A Robotic Device for Studying Rodent Locomotion After Spinal Cord Injury

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***Abstract*—We have developed a robotic device (the "rat stepper") for evaluating and training locomotor function of spinal cord injured rodents. This paper provides a detailed description of the device design and a characterization of its robotic performance capabilities.**

***Index Terms*—Gait analysis, locomotion, motor control, rat stepper, robotics, spinal cord injury.**

I. Introduction

RODENT models are commonly used to study spinal cord injury, yet there is currently a lack of technology for quantifying locomotor performance in these animals [1], [2]. In addition, locomotor training with controlled body weight support combined with manual assistance of leg movement is a promising technique for enhancing spinal cord plasticity and recovery following injury [3], but is difficult to implement and, thus, to study in rodent models. To address these problems, we have developed a robotic device, the *rat stepper*, for the evaluation and training of rodent locomotion. The device consists of a pair of lightweight, robotic arms that attach to rodent hindlimbs, a body weight support (BWS) device, and a motorized treadmill (Fig. 1). As the animal steps on the treadmill, the robotic arms can be used either passively to record hindlimb trajectories (similar to optical motion capture techniques), or actively to apply precisely controlled forces to assist or challenge the animal's ability to move its hindlimbs. The BWS device is used to stabilize the torso, support the front quarters, and partially unload the hindlimbs, as needed, as the rodent steps bipedally. This paper provides an overview of the device design and characterizes the device's robotic performance. Portions of this work have been reported previously in conference paper format [4].

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II. Design Principles

The design of the rat stepper is based on several principles that were identified through the development and testing of an initial prototype. This prototype consisted of a pair of commercially available robotic arms (PHANToM 1.0 haptic interfaces, Sensable Technologies), a treadmill, and a simple counter-weight BWS device [5]–[7]. The following design principles were developed using female, Spraque–Dawley rats whose spinal cords were completely transected as neonates (at postnatal day five) at a midthoracic level. With appropriate motor training, these spinal transected rats often show a robust recovery of hindlimb stepping that is mediated by spinal circuits isolated from supraspinal control, thus allowing us to determine the effects of different configurations of the robot on spinally-controlled stepping.

A. Loading Sensation Applied Only During Stance and Not During Swing More Effectively Facilitates Stepping in Spinal Cord Injured Rats

Our first approach to quantify stepping was to use the robot arms themselves to simulate a treadmill and to support the body weight of the rat during stance [5]. The robots were attached to the metatarsals with small clips, and a treadmill surface was simulated with a virtual block moving backward at a constant velocity relative to the rat. The animals were unable to achieve long bouts of stepping on this virtual treadmill, and stepping was even poorer when the robots were attached to the toes. In contrast, we found that stepping ability increased markedly when the rats stepped on a physical treadmill with the robots attached around the lower shank [Fig. 2(a)].

These results highlight the importance of considering fundamental spinal cord physiological principles in the design of robotic steppers: the rat spinal cord can generate stepping most effectively when there are specific, phase-dependent patterns of

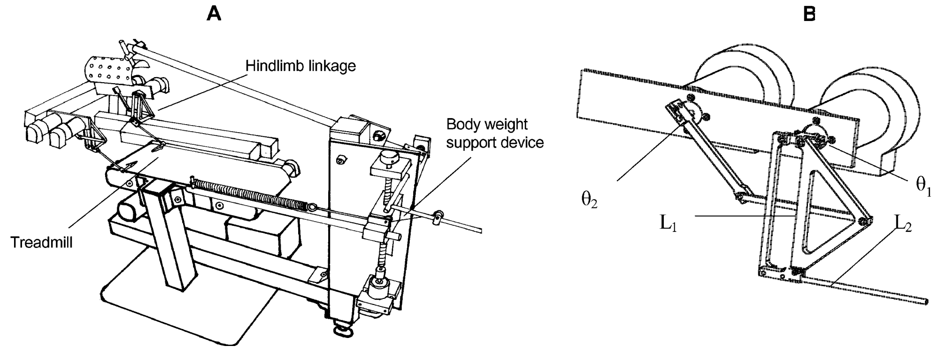


Fig. 1. (a) "Rat stepper." (b) Robotic arms incorporate two mechanically grounded motors with coupled four-bar and five-bar linkages. These robotic arms can impart forces to the animal, or simply record the trajectories of each ankle. BWS device applies forces to the animal through the deflection of a spring. The kinematic design reduces unwanted oscillation by eliminating an equilibrium point. Amount of weight support is adjustable by changing the distance of the pulley from the pivot, using a lead screw driven manually or by a motor.

