Robotic assistance that encourages the generation of stepping rather than fully assisting movements is best for learning to step in spinally contused rats

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Lee C, Won D, Cantoria MJ, Hamlin M, de Leon RD. Robotic assistance that encourages the generation of stepping rather than fully assisting movements is best for learning to step in spinally contused rats. J Neurophysiol 105: 2764–2771, 2011. First published March 23, 2011; doi:10.1152/jn.01129.2010.—Robotic devices have been developed to assist body weight-supported treadmill training (BWSTT) in individuals with spinal cord injuries (SCIs) and stroke. Recent findings have raised questions about the effectiveness of robotic training that fully assisted (FA) stepping movements. The purpose of this study was to examine whether assist-as-needed robotic (AAN) training was better than FA movements in rats with incomplete SCI. Electromyography (EMG) electrodes were implanted in the tibialis anterior and medial gastrocnemius hindlimb muscles of 14 adult rats. Afterward, the rats received a severe midthoracic spinal cord contusion and began daily weight-supported treadmill training 1 wk later using a rodent robotic system. During training, assistive forces were applied to the ankle when it strayed from a desired stepping trajectory. The amount of force was proportional to the magnitude of the movement error, and this was multiplied by either a high or low scale factor to implement the FA (n = 7) or AAN algorithms (n = 7), respectively. Thus FA training drove the ankle along the desired trajectory, whereas greater variety in ankle movements occurred during AAN training. After 4 wk of training, locomotor recovery was greater in the AAN group, as demonstrated by the ability to generate steps without assistance, more normal-like kinematic characteristics, and greater EMG activity. The findings suggested that flexible robotic assistance facilitated learning to step after a SCI. These findings support the rationale for the use of AAN robotic training algorithms in human robotic-assisted BWSTT.

Electromyography; treadmill; spinal cord injury

Body weight–supported treadmill training (BWSTT) is a form of gait training in which trainers assist leg, hip, and trunk movements during treadmill locomotion. Clinical studies have shown that BWSTT improved locomotor function in humans following spinal cord injury (SCI) (Wernig et al. 1995) and stroke (Sullivan et al. 2007). Implementing BWSTT can be difficult for trainers, because often times, a great deal of effort is required to assist movements. To facilitate BWSTT, robotic devices have been developed that fully assist stepping by imposing forces that continually move the limbs through the step cycle (Colombo et al. 2000; Hesse et al. 2000). Recently, questions have been raised regarding the effectiveness of robotic devices for BWSTT (Swinnen et al. 2010). Although robotic-assisted BWSTT has been shown to improve locomotor recovery (Wirz et al. 2005), it is not clear whether robotic-assisted BWSTT, which moved the legs in a stepping pattern, was better than or as good as manually assisted (i.e., therapist-based) BWSTT. The findings of studies comparing robotic-assisted BWSTT with manually assisted BWSTT have varied. Some results indicated that manually assisted BWSTT was superior to robotic-assisted BWSTT (Hornby et al. 2008). Other results indicated that robotic-based BWSTT was better (Westlake and Patten 2009), whereas other findings indicated that there was no difference in the effects of either type of assistance on stepping recovery (Noorijen et al. 2009).

A central question in the robotic vs. manual-assistance debate is which type of assistance provided the optimal conditions for learning to step. Robotic-assisted BWSTT enforced strict movement patterns in the limbs. This would be advantageous for the generation of precise patterns of sensory input that were known to be critical for learning to step after SCI (Edgerston et al. 2008). On the other hand, manually assisted BWSTT allowed greater variability in limb movements during stepping (Lewek et al. 2009). In addition, therapists adjusted the amount of assistance during BWSTT, and this encouraged greater effort to generate independent stepping (Israel et al. 2006).

