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Comparison of virtual and physical treadmill environments for training stepping after spinal cord injury

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SUMMARY

We are developing robotic devices for locomotion training after spinal cord injury. In this paper, we compare two approaches to controlling and quantifying bipedal stepping of spinal rats with robots. In the first approach, the rats stepped on a physical treadmill with robot arms attached to their lower shanks. In the second, the rats stepped on a virtual treadmill generated by the robots. The rats could step on the virtual treadmill, but stepping was more consistent, step height greater, and interlimb coordination improved on the physical treadmill. Implications for the role of sensory input in the control of locomotion and the design robotic of step trainers are discussed.

KEYWORDS: Treadmill environments; Stepping training; Spinal cord injury; Robotic devices.

1. INTRODUCTION

In the U.S. alone, over 10,000 people experience a traumatic spinal cord injury each year, and over 200,000 people with spinal cord injury are alive.[1] Paralysis of the legs is a common consequence of spinal cord injury, resulting in loss of walking ability. Recently, a new approach to rehabilitation called “body weight supported locomotor training” has shown promise.[2–13] The technique involves suspending a spinal cord injured subject in a harness above a treadmill and manually assisting movement of the legs in a walking pattern. The goal of this technique is to enhance residual locomotor control circuitry that resides in the spinal cord. It is hypothesized that by providing appropriate sensory input (i.e. that associated with the force, position, and touch sensors that remain in the legs) in a repetitive manner, the spinal cord will learn to generate motor output appropriate for stepping.

This training approach is supported by studies of spinal cord transected animals indicating that the spinal cord can learn a motor task without input from the brain.[14] This research showed that spinal animals are capable of generating rhythmic locomotor activity while fully bearing the weight of their hindquarters. Spinal cats that do not receive treadmill training, generally recover only 25% of the stepping capability that trained cats acquire.[15,16] When training is not maintained for several weeks, stepping ability declines, further demonstrating the use-dependent acquisition of stepping.[17]

Clinical use of body weight supported locomotor training with humans is increasing,[18] while research into the neurophysiological bases of locomotor training with animal models such as the spinal rat is also accelerating. A current limitation in both human and animal application of this training, however, is the poor experimental control of the quality of the step training. Quantification of the motor patterns as well as provision of the sensory input required for effective stepping is difficult to achieve using the current therapist dependent approach. For example, in locomotor training spinally injured humans, three therapists are often needed for each patient, one to manipulate each leg and one to stabilize the hips. The required patterns and amplitudes of forces applied by the therapists are just beginning to be quantified,[19,20] Manual assistance of the limbs of a rat during treadmill training is even more difficult to achieve and poorly understood, in part because manipulating small limbs cannot be performed in a consistent manner.

Recently there has been increasing interest in bringing advances in robotic and mechatronic technology to bear on rehabilitation training.[21] Initial research has focused primarily on devices for providing therapy to the affected arm after stroke since stroke is a leading cause of disability in industrialized nations, and arm impairment after stroke is common. However, locomotor training after spinal cord injury also provides an intriguing target for robotic technology.[19,20,24–27] Specifically, robotic technology could improve experimental control during locomotor training, thus providing a means to better understand and optimize its effects. Robotic technology could also provide a means to quantify in real-time the kinematics and kinetics of stepping. Ultimately, robotics could also provide a means to both automate and monitor locomotor training in the clinic, reducing its cost and increasing its availability.

The work reported here is a step toward developing a robotic, locomotor training device for rats. We are developing a device for rats for three reasons. First, we want to provide a tool that will enhance the basic research capability in the animal model. Second, development of a rat stepper is likely to provide useful data for development of a device for humans. We want to use the rat robot as a small-scale, well-controlled test-bed for evaluating the physiological and engineering principles to be used in a robotic step-trainer for

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spinal cord injured humans. Third, the benefits of robotic technology may also extend to other repair strategies such as regeneration and cell transplants. For example, it is possible that precisely controlled patterns of sensory input could provide a "directional" guide for regenerating fibers, so that the appropriate target neurons would be more likely not only to develop new connections, but also to make appropriate functional connections. Novel regeneration therapies intended for coupling with locomotor training tested first in animal models such as the rat are likely to significantly facilitate the development of such strategies for humans.

The specific goal of the work reported here was to evaluate two approaches to controlling and quantifying rat locomotion with robots. These approaches were (Figure 1):

(a) **Physical Treadmill Configuration**, in which the robots were integrated with an existing treadmill. In this approach, the robots were attached above the paws, so that the rat could place its paws on the treadmill. This approach is similar to that currently used in human training, in which therapists grasp the patient's lower legs and assist them in stance and swing.