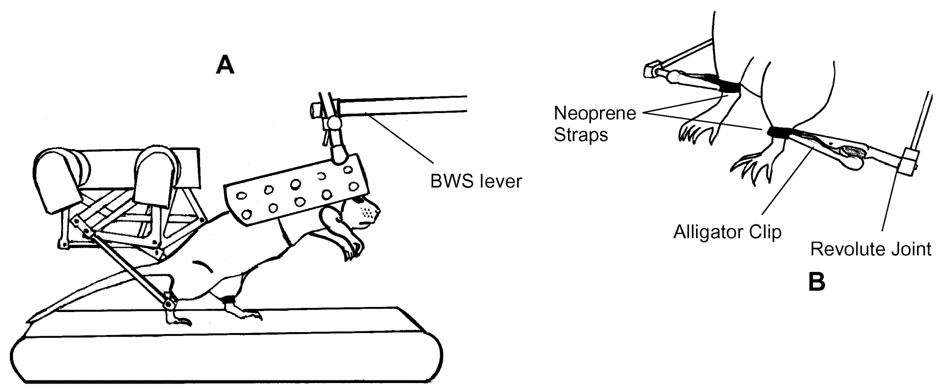


Fig. 2. (a) Rat is placed in a cloth harness and attached to the end of the body weight support device. Orientation of the rat's torso is adjustable with a lockable ball joint and the amount of weight support delivered to the animal is precisely controlled. Rat steps bipedally in the device and the small robotic arms attach to each hindlimb with neoprene straps. (b) Robotic linkages attach to the rat's hindlimb by holding together both ends of a neoprene strap with an alligator clip. Alligator clip is allowed to rotate within the parasaggittal plane of the animal.

sensory information available. For example, providing contact force through the paw with the virtual treadmill elicited limb extension, whereas contact of the robot with the paw during swing appeared to inhibit limb flexion. It appears that stepping on a physical treadmill with the robot arms attached to the shank was effective because it provided proprioceptive and cutaneous input through the paws and toes during stance, but not during swing.

B. Low Inertia and Friction Are Required for Unimpeded Stepping

The prototype design of the rat stepper made use of two commercially available PHANToM 1.0 haptic interfaces (Sensable Technologies, Woburn, MA) to apply forces to the rodent hindlimbs. These interfaces were designed to have low friction and inertia (0.29 N static backdrive friction and 75 g apparent endpoint inertia). Even these relatively low values, however, are a substantial fraction of the mass of an adult female rat (250–300 g). In initial experiments, we partially cancelled static friction and inertia in software by applying an assistive force equal to 80% of the measured static friction of the robot arms, and mechanically counterbalancing the robot arms to avoid loading the hindlimbs with their weight. However, the extent to which the backdrive impedance affected stepping remained unclear. Because friction cancellation is an inexact process that requires an accurate model of Coulumb and dynamic friction forces, it is preferable to reduce the need for this assistance by minimizing the amount of backdrive friction and inertia in the system.

To quantify the effects of viscous friction on stepping, the robots were programmed to apply an isotropic, viscous force field, and the gain of this field was ramped from −0.5 N/m/s (i.e., friction cancellation) to 23.6 N/m/s over a period of 90 s, repeated three times. Three adult (>8 weeks), Sprague–Dawley rats whose spinal cords had been transected at the midthoracic level as neonates were allowed to step on the treadmill as their limb trajectories were recorded. Relatively little change in step length and height was seen up to an average of 5 and 10 N/m/s, respectively [3]. These results indicate that the PHANToM robots have sufficiently low viscous friction so as not to noticeably impede the stepping of the rats tested. However, the devices would probably impede smaller or weaker rats.

C. A Backdrivable BWS Device With a Wide Dynamic Range Is Desirable for Studying Spinal Stepping

The ability of an untrained, spinal cord injured animal to step depends largely on the amount of body weight support provided. The prototype rat stepper used a counterweight BWS device to partially unload the hindlimbs during stepping. The amount of body weight support was adjusted by moving the counterweight relative to the pivot. Although simple, this counterweight system presented substantial inertia to the vertical motion of the rat. In addition, moving the counterweight not only changed the amount of weight support, but also the apparent inertia, possibly affecting the stepping dynamics of the animal. To reduce the inertia, the counterweight might be replaced by a spring that would pull between ground and the lever arm. However, this configuration would introduce resonance into the system dynamics. Similarly, we were unable to use a direct drive motor, as most electric motors typically have a ratio between 15 and 20 for peak continuous force to backdrive friction, thereby limiting the resolution of the system to about 5% of the weight of the rat (15 g). The ideal system should fully support a rat when needed, with little backdrive friction, low inertia, and no resonance.

III. Design of the Rat Stepper

A. Hindlimb Robots

Custom robot arms were developed to minimize backdrive friction and inertia [Fig. 1(a)]. Since the stepping motion of the hindlimbs occurs primarily in the para-sagittal planes, a planar linkage design adapted from a haptic device design by Kazerooni and Her [8] was used. The robot arms consist of mechanically grounded motors attached to a five-bar linkage and a four-bar linkage [Fig. 1(b)]. The two linkages share a common link, thereby constraining the device to planar, two degrees-of-freedom motion. An advantage of this design is that both motors are on the same side of the linkage, leaving space for rodents to be placed between two mirror-symmetric robots. Arms were developed for both the rat (workspace 7.5 by 5 cm) and the mouse (workspace 5×2.5 cm). The arms use alligator clips attached through a revolute joint to hold a neoprene strap wrapped around the lower shank of the animal [Fig. 2(b)]. Although the hindlimb robots are constrained to move within the para-sagittal planes of the animal, the neoprene strap used to attach the linkage endpoint to the animal's ankle allows for some motion (hindlimb abduction and adduction, and internal and external rotation). This small amount of "play" in the robot's workspace helps to facilitate more natural stepping, although the linkages are unable to detect any movement outside of the para-sagittal planes.

