A Novel Interactive Exoskeletal Robot for Overground Locomotion Studies in Rats

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***Abstract*—This paper introduces a newly developed apparatus, Iron Rat, for locomotion research in rodents. Its main purpose is to allow maximal freedom of voluntary overground movement of the animal while providing forceful interaction to the hindlimbs. Advantages and challenges of the proposed exoskeletal apparatus over other existing designs are discussed. Design and implementation challenges are presented and discussed, emphasizing their implications for free, voluntary movement of the animal. A live-animal experiment was conducted to assess the design. Unconstrained natural movement of the animal was compared with its movement with the exoskeletal module attached. The compact design and back-drivable implementation of this apparatus will allow novel experimental manipulations that may include forceful yet compliant dynamic interaction with the animal's overground locomotion.**

***Index Terms*—Exoskeleton, locomotion, rodent, spinal cord injury.**

I. Introduction

GROWING interest in robotic treatment of patients with neurological injury motivates the development of therapeutic robots for basic research into recovery. While humans are the ultimate beneficiaries, basic research frequently involves rodent models of the central nervous system [1]–[4] or neurological injury [5]–[10]. Different facets of research include applying traditional and established methods such as using pharmacological agents [11], [12] or cellular level treatments [13]–[15]. While these methods focus on the molecular and cellular level functionality of the bio-system under consideration, locomotion studies involving physical interaction with the environment in live animals attempt to approach the issue from the system level [6]–[10]. Response to carefully prepared physical interaction, be it assistance or perturbation, provides useful information about the bio-system.

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Currently, most available apparatus for locomotion studies with rodents are built upon treadmills [6], [9], [10], [16], [17]. There is merit to this approach, especially when the animal is severely injured or is in the early stages of recovery. For example, treadmills can be used to induce stepping in animals that are otherwise unable to produce gait-like movements [18]. They also simplify the collection of ground reaction forces during stepping by placing a stationary force plate below the treadmill belt. Direct manipulation of the hindlimb gait is possible with an external, mechanically grounded set of manipulators [16]. On the other hand, the treadmill configuration restricts the scope of possible experiments. For example, because voluntary movements such as turning are not permitted, the contribution of these movements to quadruped locomotion cannot be addressed. It is also non-trivial to implement a complex multi dimensional movement such as navigation through a maze or climbing up and down stairs. This is largely due to the single-dimensional movement of a typical treadmill belt and the lack of room for natural or voluntary movements of the animal. To better understand the bio-system, it is important to allow various modes of natural movement of the animal beyond those possible on a treadmill, especially because locomotion on a treadmill may differ significantly from locomotion overground [19].

The robotic interface presented in [20] is for overground movement studies and allows multidirectional movement of the animal in a large 3-dimensional workspace. Experiments that are impossible on a treadmill, such as on steering movements or climbing up stairs can be conducted with this device. Nonetheless, in the current evolution of the device, perturbation can be applied to the animal's body only through the weight support system. Targeted assistance to the hindlimbs, a feature required to test robotic therapy on impaired limbs, is not possible.

In order to open up new possibilities for locomotion studies with rodents, this work presents an interactive exoskeletal robotic apparatus, named Iron Rat, which allows physical interaction directly with the hindlimbs during the animal's overground movement. By allowing overground movement, many hitherto underemphasized aspects of rodent locomotion can be addressed. By introducing a compact and lightweight exoskeletal module to the animal, the apparatus may provide various forms of physical interaction with the animal's hindlimbs during overground locomotion. This exoskeleton is highly back-drivable to enable voluntary movement. The design and implementation of this apparatus is presented in Section II and III. Results from experiments with an unimpaired animal are presented in Section IV to assess the usefulness of the current apparatus. Implications for future research are discussed in Section V.

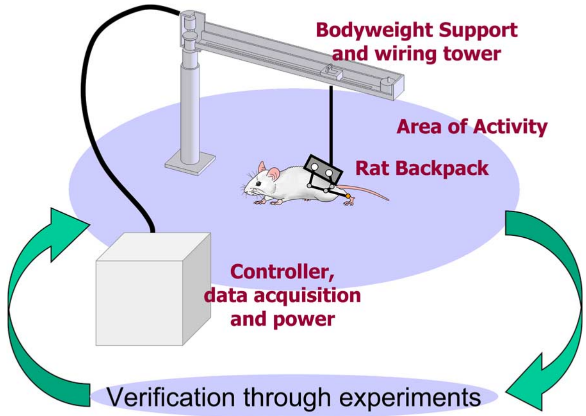

Fig. 1. The Iron Rat system conceptual sketch. The Rat Backpack is a compact and lightweight device carrying only those hardware elements essential for controlling physical interaction. The animal is free to move within an area of activity, outside of which are located other heavy and/or bulky components such as controller, data storage and power source.