(b) **Virtual Treadmill Configuration**, in which the robots were attached to the paws and generated the sensation of a treadmill through haptic simulation. This approach has been used for haptic interfaces for simulating human locomotion,[28] and is comparable to human exercise devices that attach to the bottom of the feet and move the feet in step-like trajectories.[29]

We have demonstrated previously that spinal rats can step on a virtual treadmill generated by robotic arms.[30] This previous research was motivated by three advantages that the virtual treadmill configuration offers. These are: (1) elimination of the need for a physical treadmill, thereby reducing the amount of required hardware, (2) provision of a means to directly quantify the contact forces against the foot, via knowledge of the robot actuator forces during stance, and (3) allowance of arbitrary variation of the simulated treadmill properties (e.g., surface shape, velocity profile, friction, stiffness), facilitating exploration of their effects on step training. However, it remains unclear whether the rat's spinal cord can interpret sensory information provided in a virtual environment in a way that facilitates stepping as well as in the corresponding physical environment. The purpose of the present study was thus to rigorously compare virtual and physical treadmill stepping.

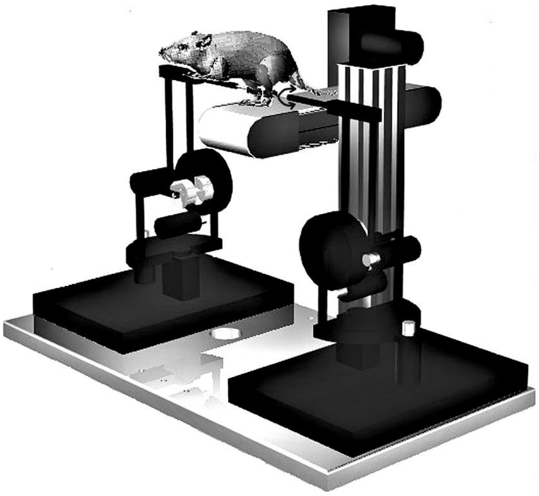

Fig. 1. The physical treadmill configuration. The rat was held manually during stepping over a conveyor-type treadmill, and a robot was attached to each lower shank. Note the rotational degree-of-freedom indicated at the end-effector. The virtual treadmill configuration was similar, but with the conveyor removed and the robots attached to the rat's metatarsus.

Toward this end, we quantified stepping of four spinal-transected rats in both configurations. Our results confirm that spinal transected rats can generate the motor output sufficient to perform bipedal stepping with robots attached to their hindlimbs. The results also confirm that stepping can be performed on a virtual treadmill generated by the robots. However, stepping is more consistent using the physical treadmill approach. The variation in performance is likely due to differences in sensory information provided through the paws during stepping for each configuration.

2. METHODS

2.1. *Description of the rats*

Experiments were performed with four rats completely transected at the mid-thoracic level as described previously in cats.[15] Transections were performed five days after birth, as a more robust recovery of stepping occurs when transections are performed shortly after birth. The transected, rat pups were returned to their mothers until they reached 21 days of age. The rats were then trained 2–3 times a week for 5–10 minutes per day to perform bipedal, hindlimb stepping on a physical treadmill. Training consisted of manually holding the rats above a treadmill to allow a sufficient amount of loading on the hindlimbs. At the time of the experiments reported here, the rats were two months old, and could perform alternating, weight-bearing hindlimb stepping on a physical treadmill. However, the rats sometimes failed to initiate swing or dragged their toes during swing. All experiments followed the guidelines of the Animal Use Committee at UCLA.

2.2. *Description of the robots*

Two commercially available robotic arms were chosen to control and quantify the movement of the rats' hindlimbs during stepping. The robotic arms were PHANToM 1.0 haptic interfaces (SensAble Technologies, Inc), which are small, cable-driven, mechanical linkages that provide high fidelity, three degrees-of-freedom force control. These devices were primarily designed to provide a sense of touch in the manipulation and deformation of computer generated 3-D objects with the hand and fingers. However, the high fidelity of their actuation and sensing, coupled with their low inertia (approximately 75 gm) and friction (approximately 14 gm), made them attractive as off-the-shelf manipulators for the rat hindlimb. Additionally, the robots have a software development kit, the General Haptic Open Software Toolkit (GHOST SDK 2.1), which allowed for the programming of a variety of virtual objects, as well as direct specification of motor forces.