Currently, each robot arm is actuated by two direct-drive, electric motors (Faulhaber # 3557K024 CR & LC3002 motor amplifier), which provide less than 0.05-N static backdrive friction (1/6 that of the PHANToMs), while generating up to 1.47 N for the manipulation of stepping. Precision optical encoders (HEDS 5540, 2048 cts./rev.) measure the rotation of each motor with a resolution of 0.18°. The robot arms are designed to apply precisely controlled forces to rat hindlimbs for step training, but their reduced backdrive friction allows them to be used passively to measure step trajectories. Ideally, locomotor training devices should be able to provide force when needed and minimize perturbations when the animal can step or move appropriately under its own power. The forward kinematics, inverse kinematics, and Jacobian equations for the robot arms are provided in Appendix A.

B. Body Weight Support Device

An improved BWS device was designed that uses a spring and lever arm in a specialized configuration to counterbalance the weight of the rodent without adding the inertia of a counterweight or the resonance of a simple spring counterbalance (Appendix B). Counterbalance force is applied by tension in the rope, which is provided by the spring. This counterbalancing force is constant when the following conditions are met: 1) the take-off point of the rope on the pulley is directly below the axis of the pivot shaft, and 2) the spring is at its resting length (no deflection) when the end of the rope is at the take-off point of the pulley (see Appendix B) [9]. Essentially, this configuration eliminates any equilibrium point to which the device might have a tendency to return, thereby reducing oscillations not induced by the animal. It also delivers a constant amount of support to the end of the support arm regardless of the height of its endpoint above the treadmill surface. The amount of body weight support can be adjusted by changing the height of the spring/pulley assembly by turning a lead screw manually or with a computer-controlled motor.

This second-generation BWS device is able to assist or challenge an animal by delivering precise levels of upward force to its torso, and it is able to alter that force rapidly, i.e., within the duration of a step. With the rat in a harness at a distance of 30 cm from the pivot, the system can generate 14.7 N of support force, with a maximum of 0.098-N static backdrive friction, twice the continuous dynamic range of the PHANToM haptic interfaces. Currently, the device is actuated by an electric motor from Maxon Motors (RE 36) together with the 4-Q direct current motor amplifier.

C. Control Software

The rat stepper is controlled using custom software created in MATLAB's XPC Target (The Mathworks, Inc., Natick, MA) to communicate with two Humusoft MF640 data acquisition boards. Position control of the hindlimb linkages is achieved using proportional-derivative feedback, either in joint space or end-effector space. Force control for the hindlimb linkages is achieved in an open-loop fashion using the Jacobian equations described in the Appendix A. Since the linkages have low friction and inertia, the force commanded to the motors is close to that achieved at the robot tip, even when the linkages are moving.

D. Analysis Software: Step Detection

A wide range of analyses can be performed on data generated by the rat stepper, many of which require the identification of individual steps. We have developed a simple offline algorithm in MATLAB for detecting steps automatically, thus decreasing the time required for analysis. This algorithm begins by filtering trajectory data in the X (anterior–posterior) direction (third order Butterworth, cutoff $= 10$ Hz) to remove any high frequency variations in movement. This filtering procedure typically leaves only one minimum (the change from backward to forward motion, or toe-off) and one maximum (the change from