Use of robotic devices for BWSTT in rodent models of SCI may shed some light on what type of assistance is best for learning. Unlike the robots used for BWSTT in humans, the rodent robots are capable of imposing flexible forces to the limbs during stepping. Cai and colleagues (2006) developed an assist-as-needed (AAN) algorithm, in which the amount of assistance applied to the hindlimbs in spinally transected mice was adjusted based on movement errors. This more closely mimicked what a human therapist provided during BWSTT and allowed variability in the stepping movements. The authors found that when robotic training was combined with pharmacological treatment, the AAN robotic training improved stepping performance in spinally transected mice more than robotic training, which moved the hindlimbs in a fixed trajectory (Cai et al. 2006). While these results suggested that the AAN robotic training was better for learning to step, the use of pharmacological treatment likely influenced the generation of stepping and possibly masked some effects that could be attributed to training (de Leon and Acosta 2006). In addition, the AAN algorithm has only been studied in spinally transected rodents. It will be important to compare AAN and full-assistance (FA) robotic training in a model of SCI that more resembles the traumatic SCIs in humans.

In the present study, we examined whether AAN robotic training was better than FA robotic training for the recovery of locomotion in spinally contused rats. An AAN, robotic-training...
algorithm similar to the one described previously (Cai et al. 2006) was used to flexibly assist stepping movements. In contrast, a second group of spinally contused rats received BWSTT, in which the hindlimbs movements were fully assisted during stepping. The findings suggested that AAN training was better for enhancing the generation of independent stepping in spinally contused rats. The findings also suggested that FA training could be useful, particularly in shaping limb trajectories during stepping. These results have important implications for understanding how robotic assistance can be best used to enhance learning during BWSTT therapy.

MATERIALS AND METHODS

Experimental design. All procedures were carried out according to the NIH guidelines and the protocols approved by the Institutional Animal Care and Use Committee at California State University, Los Angeles. Fourteen adult, female Sprague-Dawley rats (250–300 g) received electromyography (EMG) implants in their tibialis anterior (TA) and medial gastrocnemius (MG) in both hindlimbs. Two weeks later, they received a severe spinal cord contusion at the midthoracic level (T9). One week following the injury, the first testing session was conducted to measure their ability to perform weight-supported hindlimb stepping without assistance. Based on the number of steps that the rats were able to take during the baseline testing, they were distributed into two groups that received treadmill training for 5 days/wk for 4 wk. One group was trained using AAN robotic training, and the other was trained using FA robotic training. Hindlimb stepping performance was restated at the end of 2 wk and 4 wk of training. During testing, ankle movements were recorded by a robotic device, and EMG activity was acquired. These data were used to perform analyses of the kinematic characteristics of the step cycle and EMG activity.

Surgical procedures and animal care. The construction of the EMG headplug and electrodes and the surgical procedures for the implantation of the electrodes have been previously described (de Leon et al. 1994). The rats were anesthetized with isoflurane (VetEquip, Pleasanton, CA), and the skin over the skull and the hindlimb muscles were shaved and cleaned with betadine and alcohol solution. Incisions were made in the skin over the skull and the hindlimb areas above the target muscles. After the exposed surface of the skull was gently scored, and holes were carefully drilled, four small screws were placed into the skull. Dental cement was used to secure the headplug to the skull surface. The electrode wires from the headplug were passed under the skin from the skull to the right and left hindlimbs. A small, 1- to 2-mm portion of insulation was stripped from near the tip of the electrode before it was inserted into the muscle bellies of the MG and TA muscles. The skin over the vertebral column was closed with Michel clips, and the skin over the muscles was closed with ethylon sutures. Antibiotic treatment (tetracycline) was provided through the drinking water.

One week following the EMG implants, the spinal cords were contused using surgical procedures that have been previously described (Heng and de Leon 2009). Briefly, the rats were anesthetized with isoflurane (VetEquip). The skin over the vertebral column was shaved and cleaned with betadine and alcohol solution. An incision was made, and the muscle and connective tissue lying over the midthoracic vertebral area were dissected. A T9 laminectomy was performed, and the animal received a 250-kdyn contusion with the Infinite Horizon Impactor (Precision Systems and Instrumentation, Lexington, KY). The result of the 250-kdyn impact force was a severe contusion injury with recovery characterized by sweeping movements of the hindlimbs with no weight support during open-field locomotor testing (Radojicic et al. 2007; Totoiu and Keirstead 2005). The muscle and connective tissue were closed with chromic gut, and the skin was closed with Michel clips.

After all surgeries, the rats were allowed to recover on a heating pad before they were returned to their cages. Antibiotic treatment (Baytril) was given twice daily for 2 wk following the surgery. The bladders and colons were checked twice daily for the duration of the study, and if necessary, the bladder and colon were manually expressed.