To interface to the rat hindlimbs, a custom end-effector was created for the robots consisting of an alligator clip attached to a single degree-of-freedom revolute joint. The alligator clips were used to attach the robots to small cuffs placed around either the rat's lower shank or paw, as described below. The rotation axis of the revolute joint was co-linear with the distal link of the robot, allowing rotation of the rat's hindlimb in the saggital plane (Figure 1).

2.3. *Physical treadmill configuration*

For the physical treadmill configuration, the rat stepped on a conveyor belt (MK Automation Engineering 2000 Series Flat Belt Conveyor) with the robots attached to the lower shank (Figure 1). The lower shank attachment was achieved using small cuffs manufactured from nylon cable loop straps and padded with foam to provide a secure, non-irritating fit. The cuffs were placed around the lower shank then attached to the robots through the revolute joint using the alligator clips.

2.4. *Virtual treadmill configuration*

The PHANToM robots were programmed to emulate a virtual treadmill by creating a virtual block (using the Ghost SDK) moving in the horizontal plane at a constant velocity. The "virtual block" enforced a one-sided spring-damper equation normal to the surface of the block to haptically simulate the presence of a solid object. The virtual treadmill block's stiffness and damping in the vertical plane was set to 1.0 N/mm to 0.005 N/m/s. The surface friction of the treadmill was made infinite with a position-dependent velocity controller so that when the hindlimb extended at or below the plane of the virtual treadmill, the robot moved the limb backwards in a straight line under velocity control. A software option was added in which a virtual, vertical, planar constraint could be installed for each hindlimb so that the hindlimbs were restricted to preset saggital planes and could not mechanically interfere with each other.

The virtual treadmill was initially evaluated with the robots attached to the rat's hindlimb at three locations: the toes, the metatarsus, and the lower shank[30] (Figure 2). Attachment to the toes was made by taping the toes to small, plastic platforms placed on the bottom of the paw. The plastic platforms were then attached directly to the robot (i.e. not through the revolute joint). Attachment to the metatarsus and lower shank was achieved using the same small cuffs as for the physical treadmill. It was found that stepping was difficult to elicit with the toe or lower shank attachment locations, but that the rats could step with the robots attached at the metatarsus. The data presented here are thus with metatarsal attachment.

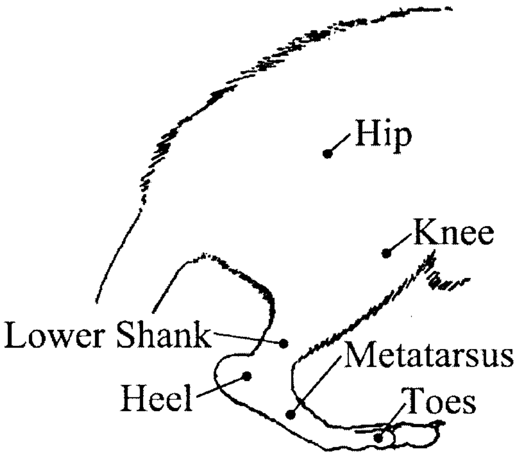

Fig. 2. The rat hindlimb. The robots were attached to the lower shank when stepping on the physical treadmill. During virtual stepping, the robots were attached to the metatarsus, which yielded more consistent stepping than attaching to the toes or lower shank.

2.5. *Experimental protocol and data collection*

To evaluate the quality of stepping on the two treadmill configurations, an experienced animal trainer manually held the rat's torso such that the feet contacted the (virtual or physical) treadmill surface. Treadmill speed was set to 0.1 m/s. For both treadmills, the trainer manually adjusted torso orientation and hindlimb loading in order to induce stepping. A one-minute stepping bout was recorded. For the virtual treadmill, stepping was quantified with and without vertical planar constraints. It was found that the constraints reduced mechanical interference between the hindlimbs that interrupted stepping, and thus the data presented are those with the vertical, planar constraints active. Limb crossing was not as prevalent with the physical treadmill, and the planar constraint was not used during the physical treadmill testing. For each robot under each configuration, the 3-D endpoint positions and motor forces (i.e. the motor torques transformed to a spatial coordinate frame at the robot endpoint) were sampled at 100 Hz and stored on a PC.