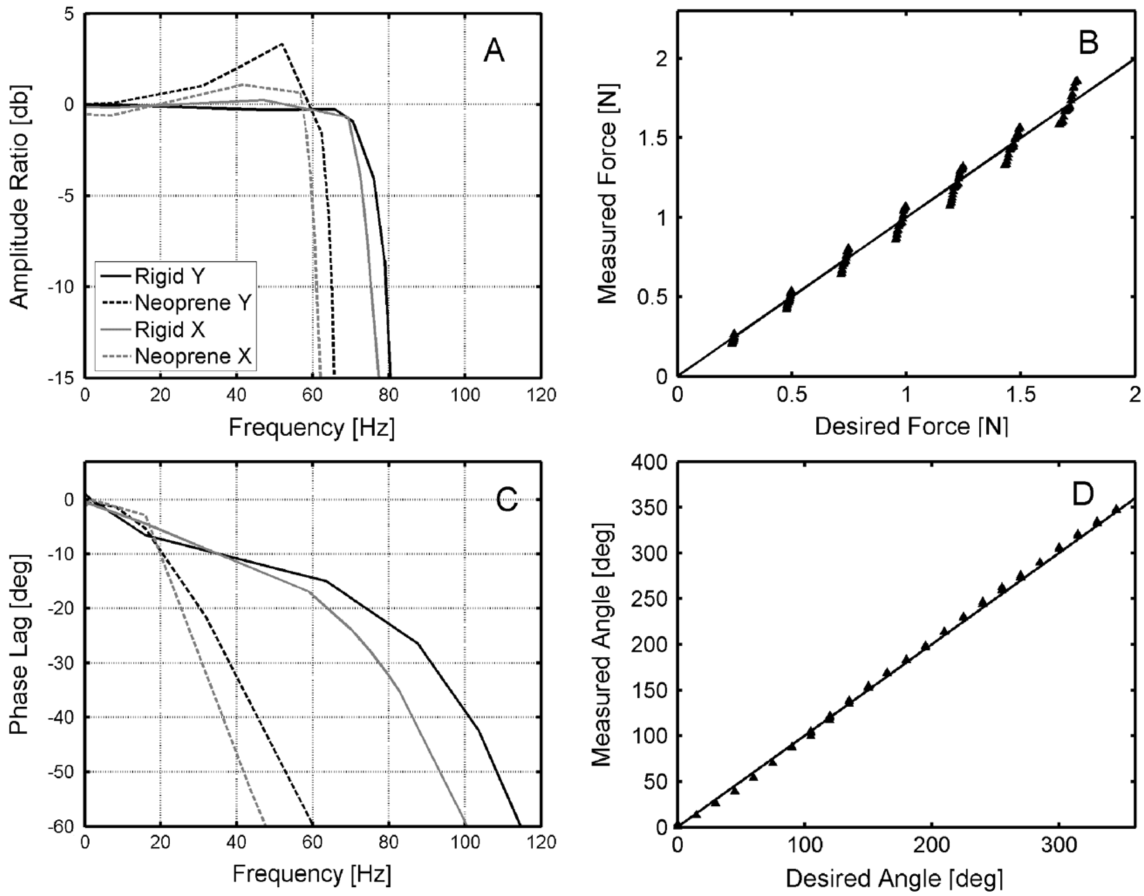


Fig. 3. (a) Magnitude and (c) phase response of the force control performance of hindlimb robots. Measurements were taken in the X (anterior-posterior, gray lines) and Y (vertical, black lines) directions using a rigid attachment (solid lines) and the neoprene attachment (dashed lines). (b) Magnitude and (d) direction of measured versus desired (i.e., commanded) force of the robotic hindlimb linkages. For these graphs, 168 desired force vectors were commanded (seven force magnitudes ranging from 0.25 to 1.75 N in 24 directions every 15°). Resulting individual magnitudes and directions are plotted but are difficult to distinguish because they overlay closely. Measurements were taken using a neoprene attachment to a simulated hindlimb that was attached to a multi axis force transducer, in order to simulate the technique used to attach to the rat's shank.

forward to backward motion or toe-down) in the horizontal trajectory for each possible step, and these data points are then used to define each step segment within the overall data. For each step segment, step duration is calculated as the time between the first and second minimum in the horizontal trajectory data, step length is calculated as the distance from the maximum to the second minimum in the horizontal trajectory data, and step height is calculated as the maximum height attained in the vertical trajectory during the step duration, all from the unfiltered trajectory data.

The algorithm then classifies each step segment (minimum–maximum–minimum sequence) as either a step or a non-step by comparing its step length, height, and duration to standard cutoff requirements. Steps that are too small are discarded because they are most likely due to short, spastic movements or vibrations due to treadmill friction on the rat's hindlimb. Steps that are too large are also omitted from analysis because they typically represent hopping, large withdrawal movements, or resetting by the experimenter. The range of allowable step characteristics used for analysis was identified previously from spinal cord transected animals, whose step characteristics were approximately normally distributed across animals [6]. For example, at a mean treadmill speed of 12 cm/s, the mean step length was identified previously as 38.0 ± 17.6 mm, and the allowable range for the current algorithm is 10–70 mm (± 2 standard deviations from the mean). Similarly, the mean step duration was previously identified as 980 ± 270 ms (0.3–1.8 s for the current algorithm). Data were not available to evaluate step height, therefore the value used in the current algorithm was set at 3–40 mm, based on inspection of rat stepping data and video footage.

After comparison with the above cutoff values, the segments that are of an appropriate duration and amplitude in both the X (horizontal) and Y (vertical) directions are recorded as steps, while the non-step segments are then combined up to the maximum step duration (1.8 s), to repeatedly check for other, more irregular steps. For example, during the swing phase of a step, an animal might generate a spastic trajectory, thereby generating several rapid changes in movement direction. Separately, each of these segments may not meet the detection criteria for length, height or duration, but combined, the overall motion may constitute a valid step.

