (16.8) | 80.9 (21.7) |
| | | | SBP, mmHg | 117.0 (20.3) | 107.1 (15.7) | 114.8 (15.0) | 100.0 (14.2) | 69.3 (16.8) | 80.9 (21.7) |
| | | | DBP, mmHg | 73.3 (10.6) | 71.4 (11.5) | 71.8 (9.4) | 74.8 (9.4) | 69.3 (16.8) | 80.9 (21.7) |
| | | | MAP, mmHg | 87.8 (13.5) | 83.3 (12.2) | 86.1 (10.7) | 83.2 (10.2) | 69.3 (16.8) | 80.9 (21.7) |

Values are means with SD in parentheses. BWSTT, body weight-supported treadmill training; HR, mean heart rate; SBP, systolic blood pressure; DBP, diastolic blood pressure; MAP, mean arterial pressure; HUT, 60° head-up tilt. *Significant decrease compared with supine baseline values (P < 0.01). ‡Main effect for condition such that HR increased on HUT (P < 0.01).

| Table 3. Measures of HRV during supine rest and orthostatic stress before and after 6 mo of BWSTT |
|-------------------------------------------------|---------------------------------|-----------------|-----------------|
| | Supine | 6 mo | LF,† (beats/min) | 5,894 (815) | 6,575 (706) | 5,121 (1,234)* | 6,337 (407) | 1.23 (0.47) | 2.06 (0.80) | 0.99 (0.40)* | 1.64 (0.29) |
| | | | LF/HF† | 5,493 (1,472) | 3,718 (1,125) | 5,642 (1,001) | 4,088 (659) | 1.23 (0.47) | 2.06 (0.80) | 0.99 (0.40)* | 1.64 (0.29) |

Values are means with SD in parentheses. HRV, HR variability; LF, low frequency power; HF, high frequency power; LF/HF, low-frequency-to-high frequency ratio. *Significant decrease compared with supine baseline values (P < 0.05). †Main effect for condition such that values of LF and LF/HF are increased and values of HF are decreased on HUT (P < 0.05).

| Table 4. Measures of BPV during supine rest and orthostatic stress before and after 6 mo of BWSTT |
|-------------------------------------------------|---------------------------------|-----------------|-----------------|
| | Supine | 6 mo | LF$_{\text{SBP}}$, mmHg$^2$ | 183.1±65.8 | 133.3±64.4 | 158.4±45.2* | 121.9±59.4 | LF$_{\text{DBP}}$, mmHg$^2$ | 191.0±26.4 | 164.5±70.2 | 170.6±34.6 | 161.9±69.3 |

Values are means with SD in parentheses. BPV, blood pressure variability; LF$_{\text{SBP}}$, low-frequency power of SBP; LF$_{\text{DBP}}$, low-frequency power of DBP. *Significant decrease compared with supine baseline values (P < 0.01).

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condition are characterized by an increase in BPV but a normal average BP (23). Sinoaortic-denervated rats have been shown to develop both aortic and left ventricular hypertrophy, both of which have been shown to correlate positively and significantly with BPV (23, 33).

It is important to mention that the aforementioned work (11, 23) used time-domain measures to demonstrate the relationship between BPV and cardiovascular risk, whereas the present study noted exercise-induced reductions in LFpSBP, a frequency-domain measure of BPV. However, various studies have provided evidence that LFpSBP is an acceptable estimate of sympathetic outflow to the vasculature (28, 29, 32), and thus it would be reasonable to expect that reductions in frequency domain measures of BPV may also confer cardiovascular benefit. Still, since direct measures of cardiovascular disease progression were not measured in the present investigation, the observed decline in LFpSBP should be interpreted with some caution. Furthermore, there is some debate as to the most appropriate interpretation of LFpSBP. Although there is considerable evidence supporting LFpSBP as a representation of sympathetic outflow to the vasculature, it must be noted that such work is somewhat inferential and may not be considered definitive. For example, although studies have shown LFpSBP to increase during conditions that are associated with increased sympathetic outflow to the vasculature [HUT (20) or coronary occlusion (32)], the association between the two is not absolute. It is more likely that although sympathetic outflow to the vasculature is a major modulator of LFpSBP, it is not the sole contributor. This position is supported by studies that have shown that 1) sympathetic activity contributes only modestly (albeit significantly) to the explained variance in Mayer waves (25) and 2) α-adrenergic blockade decreases but does not completely eliminate LFpSBP (36). Taken together, the present data clearly demonstrate a link between sympathetic outflow to the vasculature and LFpSBP; however, the latter should not be viewed as an analog of the former.

The exercise-induced reduction in LF-to-HF ratio may be a particularly encouraging finding for individuals with SCI. Previous investigators have hypothesized that the reduction in cardiac sympathetic outflow that may result from SCI causes a compensatory reduction in cardiac vagal tone in an attempt to maintain autonomic balance (13, 37). Such a compensation would be problematic for individuals with SCI, as reductions in cardiac vagal tone have been shown to be an independent risk for cardiovascular mortality (19). However, the observed reduction in the LF-to-HF ratio in the present study helps to confirm preliminary work from our laboratory and suggests that cardiac autonomic balance remains receptive to change after SCI and that favorable exercise-induced changes in autonomic balance are possible in this population.