2.6. *Data analysis*

The position trajectories of the robot end-effectors were analyzed to compare the quality of stepping in the two treadmill configurations. To quantify the periodicity of stepping, the power spectrums of the vertical position trajectories of both limbs during stepping were estimated using the Welch method of spectral estimation.[31] To quantify interlimb phasing during stepping, the position trajectories of the two limbs were cross-correlated. Both the vertical and horizontal interlimb positions were correlated. Before correlation, the position data were filtered with a 9th order Butterworth low-pass filter with a cutoff of 2.5 Hz (roughly twice the primary stepping frequency, as determined by the power spectral analysis).

Individual step height and stride lengths were calculated using the following algorithm. Stepping was assumed to yield a periodic vertical position trajectory where each period was analogous to one step. To find these periods, the vertical trajectories were low-pass filtered with the Butterworth filter at a cutoff frequency of 2.5 Hz, and the local maxima were located by searching for zero crossings (from positive to negative) in the corresponding velocity trajectory. An individual step was defined to occur between each of these peaks. The difference between the maximum and minimum value of the horizontal and vertical trajectories during one step period was defined as the step height and stride length of each step, respectively. Identified steps that had step heights smaller than an arbitrary cutoff of 5 mm or

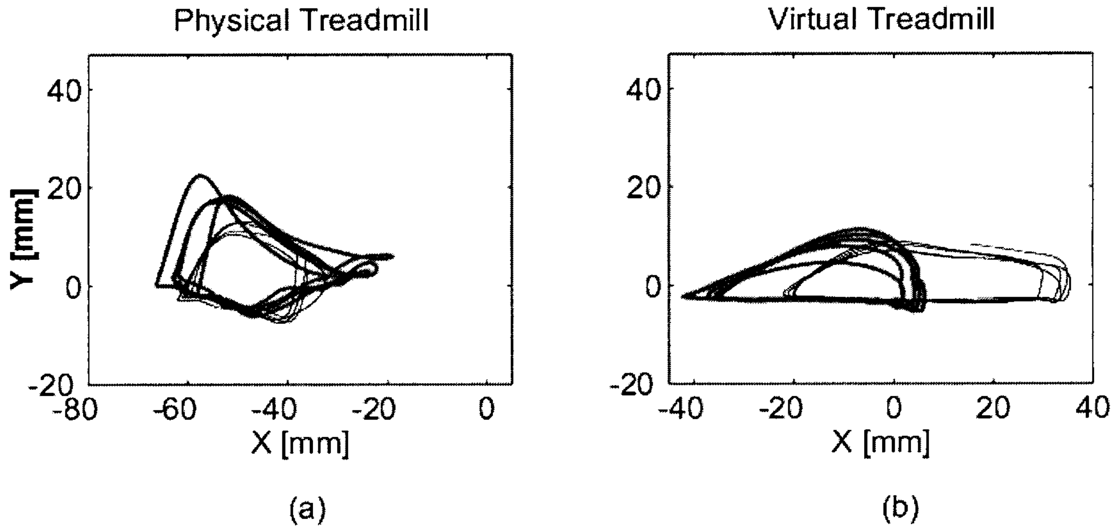

Fig. 3. Robot end-effector movement of left limb (thick line) and right limb (thin line) in the saggital plane during stepping on the: (a) physical treadmill, and (b) virtual treadmill. Both treadmills moved to the left (-X direction) at 10 cm/sec.

stride lengths smaller than 10 mm were discarded. The mean and standard deviation of stride length and step height of all steps taken by all rats on the virtual and physical treadmills, respectively, were calculated and compared using t-tests.

3. RESULTS

We quantified bipedal stepping performed by four spinal transected rats with small robots attached to their hindlimbs. Two configurations were compared (Figure 1). For the physical treadmill configuration, the passive robots were attached at the lower shank and were moved passively by the hindlimbs as the rat stepped on a treadmill. In the virtual treadmill configuration, the robots were attached at the metatarsus, and the rats stepped on a haptically simulated treadmill.