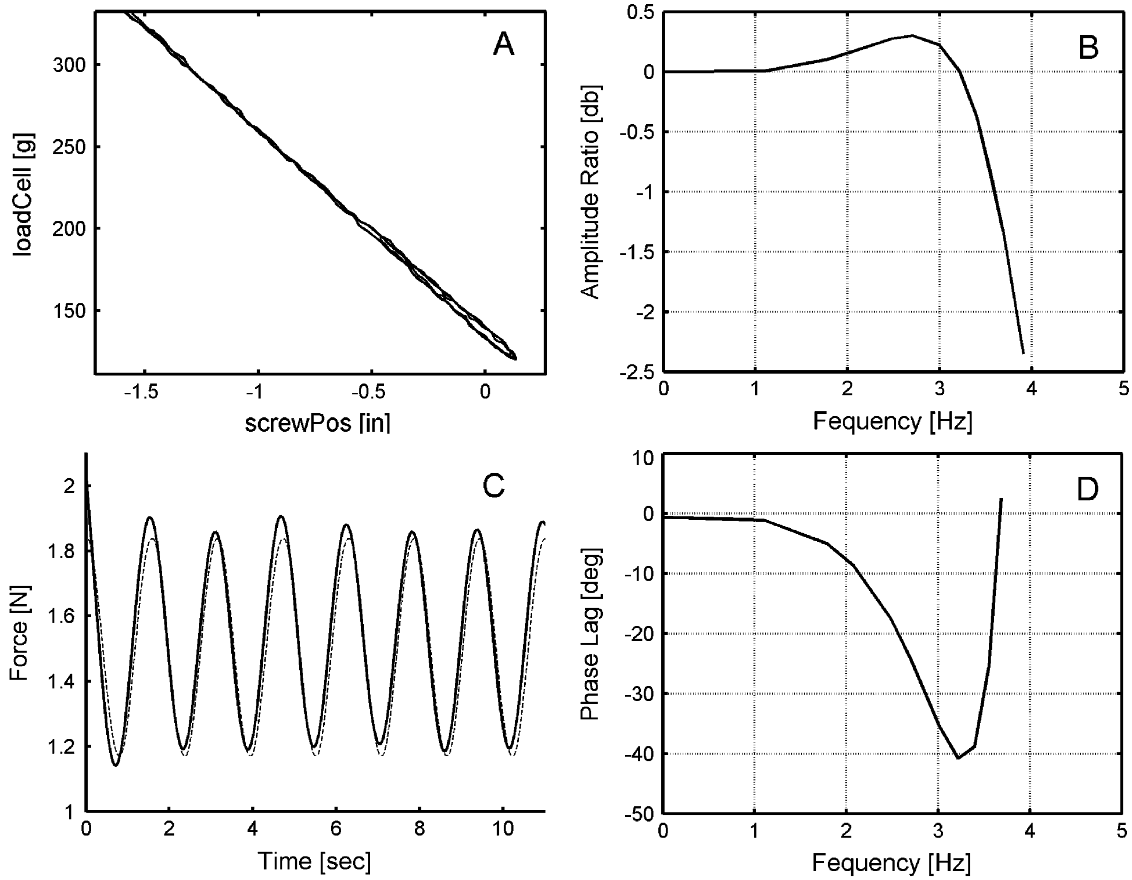


Fig. 4. Force control performance of the body weight support device. (a) Measured force versus lead screw position of the device. (b) Magnitude and (d) phase response of the device for a commanded sinusoidal force, measured with an isometric load cell mounted at the harness. (c) Good force tracking is achieved at 0.65 Hz.

IV. Device Performance

A. Force Control Capability

We used a three-dimensional force sensor (JR3, model: 20 E12A-125) to evaluate the force control capabilities of the hindlimb robots and BWS mechanism. We first evaluated the ability of the hindlimb robots to generate precise magnitudes and directions of forces [Fig. 3(b) and (d)]. The directional error was less than $3.63^\circ \pm 1.4^\circ$ on average, and the magnitude error was less than 0.005 N on-average. We also tested the bandwidth of force control for the hindlimb robots using both a rigid attachment to the force sensor and a setup designed to simulate the technique used to attach the rat hindlimb (a neoprene strip attached to a fixed rod with a diameter approximately that of a rat's lower shank) [Fig. 3(a) and (c)]. The bandwidth (-3 dB point) of the linkages was about 60 Hz with the neoprene strips, and about 70 Hz without the neoprene strips, with the strips adding a slight resonance (3 dB). The accuracy of endpoint position measurement of the hindlimb linkages was also evaluated using a custom made grid of nine holes spaced in a 10- by 7.5-cm region with machine precision of .025 mm. The mean position error calculated between 50 pairs of points was 1.1 ± 0.6 mm.

The force provided by the BWS system was linear with the lead screw position, with a maximum hysteresis of 0.098 N [Fig. 4(a)]. The BWS system provided accurate tracking of forces within its expected operating range (0–3.5 N), up to about 2 Hz [Fig. 4(b)–(d)]. Above 2 Hz, it exhibited a small resonance (3 dB), and above 3 Hz, the system exhibited a

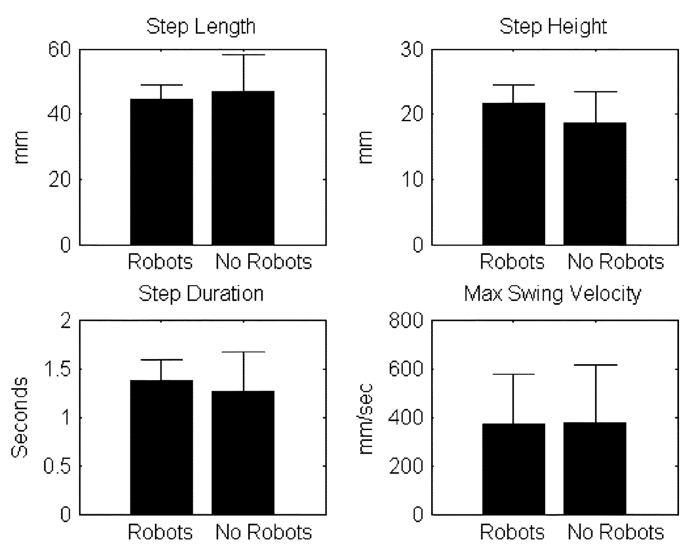


Fig. 5. Comparison of step length, step height, step duration, and maximum horizontal swing velocity for bipedal, treadmill stepping when robotic linkages were attached or not attached. These data were obtained by hand digitizing the ankle location of five rats, for five consecutive steps, from 30-Hz video. Error bars show one standard deviation across rats.