Locomotor training and testing. All training and testing sessions were conducted using a robotic device (Rodent Robotic Performance System, Robomedica, Mission Viejo, CA). The robotic device has been previously described (Timoszyk et al. 2005). It has a motorized, variable-speed treadmill, two robotic arms, and a body weight support arm. The rats wore a vest that was secured to the weight-supporting arm of the robotic device. The ankles of the animals were attached to the distal ends of the robotic arms with neoprene loops that wrapped around the ankle. The animals were acclimated to the robotic system by wearing the vest during quiet, weight-supported standing on the treadmill two to three times prior to baseline testing. During testing, the ability to perform treadmill stepping at a speed of 8 cm s\(^{-1}\) was recorded for 30 s at 95% and for 30 s at 85% weight support. No robotic assistance was provided to the ankle during tests. During training, the speed of the treadmill was kept constant (8 cm s\(^{-1}\)), and 85–95% of the body weight was supported.

To train the rats, custom-made software was used to control robotic assistance delivered to the ankles as previously described (Cai et al. 2006). Briefly, a desired ankle trajectory was derived from the ankle movements recorded by the robotic device when an experienced human trainer manually assisted stepping for five consecutive step cycles (see Five recorded step cycles from trainer and Average trajectory in Fig. 1A). During training, the recorded ankle trajectories were played back in a repeating loop (Fig. 1A). To implement the FA and AAN algorithms, assistive forces were applied to the ankle whenever the ankle moved away from the desired ankle-trajectory pattern. The amount of assistance was proportional to the magnitude of the movement error multiplied by a scale factor (i.e., gain). To implement the FA training, a large scale factor was used such that the ankles were forced to follow the desired trajectories (compare Fig. 1, B with A). To implement the AAN training, a lower scale factor was used such that the amount of the assistive force was less, thereby allowing ankle movement to stray away from the trajectory (compare Fig. 1, C with A). The overall effect was that when the ankle did not move or moved little during AAN training, the robot gently guided the ankle. However, the robot did not interfere with movements when the rats generated independent stepping (Fig. 1C). In contrast, FA training moved the ankles regardless of the rats’ ability to perform steps. A single training session was completed when a rat performed 1,000 steps. Training was performed for 5 days/wk for 4 wk.

Data analyses. The arms of the robotic device recorded all ankle movements, and all information was stored on a computer for subsequent analysis. The collected data were analyzed using custom-made software, as previously described (Timoszyk et al. 2002, 2005). Briefly, toe-off (TO) and paw contact (PC) were detected based on ankle velocity. Step-length was defined as the distance between TO and PC. Step height was defined as the distance between the maximum and minimum vertical positions of the ankle during a step. Stance duration was the time between PC and TO, and swing duration was the time from TO to PC. The number of steps performed during the 30-s test of stepping at 85% weight support was determined by counting the number of steps that was >1 mm in length. We have found that this criteria distinguished successful weight-bearing steps from small-amplitude ankle movements that were not weight bearing (Heng and de Leon 2009).

To analyze ankle trajectory during stepping, the slope of the swing and stance phases was calculated for the contused rats and compared with a normal trajectory and the desired trajectory imposed during training. Robotic data recorded during 30 s of testing (85% weight support) in each contused and normal rat were used to generate scatter plots of the ankle position. During swing phase, the shape of the
trajectory could generally be characterized by two slopes: one during forward movement (see Forward swing in Fig. 4) and the second during backward movement (see Backward swing in Fig. 4). The two slopes during swing and the slope during stance were calculated by performing a least-squares linear regression on the scatter plots of the ankle position (e.g., see black lines in Fig. 4). The slopes were averaged across rats in the same group (FA, AAN, or Normal Swing). The slopes of the desired training trajectory during 30 s of training in FA rats were calculated in the same manner.

To analyze the EMG activity, the start and end of EMG bursts ($t_{on}$ and $t_{off}$, respectively) were detected using a custom-written program in MATLAB (MathWorks, Natick, MA). The envelope of EMG activity was found by rectifying raw EMG data and filtering the rectified EMG with a 36-point (20 ms) moving average filter. The user could adjust two thresholds, which were used to define EMG bursts, a positive-slope threshold, and a negative-slope threshold. Within each step cycle, the first positive-slope threshold crossing was considered the onset of an EMG burst, and the first negative-slope threshold crossing following burst onset was considered the end of the EMG burst. EMG burst duration was computed as the difference between end and start times ($\Delta = t_{off} - t_{on}$).