All four rats achieved some degree of rhythmic stepping in both configurations. Examples of hindlimb trajectories for the physical and virtual configurations are shown in Figures 3 and 4 in which the hindlimb trajectories in both the horizontal and vertical directions exhibited rhythmic movement. The average amplitudes of this movement were approximately 3.0–4.0 and 1.5–2.5 cm in each direction, respectively (Figure 5). These results indicate that the spinal

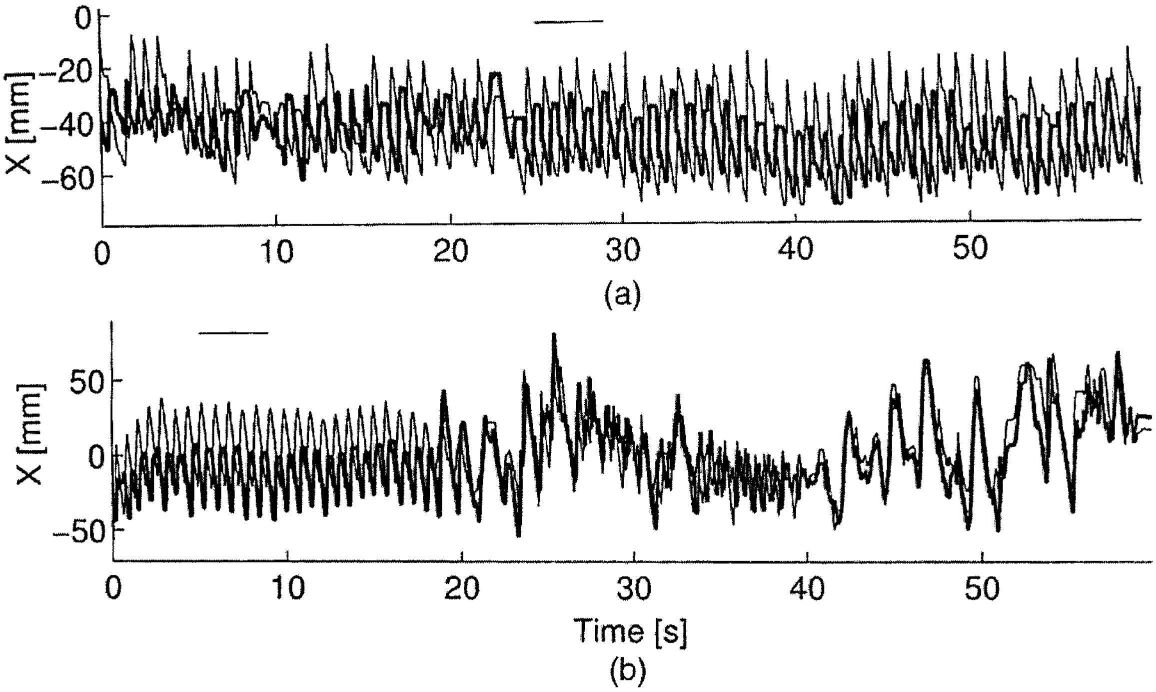

Fig. 4. End-effector movement of left limb (thick line) and right limb (thin line) during stepping on: (a) the physical treadmill, and (b) the virtual treadmill. Stepping on the physical treadmill yielded more consistent, alternating-limb stepping for longer periods than on the virtual treadmill. Note the change from alternating stepping to hopping at 19 seconds on the virtual treadmill position trajectories. Unlike the physical treadmill, the virtual treadmill measured the forces required to support the rat during stance. The bars indicate the sequences shown in Figure 3.

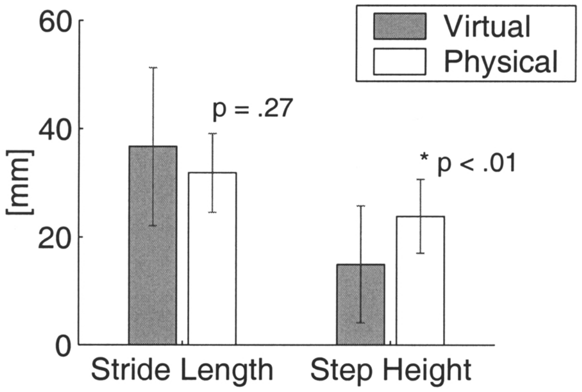

Fig. 5. Average and standard deviations of stride lengths and step heights for both hindlimbs for all steps taken by all four rats on the virtual and physical treadmills. Significance levels from a t-test are shown, indicating that step height was significantly higher for physical treadmill stepping.

rat hindlimbs were able to overcome an inertia of 75 g in the horizontal plane (about one-third of body mass) and friction (14 g) added by the robots in order to step repetitively.

Although stepping was possible in the virtual treadmill configuration, it was generally more consistent and better sustained in the physical treadmill configuration. The power spectrums of the vertical limb trajectories of each leg exhibited larger and more sharply tuned peaks at the step frequency for the physical but not the virtual treadmill (Figure 6). Sharper spectral peaks are consistent with more uniformly maintained, periodic stepping. Individual step heights were also significantly greater on the physical treadmill than the virtual treadmill, although stride lengths were not significantly different (Figure 5).