Despite these encouraging results, it is important to point out some potential limitations to our data. First, the participants in this study exhibited a fairly well preserved sympathetic outflow to the cardiovascular system, as seen by the maintenance of MAP on postural stress and by the relatively high HRs that were experienced during exercise training [average HR: 127.1 beats/min (SD 21.3); peak HR: 147.1 beats/min (SD 23.7)]. Therefore, it is unclear whether individuals with more severe sympathetic decentralization can bring about the same exercise-induced changes in the LF-to-HF ratio. However, in the present study, even those with the lowest peak HR during exercise training (participants 3 and 5, 120 beats/min) still experienced representative decreases in the LF-to-HF ratio after the 6-mo training protocol (participant 3, 19%; participant 5, 32%). Parenthetically, it should also be emphasized that the participants of this study were able to progress to durations and frequencies of exercise that fell well within the guidelines for the able-bodied population despite their lack of experience with BWSTT. This should be viewed as highly encouraging for those living with SCI who may feel apprehensive about starting new exercise rehabilitation programs.

Second, the reduction that was observed in the LF-to-HF ratio was accounted for by a significant reduction in LF power and only a nonsignificant increase in HF power. Thus the changes that were noted in cardiac autonomic balance seemed to be driven more by reductions in sympathetic tone rather than by increases in vagal tone. (Although LF power contains both sympathetic and vagal components, the present finding of decreased LF power in conjunction with increased or maintained HF power strongly suggests a reduction in sympathetic outflow per se.) The absence of vagal enhancement may make any associated health benefits questionable, as the majority of studies regarding HRV and cardiovascular risk have used time-domain measures (5) and thus have primarily commented on the cardioprotective nature of vagal outflow. Still, others have found an association between reductions in the LF-to-HF ratio and protection from cardiovascular mortality (21). Furthermore, norepinephrine has been shown to have deleterious effects on myocardial tissue (6, 22).

In contrast to the exercise-induced changes in resting autonomic function, the 6-mo BWSTT program did not substantially affect our participants’ ability to tolerate orthostatic stress. There was a trend ($P = 0.09$) for a condition × time interaction for LF power such that the change in LF power from supine to 60° HUT tended to be enhanced after the training program (again, relative increases in LF power, in the face of decreases in HF power, may be interpreted as a relative enhancement of sympathetic outflow). This would suggest that the 6-mo BWSTT program resulted in a relative exaggeration of the pressor response to orthostatic stress, an observation that should be pursued in future studies. There is some evidence from previous research that exercise training might enhance sympathetic outflow in individuals with SCI. Specifically, a relatively increased catecholamine response to maximal arm ergometry exercise after 6 mo of FES cycling has been shown (4). It is reasonable to hypothesize that the exercise-induced reduction in LFpSBP that we observed was accompanied by similar reductions in resting peripheral vascular resistance. Support for this hypothesis may come from training studies that have noted decreases in vascular resistance in individuals with complete SCI after 6 wk of FES cycling exercise (14). It may follow that such a decrease in vascular resistance would necessitate a greater relative pressor response to postural stress to maintain MAP. Regardless, it is still interesting and relevant that none of our participants became less tolerant to postural stress after the exercise training program, as indicated by the maintained MAP during 60° HUT at posttesting. This is an encouraging finding because it suggests that individuals with incomplete SCI may retain orthostatic tolerance after an exercise training program involving the lower limbs, despite the fact that such an intervention likely decreased resting vascular resistance. However, as previously mentioned, our participants...
did not suffer from severe sympathetic decentralization. Thus it remains unclear whether individuals with more severe SCI may retain relative orthostatic tolerance after BWSTT.

In terms of BWSTT itself, the present study is the first to show that this exercise training modality may confer cardiovascular benefit to individuals with incomplete tetraplegia. Although cardiovascular benefit has been shown to follow FES exercise (14, 26), many individuals with incomplete SCI will find electrical stimulation excessively painful. Thus BWSTT should be encouraged as a means of promoting cardiovascular health in individuals with SCI regardless of the individual’s gains or lack thereof in terms of ambulation. This is an important point because, despite the findings of others (39), in our experience long-term BWSTT does not confer consistent overground walking capabilities even in those who eventually progress to zero body weight support.

In conclusion, the present study is the first to show that individuals with incomplete tetraplegia retain the ability to make positive adaptations to the autonomic regulation of the cardiovascular system after 6 mo of three times per week BWSTT. These findings may be particularly valuable to individuals who have trouble tolerating FES exercise. Future work should examine whether individuals with more severe SCI, and thus less motor function, may make the same cardiovascular adaptations after BWSTT despite the more passive nature of ambulation that would be expected.

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