One-way ANOVA was used to determine significant differences between groups, and the Tukey post hoc test was used for paired comparisons. A repeated measures ANOVA was used for determining if the kinematic characteristics were significantly different over time between and within the AAN and FA groups. All statistical analyses were performed using SPSS 13.0 for Windows software.

RESULTS

Spinally contused rats that received AAN robotic training performed better hindlimb stepping than rats that received FA robotic training. We examined the effects of two types of robotic-assisted treadmill training on locomotor recovery in spinally contused rats. During training, the robot device fully assisted stepping by moving the ankles through a desired trajectory (FA training) or assisted stepping only when needed (AAN training). Figure 2 shows horizontal ankle movements in a normal rat and from spinally contused rats from the two groups. Normal rats produced consistent weight-bearing stepping, as is evident from the consistent forward and backward movements of the ankle during each step (Fig. 2A). In the spinally contused rats, a poor stepping pattern was observed during baseline testing at Week 0. Stepping movements were not generated, and the hindlimbs dragged. Assistance was necessary to move the paws forward on the treadmill belt in an attempt to initiate stepping (Fig. 2, B and D). Only small forward-stepping movements occurred as the paws moved backward with the treadmill belt (Fig. 2, B and D). By Week 4, large-amplitude stepping movements were observed in both the FA and AAN groups (Fig. 2, C and E). However, more frequent stepping occurred in the AAN group than in the FA group (Fig. 2, C and E). To quantify the amount of stepping, the robotic device was used to count the number of steps performed by the rats within a 30-s test (Fig. 2F).

Ankle trajectories during stepping in representative normal and spinally contused rats are shown in Fig. 3. In normal rats, the ankle moved in a trajectory that resembled a semicircle (Fig. 3A). The overall size of the stepping trajectories in the spinally contused rats tended to be smaller than normal. The ankle trajectory in the AAN group had similar length but was flatter than the normal trajectory, indicating less elevation of the ankle during swing (Fig. 3, B and A). The ankle trajectory in the FA group was shorter than normal and appeared to have...
The data shown were recorded during 8 s of testing. B and D: testing at Week 0 (baseline test performed 1 wk after spinal contusion); C and E: testing at Week 4 (i.e., following 4 wk of training) from the same rats as in B and D, respectively. B and D: the thick, black lines indicate that the trainer moved the hindlimbs forward to help initiate stepping. A–E: the dots indicate steps detected by the robotic device. All data are from tests of stepping at 8 cm s\(^{-1}\), with the robotic device supporting 85% of the body weight and without any assistance to move the ankle. F: number of steps in normal rats (Δ) and in the AAN (●) and FA (□) rats during Weeks 0, 2, and 4 testing. The number of steps was measured during 30 s of testing at 8 cm s\(^{-1}\), with the robotic device supporting 85% of the body weight. At Week 0, the AAN and FA groups performed significantly fewer steps than the Normal group (compare Week 0 with Δ; one-way ANOVA; \(P < 0.05\)). The number of steps in the AAN group increased from Weeks 0 to 4 and was similar to the number of steps taken by normal rats (compare Weeks 0 and 4 Δ; within subject effect of week; \(P < 0.05\)). In contrast, the FA group did not show any improvement in its ability to take more steps over time (compare Weeks 0 and 4 □; within subject effect of week; \(P = 0.76\)). By Week 4, the number of steps was significantly different among the Normal, FA, and AAN groups (one-way ANOVA; \(P < 0.01\)). The AAN group performed significantly more steps than the FA group (compare Week 4 □ and △; \(P < 0.01\)). The FA group performed a fewer number of steps than the Normal group, but this difference only approached significance (compare Week 4 □ with Δ; Tukey post hoc test; \(P = 0.07\)). *Significantly different (\(P < 0.01\)); #significantly different than Normal (\(P < 0.05\)). Data are average values ± SE.