Interlimb coordination was also controlled differently in the physical and virtual treadmill configurations. For three of four rats, correlations of hindlimb positions between limbs were more negative for the physical treadmill and more positive for the virtual treadmill (Figure 7). The fourth rat (Rat #3) stepped the least consistently in both the physical and virtual treadmill configurations (Figure 6). Negative correlations are consistent with alternating stepping, while positive correlations are consistent with more symmetrical or hopping-like gait in which the two limbs move in phase. An example of a transition from alternating to in-phase stepping on the virtual treadmill can be seen in Figure 4b at about 19 sec.

In the physical treadmill configuration, the robots measured only the hindlimb trajectories, while in the virtual

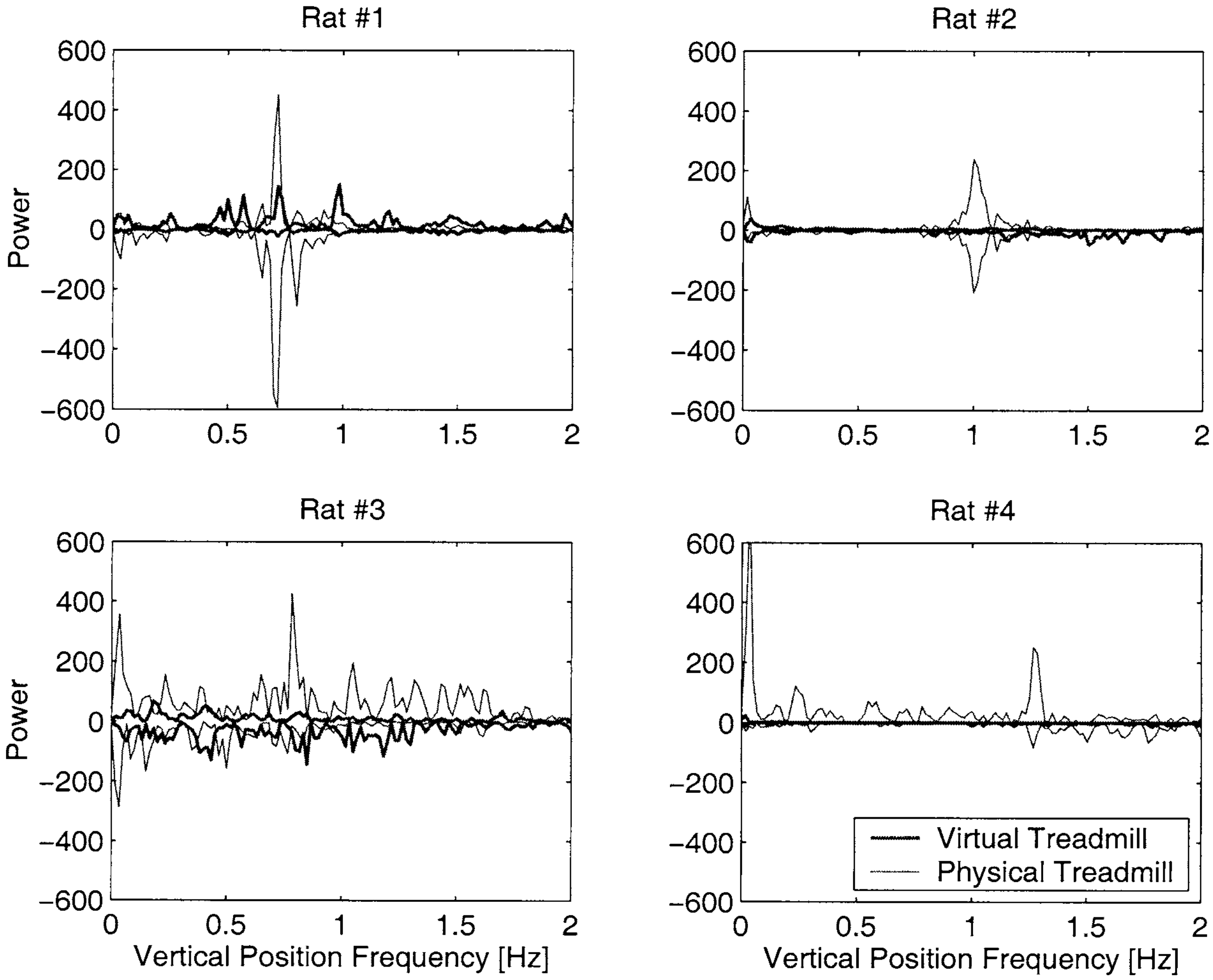

Fig. 6. Estimate of the power spectral densities of the vertical stepping trajectory (Y-direction) signals while stepping on the physical and virtual treadmills. The spectrums in the negative range indicate left hindlimb trajectories. Note the larger and more sharply tuned peaks in the stepping frequency range (~0.5–1.5 Hz) for the physical treadmill. Lesser peaks at these frequencies exist for virtual stepping by all rats.