II. Apparatus Concept

High priority was given to designing an apparatus that would allow the animal to move freely in an open space or 'arena'. Fig. 1 illustrates the general concept. Iron Rat was intended to achieve the following.

1) Permit a wide range of voluntary overground movement: It is beneficial to be able to examine various modes of locomotion, especially when they might be important aspects of overground quadrupedal behavior. Also, voluntary movement should be permitted as much as possible in order to address the role of specific experimental manipulations (e.g. new pharmacological agents) whose effect may result in sustained change to features of voluntary locomotion.
2) Mechanical loads and kinematic constraints imposed on the animal should be minimal. To reduce weight and especially inertia, the number of hardware elements moving with the animal should be minimized. All other elements may be placed further from the animal. The apparatus near the animal should be compact in size. The output mechanical impedance of the machine (how much it resists motion) must be small for sufficient back-drivability. Movement constraints should be minimal. For example, constraining relative motion of the animal's body parts is strongly discouraged, as it might restrict voluntary overground movement.
3) Provide various modes of physical interaction: The apparatus is intended to allow experiments including, but not limited to, passively monitoring the animal's movement overground. For example, a new locomotor therapy protocol for patients with neurological injury may be implemented and tested with this apparatus. Specific sensory cues may be provided to the animal to evoke responses from the neural circuitry affecting locomotion. The apparatus may also be used to simulate unique, challenging locomotor conditions.

To provide physical interaction, Iron Rat should have a sufficient number of actuated and sensor-monitored degrees of freedom. Sufficient force and power is also required. Robust coupling between the apparatus and the animal is important.

The Rat Backpack shown conceptually in Fig. 1 is part of the Iron Rat system. It is a compact and lightweight robotic module that includes only those elements essential to allow forceful interaction with the animal. Every other element of the apparatus, such as an external weight support system, servo-amplifiers, controller, data storage or power source, are located away from the animal. Communication between the Rat Backpack and rest of the system is accomplished via flexible wires mounted on a robotic arm which also serves as a body-weight support system (BWSS).

At first glance, it is not obvious that this apparatus will satisfy the requirements listed earlier. Justification of the design through animal experiments is an essential part of the design process (Fig. 1). Experiments to assess the design are presented in Section IV.

III. Apparatus Implementation

A. Rat Backpack

The Rat Backpack was designed as an exoskeletal module for the animal's hind-quarters. While it may be interesting to develop a full-body exoskeleton for rodents, we focused on first investigating hindlimb locomotion, as it is more related to human locomotion. Also, one specifically-targeted area of application of this machine is for research into Spinal Cord Injury (SCI) and its treatment. Rats are a common animal preparation in SCI research, and are typically given surgery that interrupts the motor and sensory functions of the hind-quarters only [5]–[10], [16], [17], [21].

The Rat Backpack was coupled to the animal at three "ports", locations at which force may be applied. The bulk of the device was mounted on the lower back of the animal near the pelvic bone using a medical tape and Velcro. Two other coupling points were close to the animal's hindlimb ankle joints. Semi-elastic strings attached at the end of the manipulator arms were wrapped around the ankles of the animal The Rat Backpack nominally allowed two actuated degrees of freedom (DOF) of each hindlimb relative to the attachment near the pelvis, corresponding to sagittal plane ankle motion. However, each of the attachment points, and especially that at the pelvis, had some degree of compliance. Thus while movement normal to a parasagittal plane was not actuated nor recorded, it was not completely restricted. The consequence of this design choice is addressed in the discussion section.

Fig. 2 shows the present version of the Rat Backpack. Four motors (Maxon EC6), each with a planetary gearhead providing a 57:1 speed reduction, were onboard the Rat Backpack. The corresponding torque amplification due to the gearhead was able to produce a maximum force of 2 N ($\sim$200 gram-force) on each side. However, the motor and especially the gearhead exhibited significant static friction which compromised back-drivability. Force feedback was necessary and sufficient to reduce output impedance, as discussed in subsequent sections.