A triangular shape (compare Fig. 3, C and A). Kinematic analyses confirmed that step trajectories were significantly smaller in the contused rats. In the FA group, stance duration, swing duration, step length, and height were 54%, 70%, 65%, and 62%, respectively, of Normal (Fig. 3E). Likewise, stance duration, swing duration, and step height in the AAN group were 63%, 76%, and 70% of Normal (Fig. 3D). The one exception was step length in the AAN group, which reached 104% of normal values (Fig. 3D). Step length in the AAN group was also significantly greater than step length in the FA group (Fig. 3F; one-way ANOVA; \(P < 0.01\)).

We next compared ankle trajectories during the swing phase of stepping. Figure 4 shows the ankle trajectory during the swing phase of two-step cycles in Normal, AAN, and FA rats at Week 4. Following TO, the ankle in the normal rat moved forward and slightly downward (Fig. 4A). This was followed by backward movement in the ankle prior to PC (Fig. 4A). The ankle movement in the AAN rat resembled the Normal pattern (compare Fig. 4, A and B). In particular, the ankle moved forward with little overall change in vertical position and then backward to PC (Fig. 4B). In contrast, there was a noticeable rise in the ankle of the FA rat during forward movement (Fig. 4C). This resembled the desired ankle trajectory that was imposed during FA training (compare Fig. 4, C and D). The slope of the ankle trajectory during the forward and backward phases of swing was calculated for each rat. The slopes were calculated from ankle position data collected during 30 s of testing for each rat (85% weight support). The average slopes for each group are shown in Fig. 4E.

Greater ankle muscle EMG activity resulted from AAN robotic training. EMG from the TA and MG muscles in representative rats from the AAN and FA groups is shown in Fig. 5. There was more consistent and more frequent muscle activity in the AAN group than in the FA group, evident in the EMG-bursting patterns (compare Fig. 5, A with B). The TA and MG EMG bursts were appropriately timed with the step cycle in the AAN group. TA bursts occurred during swing, whereas MG bursts occurred during stance (see EMG bursts during swing; Fig. 5B). In contrast, EMG bursts did not consistently occur in the FA group. For example, TA bursts were not observed during each swing phase (see swing, Fig. 5A).

Analyses of EMG bursts showed that a significantly greater number of TA and MG EMG bursts were generated in the AAN group than in the FA group during testing (Fig. 5C; one-way ANOVA; \(P < 0.05\)). The duration of EMG bursts in the MG was significantly longer in the AAN than in the FA group (Fig. 5D; one-way ANOVA; \(P < 0.05\)). In the AAN group, the MG was active during a significantly greater portion of the step cycle than in the FA group (Fig. 5E; one-way ANOVA; \(P < 0.05\)). TA EMG burst characteristics (Burst duration, On time) were not significantly different between the groups (Fig. 5, D and E).

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In the present study, we demonstrated that robotic training, which provided assistance on an as-needed basis during BWSTT, resulted in greater locomotor recovery in spinally contused rats compared with robotic training, which provided full assistance to the hindlimbs during stepping. AAN training increased the number of steps, enhanced EMG burst activity, and resulted in more normal step-cycle kinematic characteristics and trajectory shape. Although FA robotic training was less successful in improving stepping performance, imposing a rigid trajectory did appear to influence the shape of the step-cycle trajectories, in particular, the trajectory during forward swing. These findings suggested that robotic-assisted BWSTT, which facilitated the generation of independent stepping rather than guiding limb movements, was best for learning to step following SCI.

Robotic training and motor learning. From a motor-learning perspective, it is perhaps not surprising that AAN robotic training was better in improving the generation of stepping than FA training. Constant physical guidance during movement can hinder task learning. The problem is that a reliance on physical guidance develops such that when the external assistance is no longer provided, performance of the task is poor (Schmidt and Wrisberg 2004). In the context of learning to step, the rats that trained with full assistance became reliant on the constant robotic assistance and did not learn to generate stepping on their own. AAN training was more likely to encourage independent movement. This was because less assistive force was delivered during training, thereby allowing the nervous system to generate step-cycle trajectories that were markedly different than the desired trajectory.