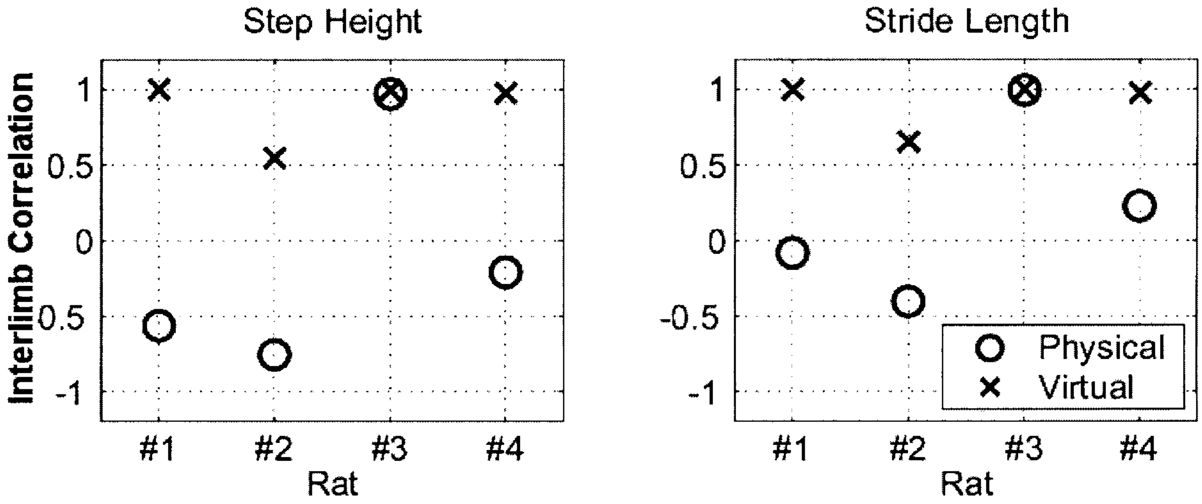

Fig. 7. Normalized correlations between left and right hindlimb trajectories during stepping on two treadmill configurations. Generally, correlations were more negative for the physical treadmill and more positive for the virtual treadmill, indicating a more alternating-type gait on the physical treadmill.

treadmill configuration, the robots measured the hindlimb trajectories and virtual treadmill, vertical reaction forces, i.e. the motor forces required to support the hindlimbs during stance. The peak single-limb reaction forces (excluding the initial paw-treadmill contact transient) for the rat that stepped best on the virtual treadmill (Rat #2) were approximately 50 g, or roughly 25% of the rat's total body weight.

4. DISCUSSION

These results confirm our previous result[30] that spinal transected rats are able to step with robots attached to their hindlimbs. Thus, it is feasible to quantify and control spinal rat locomotion with robotic technology. The results also confirm that spinal transected rats can step in a virtual treadmill environment created with robots. Thus, it is also possible to use haptic simulation to provide sensory input sufficient to generate stepping in these animals. However, the present results demonstrate that the physical treadmill configuration better facilitates stepping than the virtual configuration. Step consistency was improved and step size was greater on the physical treadmill. Furthermore, interlimb motion was more negatively correlated on the physical treadmill, consistent with a more alternating-type gait. The physical treadmill configuration thus better minimized disruptions to alternating stepping.

Three caveats with respect to the step trajectory measurements should be mentioned. First, the rats were manually held during the experiments, and their horizontal position may have varied to some degree. Changes were less likely in the vertical direction because the (physical or virtual) treadmill surface served as a constraint. However, horizontal changes may have influenced stride length calculations and may have introduced power at low frequencies in the spectral analysis (Figure 5). Second, there was some relative motion between the robot's end-effector and the rat's hindlimb in the physical treadmill configuration due to skin movement, although this movement was small because of the relatively high skin tautness at the lower shank. Third, the attachment points differed for the physical and virtual treadmill configurations (lower shank and metatarsus), and thus even identical stepping in the two environments would yield different robot end-effector trajectories. However, the hindlimb joint trajectories of the rat are such that the metatarsus moves through a greater distance horizontally and vertically than the lower shank during stepping. The joint trajectories, therefore, reinforce the observation that, when compared to virtual stepping, step height was greater for the physical treadmill and also suggest that stride length may have been larger for the physical treadmill.