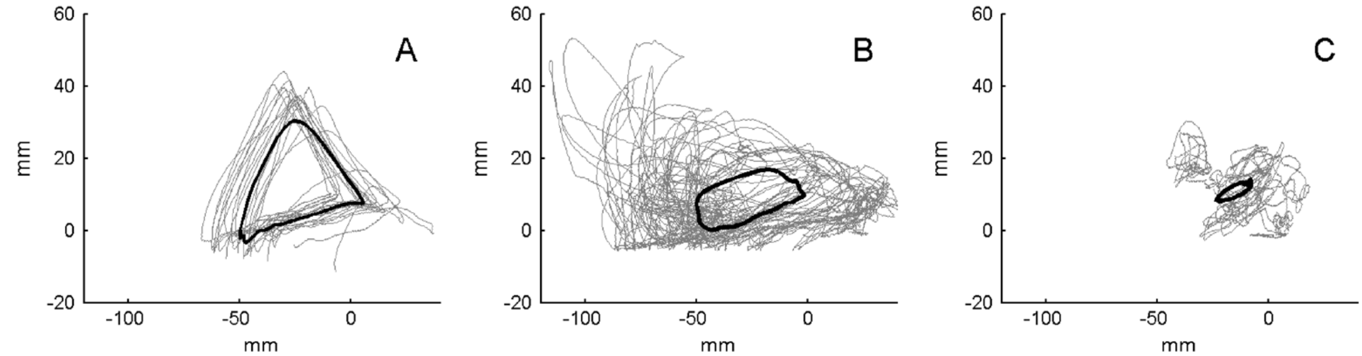


Fig. 6. Mean step trajectory (bold lines) and total movement trajectories (gray lines) for a (a) control (no injury), (b) moderately injured (200 kdyne impact to midthoracic spinal cord), and (c) a severely injured (250 kdyne impact) animal. Animals stepped bipedally on a motorized treadmill at 12 cm/s, while the attached robots recorded the movement trajectories of their ankles. From these overall movement trajectories, good steps were identified, and the mean of those steps was calculated. Number of steps identified and used to calculate the mean trajectory was 19 for the control animal, 65 for the moderately injured animal, and 23 for the severely impaired animal.

second mode of vibration in the spring, in which the spring began to oscillate in the direction perpendicular to its long axis.

B. Does the Device Impede Stepping?

We quantified how the hindlimb robots affected the stepping of five female, adult (>8 weeks), Sprague Dawley rats that had received a moderate contusion injury (200 kdyne impact to the midthoracic spinal cord using an impactor from Infinite Horizons) [10] by hand digitizing the ankle trajectories from video of bipedal stepping at a constant 75% BWS with and without the hindlimb robots attached. Video footage was captured using a standard 30 Hz miniDV camera (Cannon Optura 30) and then digitized using Matlab's image acquisition and analysis toolbox. For each recording, the camera was placed perpendicular to the sagittal plane of the animal, and the lower portion of the hindlimb linkage [L2, in Fig. 1(b)] was used as a reference scale. The results demonstrate that there was little difference in step length, step height, step duration, and swing velocity with and without the robots attached (Fig. 5).

C. Step Detection Example

Fig. 6 illustrates stepping trajectories recorded from a control (no contusion), moderately (200 kdyne impact), and severely (250 kdyne impact) impaired animal [female, adult (>8 weeks), Sprague–Dawley]. The mean trajectory of the steps detected reflects the general shape and size of the actual steps taken as defined by movement of the distal end of the shank. The number of steps taken by each animal in Fig. 6 was 19 for the control animal, 65 for the moderately contused animal, and 23 for the severely injured animal. Thus, the rat robot and software are able to effectively capture and compare differences in locomotion between injured and control animals.

V. Discussion

The rat stepper opens new experimental prospects for studying spinal control of stepping, spinal cord plasticity, and effects of nerve cell regeneration techniques on the recovery of locomotor performance. The key design principles that it incorporates are to generate normal, consistent sensory input associated with locomotion while minimizing the encumbrance to limb movement, and maximizing the dynamic range and resolution for weight support. The hindlimb robots provide high-bandwidth, two-axis, force control for assisting and perturbing hindlimb movement, while minimally encumbering that movement. The body weight support device allows the experimenter to precisely control levels of force applied to the rat's body over a wide range of forces. We have also built a smaller device for mice, and a commercial version of the rat stepper is available (Rodent Robot 3000, Robomedica, Inc., Irvine, CA). The current device is different from the original version of the rat stepper that we developed [5]–[7] in that it uses the custom two degrees-of-freedom robot arms instead of the PHANToM haptic robots, thereby reducing cost, friction, and inertia. In addition, it incorporates the spring-based body weight support system, thereby providing precise levels of support force without a changing inertia. We have begun using the device and its commercial version to study locomotor training and evaluation in spinal cord transected and contused rats [6], [7], [11], [12].