Differences in stepping between the AAN and FA groups may have been related to how much the rats participated in the generation of hindlimb movements during training. Motor training that involved active participation in the production of movements has been shown to be more effective for task learning than training that consisted of passive limb movements (Kaelin-Lang et al. 2005; Lotze et al. 2003). Robotic assistance that moved the legs of SCI subjects during BWSTT resulted in less energy expenditure relative to therapist-assisted BWSTT (Israel et al. 2006). This indicated that the subjects exerted less effort to move their legs when robotic assistance was provided. The reduced effort may be related to a “slack” theory regarding how the nervous system interacted with robotic assistance (Emken et al. 2007). According to this theory, the nervous system tended to minimize its contribution to movement production if external assistance were provided. One possibility was that because the robots did all of the work during FA training, less effort was required, and the rats could simply “go along for the ride”. Cai and colleagues (2006) hypothesized that forcing the limbs to move in rigid trajectories may result in a habituation effect and might even instill a kind of “learned helplessness” in which the rats stop responding to the training.

Another factor in determining the success of robotic-assisted training may be related to how much variability in stepping movements occurs during training. Allowing variation during the task performance facilitates learning of a motor task. A recent clinical study reported that the coordination of hip and knee movements was improved by therapist-based training, which consisted of more varied leg movements than fixed, robot-enforced leg movements (Lewek et al. 2009). The authors concluded that the therapist-based training was best, because it allowed the nervous system to explore various movement solutions, and this was critical for teaching the nervous system how to generate the most effective stepping patterns. A slightly different perspective on the importance of variability was recently provided by Ziegler and colleagues (2010), who examined stepping and EMG activity patterns in spinally transected rats during robotic-assisted BWSTT. They postulated that a
certain amount of variation or “noise” in the system was crucial and played an important role in the strengthening of synaptic connections with the spinal cord circuitry. Moving the limbs in a fixed pattern prevented the expression of the intrinsic variation in stepping and ultimately interfered with learning.

We can only speculate as to how FA and AAN training affected the recovery observed in the spinally contused rats. Certainly, imposing the FA training reduced the variability in stepping movements, whereas greater variability in stepping occurred with AAN training (see Fig. 1). It was also possible that AAN training reinforced the independent generation of movements, whereas FA training resulted in less-active involvement in movement production (i.e., habituation). Recent evidence suggested that when robots fully assisted hindlimb stepping in spinally transected rats, hindlimb muscle activity was elicited (Ziegler et al. 2010). This activity, however, was not organized and often included coactivation of flexor and extensor motor pools. These findings suggested that FA training did not result in the habituation of motor responses. Rather, FA training was detrimental for learning, because it elicited perturbations that interfered with the expression of meaningful stepping movements (Ziegler et al. 2010). The advantage of the AAN training was that unlike FA training, it facilitated the generation of appropriate sensorimotor cues that were important for locomotion.

Fig. 4. Ankle trajectories during the swing phase of 2-step cycles are shown in Normal (A), AAN (B), and FA rats (C) rats. The Desired Swing trajectory during training is also shown (D). Forward and backward movements of the ankle are indicated by the yellow and white lines, respectively. A line through the data points collected during forward and backward swing and stance was drawn (for example, see black line), and the slope through the line was calculated. E: the average slopes are shown. These average slopes were generated from data collected during 30 s of testing (85%) for each rat in the Normal, AAN, and FA groups. The desired average slope is from data collected during 30 s of training for rats in the FA group. The forward swing slope was not significantly different between the AAN and Normal groups (compare AAN and Normal, Forward swing). In contrast, the slope of forward swing in the FA group was significantly different than the Normal and AAN groups (compare FA vs. Normal and AAN, Forward swing; Tukey post hoc test; P < 0.05). The slope of the trajectory in the FA group was similar to the slope of the desired trajectory imposed during training (compare FA and Desired, Forward swing). Similar analyses showed that the slopes of the backward phase of swing were positive in all of the groups, and no significant differences were found (see Backward swing). The slope of the ankle movement during stance was also analyzed, and significant differences were found between the Normal and the FA and AAN groups (see Stance). This indicated that greater ankle extension occurred during stance in the normal rats compared with the spinally contused rats. The stance slope of the Desired trajectory was also significantly different than the Normal stance slope (compare Normal and Desired, Stance). *Significantly different than Normal (P < 0.01); #significantly different than FA (P < 0.01). Data are average values ± SE.
Influence of imposed trajectory on stepping. The results depicted in Fig. 4 implied that FA rats would largely take on the shape of the swing trajectory imposed during training. This finding suggested that the rats learned the movement pattern that was enforced. Sensory input from the hindlimbs drives plasticity within the spinal cord circuitry (Edgerton et al. 2008). It was possible that imposing the desired trajectory generated a flow of sensory input that selectively activated specific sensorimotor pathways controlling the hindlimbs. The result of repetitively imposing a movement pattern would be that specific synapses within the spinal cord circuitry were strengthened. In this sense, FA training would be advantageous, because it ensured that precise patterns of proprioceptive and mechanoreceptive sensory input were generated during training.