The motor shaft angular positions were recorded by miniature optical encoders. These motors drove 2-DOF manipulator arms on each side. The end of each manipulator arm included

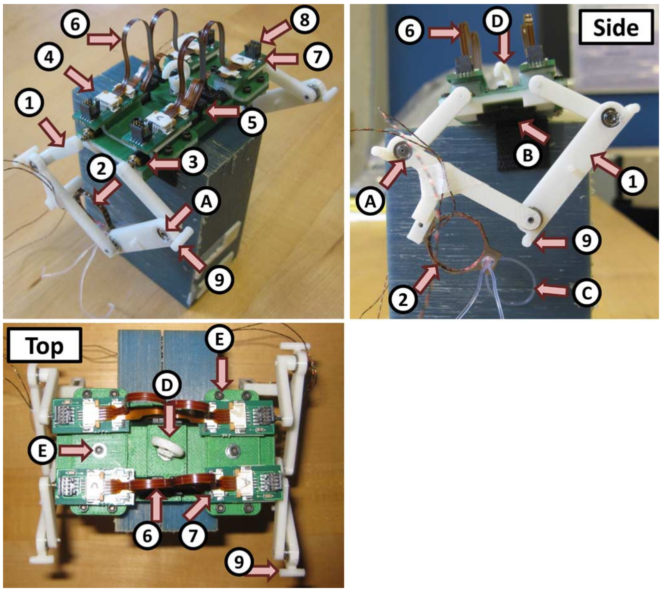

Fig. 2. Fig. 2. Photo of the Rat Backpack placed on a plastic block. The weight of the Rat Backpack is 75 grams. 1) Linkages built in ABS plastic. 2) Custom 2D force sensor. 3) Gearhead 4) The motors are under the PCB boards. 5) Optical encoder for each motor. 6) Flat wire from the motors and encoders 7) PCB board with wiring terminals. 8) Wiring junction for motors and encoders. 9) Mechanical stops to avoid mechanism singularity A) Rotary bearings and coil-spring pins are used to connect the linkages. B) Velcro attachment for biomechanical coupling at the lower back of the animal C) Elastic strings for biomechanical coupling at the ankles of the animal. D) Plastic hook for weight support E) Screws, washers and nuts keep the two covers on the base.

a custom-designed 2D force transducer which measured the interaction force between the animal's hindlimb and the Rat Backpack [22]. The motor mounting and manipulator linkages were fabricated in ABS plastic using rapid prototyping. The overall weight of the Rat Backpack was 75 grams. For further details of this design of the Rat Backpack, see [23], [24].

B. Supporting Systems

All sensor signals were sampled and processed on a master computer running a real-time Linux operating system. Motor commands were issued through the motor servo amplifiers (Copley Controls, Accelnet) which were connected through wires to the Rat Backpack. Limp and flexible wires were used between the body-weight support system (BWSS) and the Rat Backpack.

Fig. 3 shows the Iron Rat system used for the experiments described in Section IV. To facilitate transport between laboratories, the supporting systems, including electronic controller for the Rat Backpack, power supply, the body-weight support system electronic controller, desktop computer (the "master computer") and a laptop computer (for control of the body-weight support system), were put on a low-profile utility cart. The body-weight support system was mounted on one corner to maximize the reachable workspace on the floor.

IV. Design Assessment by Experiments With an Animal

Experiments with a live animal were conducted to assess the performance of the design. The main purpose of these experiments was to test how the exoskeletal design with force feedback interacted with the animal. The principal question addressed was, to what degree does the equipment allow voluntary overground locomotion?

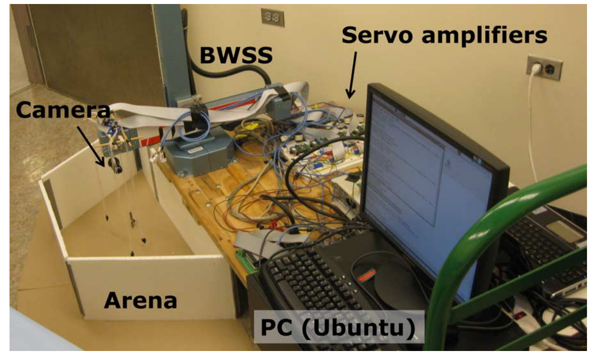

Fig. 3. Supporting systems were mounted on a utility cart which could easily be transported between laboratories. The arena shown here is a trapezoid with a 1.1 m base and an approximate area of 0.4 m^2.