To date, we have primarily focused on using the rat stepper to evaluate bipedal stepping. Bipedal stepping is not the normal mode of locomotion for rats, but it has allowed us to precisely control the loading to the hindlimbs, because the loading on the forelimbs is known and fixed (i.e., it is zero). However, we are interested in studying quadrupedal stepping in future work. One reason is that the role of forelimb motion in influencing hindlimb motion is of particular interest following spinal cord injury. Similarly, bipedal stepping typically requires that the animal be placed in a more upright posture to support its weight. This has the effect of changing the range of motion traveled by the hip and knee compared to normal, quadrupedal gait. This change in sensory information may change the way that the animal responds to some perturbations, and this limitation should be considered in extrapolating results obtained with bipedal stepping to the control of quadrupedal stepping. The effect of restricting the hindlimbs to motion within the parasagittal planes should also be studied in future research.

Forward Kinematics

$$X_T = -L_1\cos(\theta_3) + L_2\cos(\theta_r + \theta_3)$$

$$Y_T = -L_1\sin(\theta_3) + L_2\sin(\theta_r + \theta_3)$$

Inverse Kinematics

$$\theta_3 = \tan^{-1}\left(\frac{X_T}{Y_T}\right) + \tan^{-1}\left(-\frac{\sqrt{1-D_1^2}}{D_1}\right)$$

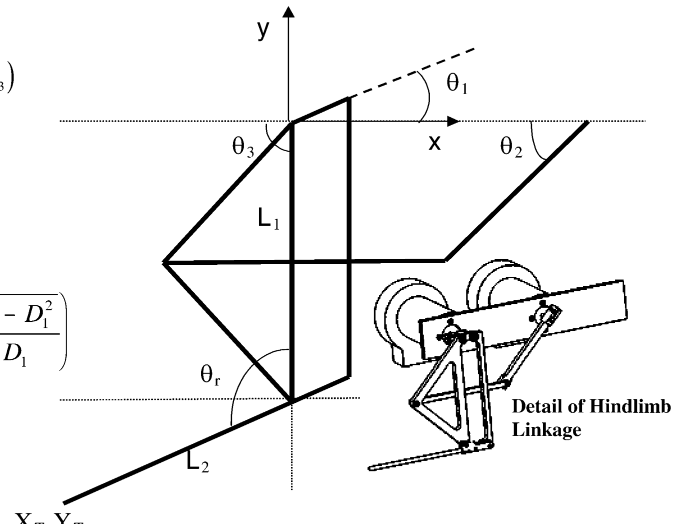
$$\theta_r = \tan^{-1}\left(-\frac{\sqrt{1-D_2^2}}{D_2}\right)$$

$$\theta_r = \theta_1 - \theta_3 + 180^\circ$$

$$D_1 = \frac{L_1^2 - L_2^2 + S^2}{2L_1S}$$

$$D_2 = \frac{L_1^2 + L_2^2 - S^2}{2L_1L_2}$$

$$S = \sqrt{X_T^2 + Y_T^2}$$



Hindlimb Robot

Motor 1 angle = θ_1
Motor 2 angle = θ_2
$\theta_3 = \theta_2 + 45^\circ$
Relative angle between links 1 and 2 = θ_r
$\theta_r = \theta_1 - \theta_3 + 180^\circ$

Force Control Equations:

$T = J^TF$
Where:

$$J = \begin{bmatrix} \frac{\delta X}{\delta\theta_r} & \frac{\delta Y}{\delta\theta_r} \\ \frac{\delta X}{\delta\theta_3} & \frac{\delta Y}{\delta\theta_3} \end{bmatrix}$$

$$X = -L_1\cos(\theta_3) - L_2\sin(\theta_r + \theta_3 - 90^\circ)$$

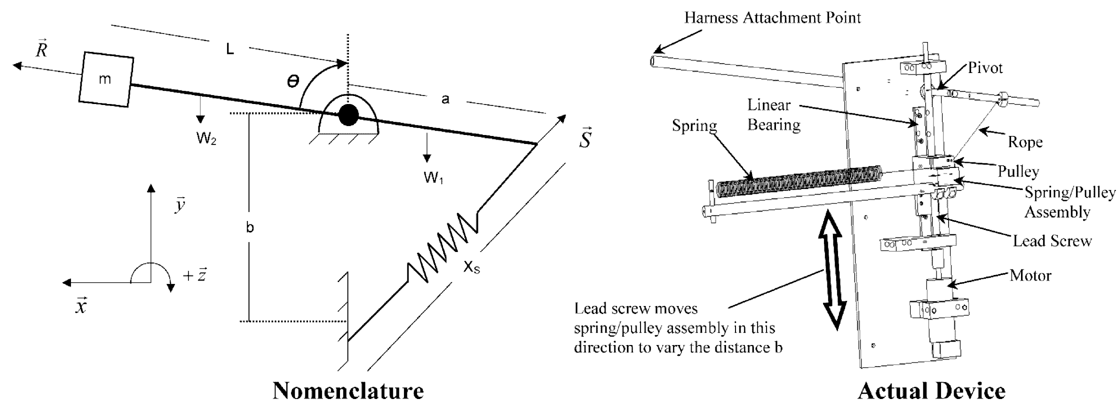
$$Y = -L_1\sin(\theta_3) + L_2\cos(\theta_r + \theta_3 - 90^\circ)$$

Fig. 7. Kinematics of hindlimb linkages.