Given the influence of the desired trajectory, an important consideration will be the choice of movements imposed during robotic training. In human studies, the movements imposed on the legs were patterned after normal leg movements during stepping (Westlake and Patten 2009). This was a logical strategy given that the goal of therapy typically was to recover normal locomotor function. Our approach instead was to develop a desired trajectory that was based on the ankle movements imposed by an experienced trainer. Other rodent robotic studies have used a similar trainer-based strategy for developing the desired trajectory (Cai et al. 2006).

This desired trajectory used in the present study was clearly different than the normal trajectory. This raised the question: Did imposing an abnormal stepping pattern cause the inferior stepping and EMG characteristics observed in the FA rats? Although we cannot rule out this possibility, we feel it was unlikely that imposing a normal trajectory during training would have been better. We found in pilot studies that imposing a normal trajectory did not move the ankle effectively, causing paw dragging and dorsal stepping. In this case, inappropriate sensory cues would have been generated, thereby interfering with stepping. Likewise, a normal kinematic pattern may not be best for adjusting other biomechanical factors crucial for functional stepping in SCI rats, such as ground reaction forces on the limbs and the motion of the center of pressure (Giszter et al. 2010). These findings illustrate the importance of determining the optimal kinematic and kinetic patterns and not necessarily relying on assistance that enforces normal stepping movements. The challenge will be to identify the robotic assistance parameters that facilitate the expression of new gait patterns acquired after SCI (de Leon et al. 1998).

Clinical implications. Given the physically demanding nature of implementing BWSTT, there is a great potential for robotic devices to facilitate BWSTT. Robotic assistance that moves the limbs can be helpful, particularly in cases where there is little voluntary movement in the legs, and fully assisting movements is necessary. This type of robotic assistance, however, does not appear to be as effective as therapist-based BWSTT for enhancing the recovery of independently generated locomotion in patients with residual motor function or after some motor function has been regained. If robotic-assisted BWSTT is to be successful, new robotic assistance algorithms that facilitate the implementation of BWSTT but more closely mimic the actions of a human therapist will need to be developed. The present findings, along with the results from another previous study (Cai et al. 2006), suggest that robotic assistance, which guides limb movements based on errors, was effective for improving locomotor recovery in SCI rodents. One advantage of this type of “smart” robotic assistance is that the amount of assistance would automatically adjust to an individual’s movement capabilities. Thus greater assistance would be provided during the early stages of recovery when little to no independent movement is generated. As stepping improves, the robotic assistance would be adjusted such that less assistance was provided, thereby encouraging independent movement. The use of an AAN robotic training algorithm would facilitate this strategy, and the “gain” of the

Fig. 5. Electromyography (EMG) data recorded during 5 s of testing in spinally contused rats. EMG data from the tibialis anterior (TA; red) and medial gastrocnemius (MG) muscles (blue) are shown for 1 FA rat (A) and 1 AAN rat (B). The dashed line is the ankle movement recorded by the robotic device; black arrows are TO (black to white arrows represent swing); white arrows are PC (white to black arrows represent stance). A and B: the calibration bar is 30 mm for the ankle movement and 2 mV for EMG bursts. Plots are shown of average burst number (C), burst duration (D), and on time (E) for the MG and TA in AAN and FA groups. On time was calculated by dividing burst duration by cycle period (×100%). Average ± SE are shown in the plots. *Significantly different than AAN (P < 0.05).
algorithm could be adjusted to more finely tune assistance for individuals.

Algorithms that can provide flexible robotic assistance during BWSTT have already been developed, and preliminary testing has been performed (Aoyagi et al. 2007; Duschau-Wicke et al. 2010). The next important step will be to understand how to use flexible-assistance algorithms to facilitate weight-supported treadmill training while also maximizing its effects on stepping.

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GRANTS

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

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