A. Methods

One healthy female Sprague-Dawley rat (8+ weeks, body weight 250 grams) was used in this study. All animal experiment procedures were reviewed and approved by the MIT Committee on Animal Care. The animal was housed at the animal-care facility at MIT and was given ordinary diet and routine health monitoring. Prior to the experiment, the animal was handled daily for a week to get it accustomed to human hands.

Self-paced forward locomotion was observed under three conditions: 1) Unconstrained animal, 2) Animal with a 'mockup' (described below), 3) Animal with the fully active Rat Backpack. The 'unconstrained' measurement was conducted first, followed by 3 days of measurement with the mockup and a subsequent 5 days of measurement with the active Rat Backpack. On each day the experiment lasted 30 minutes including preparation time. Throughout the experiment, the animal was visually monitored for any signs of anxiety or agitation.

The mockup is a passive version of the Rat Backpack that does not carry any sensors or actuators and is significantly lighter and more back-drivable than the Rat Backpack. Hence the mockup does not encumber the animal as much as the Rat Backpack. Nonetheless, the mockup still limits the hindlimb movements approximately to a para-sagittal plane. Using the mockup for a few days on the animal before applying the Rat Backpack served two purposes; Firstly, it allowed the animal to get used to the sensation of being attached to Rat Backpack, because the mockup was coupled to the animal at the same points where the Rat Backpack was coupled. Secondly, the mockup allowed us to address whether the 2-DOF movement constraint on the hindlimbs limited movement functions.

The experiment with the active Rat Backpack was conducted with force feedback implemented, which was termed 'low-impedance mode'. Without force feedback, the motors and gearheads used in the Rat Backpack exhibited significant static friction which compromised back-drivability. A novel force feedback controller compensated for the friction and reduced the root-mean-square interaction force (without the

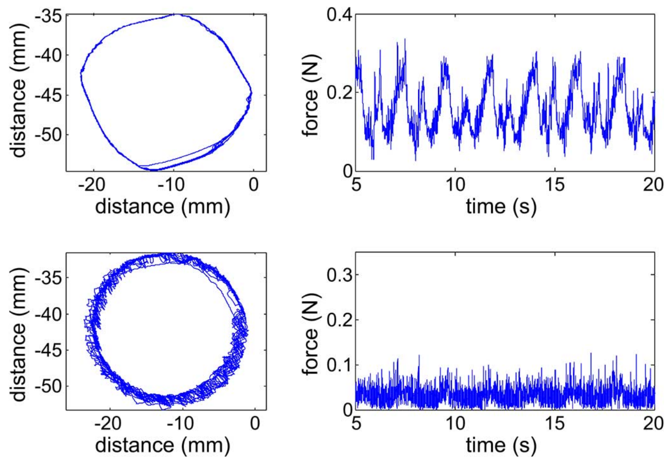

Fig. 4. Trajectories and interaction forces while back-driving the right side of the Rat Backpack in circles. Top row: Open-loop measurement with no controller. Root-mean-square of interaction force over ten cycles is 0.187 N. Bottom row: Closed-loop measurement with force feedback. Back-drivability is significantly enhanced with an RMS force of 0.036 N, over 5 times smaller. Due to backlash, the measured trajectories in both cases are not perfect circles (see [23] for more detail).

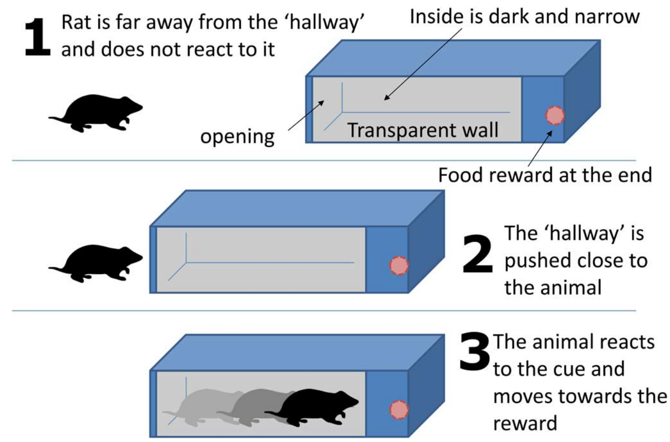

Fig. 5. The animal was trained to respond to and walk through a dim 'hallway'. A side wall was transparent to allow video recording of the locomotion.

semi-elastic coupling) by as much as a factor of five as shown in Fig. 4. More detail on this control mode can be found in [23].