The capabilities of the rat stepper to deliver precise amounts of weight support, to accurately and easily capture step trajectories, and to perturb and assist in stepping of injured animals are promising tools for outcome assessment and training. For example, by providing appropriate levels of body weight support, locomotor control can be assessed, even in severely impaired animals that cannot fully support their weight independently, thereby eliminating the "threshold" nature of many assessment techniques [12]. In addition, by systematically determining the maximum amount of load that an animal can bear and still step successfully, weight-support ability can be quantified [11]. Detailed kinematic features of hindlimb end-point movements, such as step length and height, swing and stance duration, and swing velocity can be obtained readily, and show potential for objective, quantitative impairment, and outcome assessment [1], [2], [12]. However, measurement of individual joint angles is not possible with the rat stepper. The active, robotic properties of the device have the potential to bring a new, interactive dimension to gait assessment. The device might be used to deliberately perturb an animal's limb movements or postural support during locomotion, and then to quantify the capacity of the injured motor control system to compensate for error [6], [7]. Finally, for locomotor training, the device's abilities to assist in hind limb movement and to provide graded levels of weight support have the potential to assist the injured nervous system in gradually learning to control full weight bearing stepping.

Thus, the device should help to answer several important questions, including the following.

1) What are the best locomotor training techniques for retraining neural circuits to control stepping after spinal cord injury?
2) How is sensory input interpreted by the nervous system during stepping?
3) What robotic measures of locomotor function best quantify recovery?
4) Can robotic measures provide insight into the physiological mechanisms of recovery?



The motorized lead screw adjusts the distance b in order to counterbalance different masses, M, independently of Θ

Proof:

(1) $X_S\vec{S} + a\vec{R} = b\vec{y} \quad \Rightarrow \vec{S} = \frac{b\vec{y} - a\vec{R}}{X_S}$ This equation expresses the necessary design condition that the take-off point on the pulley be directly below the axis of the shaft pivot.

(2) $\vec{R} = Sin(\Theta)\vec{x} - Cos(\Theta)\vec{y}$

Equation (3) is for the case where the system is counterbalanced, and assumes that the spring is at its resting length ($X_s = 0$) when the end of the rope is at the take-off point of the pulley.

(a) (b) (c) (d)

(3) $\left(-a\vec{R}\times -kX_S\vec{S}\right) + \left(-\frac{a}{2}\vec{R}\times -W_1\vec{y}\right) - \left(\frac{L}{2}\vec{R}\times -W_2\vec{y}\right) - \left(L\vec{R}\times -mg\vec{y}\right) = 0$

(a) - Force Spring
(b) - Weight, Spring Side of Bar
(c) - Weight, Mass Side of Bar
(d) - Weight of Mass

(4) $\vec{R}\times\left(akX_S\vec{S} + \frac{a}{2}W_1\vec{y} - \frac{L}{2}W_2\vec{y} - mgL\vec{y}\right) = 0$

(5) $\vec{R}\times\left(akX_S\left(\frac{b\vec{y}-a\vec{R}}{X_S}\right) + \left(\frac{a}{2}W_1 - \frac{L}{2}W_2 - mgL\right)\vec{y}\right) = 0$

(6) $\vec{R}\times\left(akb\vec{y} - a^2k\vec{R} + \left(\frac{a}{2}W_1 - \frac{L}{2}W_2 - mgL\right)\vec{y}\right) = 0$

(7) $\vec{R}\times\left(akb + \frac{a}{2}W_1 - \frac{L}{2}W_2 - mgL\right)\vec{y} = 0 \quad \Rightarrow \vec{R}\times N\vec{y} = 0, \quad \vec{R}\neq\vec{y} \quad \Rightarrow N = 0$

(8) $k = \frac{LW_2 - aW_1 + 2mgL}{2ab}$

(9) $k = \frac{2LF_{rat}}{2ab}$ Assuming $LW_2 \approx aW_1$ where F_{rat} = mg = force due to weight of rat

If $F_{rat} = \frac{kab}{L}$, system is counterbalanced for all Θ by setting the distance b with the lead screw.

Fig. 8. Proof that the BWS mechanism provides a constant amount of support.

There are also a large number of possible training and assessment techniques (assistance, resistance, perturbation, force fields) to be explored.

An important direction for future device development is to develop a version of the device that can also measure overground and quadrupedal stepping. In addition, we expect the rat robot to act as a small-scale test-bed for determining the physiological principles that will optimize robotic gait training in humans.

APPENDIX A
KINEMATICS OF HINDLIMB LINKAGES

See Fig. 7.

APPENDIX B
PROOF THAT THE BWS MECHANISM PROVIDES A CONSTANT AMOUNT OF SUPPORT

See Fig. 8.

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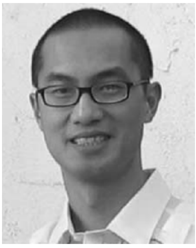

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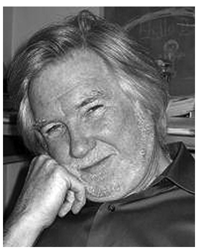

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