4.1. Sensory input and robotic step trainers

Why did the physical treadmill result in more effective stepping? We hypothesize that sensory information provided during stance and swing is critical for generating stepping in spinal animals.[32] The physical treadmill configuration provided a normal pattern of loading during stance (since the toes were placed on an actual treadmill surface) and there was no contact forces imposed on the paws during swing (since the robots were attached at the lower shank). We further hypothesize that the improved loading during stance enhanced interlimb coordination and swing initiation, which resulted in more consistent stepping and greater swing height. In contrast, with the robots attached at the metatarsus in the virtual treadmill configuration, inappropriate sensory information was generated and interfered with the execution of swing and stance. One way to improve sensory feedback during stance loading would be to attach the robot arms to the toes rather than at the metatarsus, but we have found that toe attachment dramatically inhibits stepping.[30] The key point is that the virtual treadmill as currently conceived requires the same attachment point during stance and swing, but the required sensory input during these phases differs dramatically.

The tendency toward in-phase hopping on the virtual treadmill may be related in part to inertial loading of the metatarsus during swing by the robot. That is, the spinal cord may interpret any loading to the ventral surface of the paw during swing as stance contact, causing it to identify its current mode as bilateral stance, and to generate a symmetrical output, i.e. hopping.

The rat spinal cord was able to generate stepping while overcoming the interference created by the inertia (approximately 75 g) and friction (approximately 14 g) of the robots. An interesting direction for future research is to quantify the maximum impedances that the rat spinal cord can overcome. The ability to generate power while overcoming environmental impedance may be a valuable measure of spinal stepping recovery.

4.2. Future directions

Our ultimate goal is to assist in spinal locomotor training with the robotic system and to identify the optimal assistance algorithm and corresponding neural adaptation mechanisms for promoting locomotor recovery. To meet this goal, we are implementing current manual training techniques as robot control algorithms. In addition, we are exploring alternate training techniques not possible with the manual approach, such as the use of state-dependent force field controllers to sculpt motor output.[33] Based on the results presented here, applying forces to the hindlimbs using the physical treadmill configuration is a rational first approach for testing these training techniques. We do not rule out use of the virtual treadmill approach, however, as rats trained to step specifically on the virtual treadmill may be able to learn to step more effectively in that environment.

A disadvantage of the physical treadmill configuration is that hindlimb loading cannot be measured directly with the robots. Hindlimb loading is an important measure of stepping ability, and is useful for implementing state-dependent training algorithms because it aids in identification of the gait phase (stance, swing, bilateral stance, etc.). It may be possible to measure hindlimb loading in the physical treadmill configuration by adapting previous limb loading measurement techniques developed for treadmill locomotion.[34]

We intend for the rodent robotic system to be a small-scale, well controlled test bed for evaluating the engineering and physiological principles to be used in a robotic step-trainer for spinal cord injured humans. At a minimum, the results presented here suggest that a detailed evaluation of robot/lower limb contact locations is essential for the rational design of a step-training device for humans. Designs for human training devices and ways to interface them with the limb will need to be carefully evaluated. There is a need to identify potential disruptive sensory patterns on stepping as well as those sensory inputs that can potentiate the ability of the spinal cord to generate stepping. We have followed this approach in designing a second generation rat stepper.[35]

5. CONCLUSION

Our working perspective of the spinal cord is that it "perceives" temporal sequences of input patterns that can be used to facilitate the generation of a step. A distributed biological sensor array comprised of touch, position, and force sensors reports to the spinal cord about the limbs' physical state and environmental interactions. If the sensor array reports a specific pattern of sensory input consistent with a given phase of the step cycle, the spinal cord is able to recognize this pattern and generate physically appropriate motor output for stepping. The experiments reported here demonstrate that, even with robots attached to the hindlimbs, the spinal cord receives sensory patterns sufficient to generate stepping. Haptic simulation of the treadmill, however, degrades the sensory patterns, relative to the physical treadmill approach. Our next goal is to use the physical treadmill approach to explore how physical training can best reinforce the functional interactions between sensory input and motor output, thereby promoting stepping recovery.

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