When the active Rat Backpack was used, passive weight support was provided through two compliant elongation springs (initial length 5 cm, stiffness 45 N/m) between the Rat Backpack and the end effector of the BWSS. The robot initially intended as an active BWSS system (ST-Robotics, R19, robot arm inertia >5 kg) had very low bandwidth and failed to reliably track the movement of the rat. Manual adjustment was thus added during the experiment. By measuring the length of the springs, the supported weight was estimated to be approximately 75 grams, which equals the weight of the Rat Backpack.

Because the apparatus was designed to allow voluntary movements, the animal wearing this equipment was unlikely to perform consistently repeatable movements conducive to straightforward analysis. To address this problem, a relatively dark 'hallway' was introduced as illustrated in Fig. 5. Inspired by the fact that rats prefer narrow openings or corners with reduced ambient light, the purpose of the 'hallway' was to encourage the animal to perform approximately straight-line forward locomotion solely for data collection and analysis. First, the animal was placed in the open area. Then the 'hallway' was pushed towards the animal with the opening facing the animal. The rat then chose to walk into the dark corridor and find a food reward at the closed end. The self-paced forward locomotion during this period was recorded on video using a camera placed at the same height and perpendicular to the hallway. After the reward was consumed, the rat was manually removed from the hallway and placed in the open arena to prepare for the next observation. The number of repetitions of this procedure required for the animal to understand the protocol was minimal—less than 5 minutes of training sufficed. Using this protocol was especially beneficial when using the active Rat Backpack. Note that the 'hallway' was used in this experiment only, and is not a requirement for the device to function properly.

In all three conditions (unconstrained, with mockup, with Rat Backpack), voluntary forward movements were recorded on video at 30 frames per second and a resolution of 1.5 mm per pixel (Fig. 6). The positions and timings of toe contact were manually collected from the video frames. No visual marker was necessary. On each day, 9 to 20 clearly visible forward steps were extracted to provide position and timing data. These steps did not include the initial and final steps of a forward walking sequence or interrupted steps such as when the animal briefly paused during double stance.

When the active Rat Backpack was used, the position of the end-effectors and the 2D interaction force on each hindlimb were recorded at 1 kHz. The normality of the datasets for each condition was addressed with a Jarque-Bera test where the null hypothesis was that the dataset came from a normal distribution. A two-sample t-test was used when pairwise comparison was required.

B. Results

1) Observed Movements: A variety of voluntary movements were observed throughout the experiment. Forward locomotion was most often observed, as this movement was encouraged by using the 'hallway' (Fig. 5). Other movements were also observed, include turning, rearing up, grooming, and backward locomotion (Fig. 7). Note that turning and rearing up against the side walls required deviation from 1D motion. In general, the animal appeared to move as freely in the mockup or active Rat Backpack as when it was unconstrained. However, a partial tail dragging was observed while using the mockup or the active Rat Backpack. Because of this observation, the quality of forward locomotion with the mockup or with the active Rat Backpack would score approximately 20.5 on the Basso, Beattie and Bresnahan (BBB) locomotor rating scale, which is 0.5 less than the highest score of 21 corresponding to ideal natural gait.

Throughout the experiment, the animal showed no sign of anxiety or agitation due to the equipment. The animal did not react to the added inertia, couplings, or ankle motion constrained to para-sagittal planes. Also, a variety of movements that are typically seen in the unconstrained animal were also seen when the active Rat Backpack was attached (Fig. 7). This

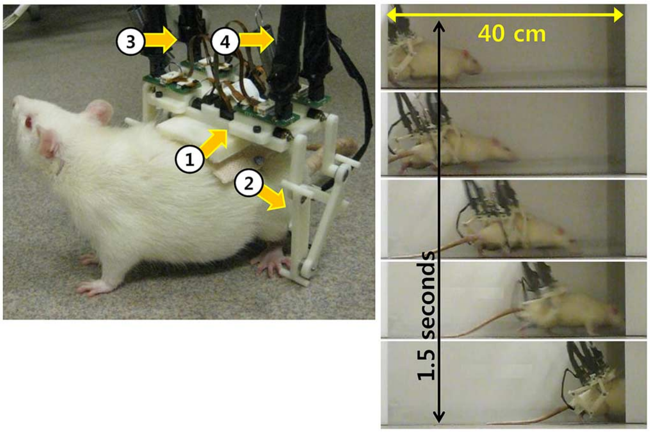

Fig. 6. Snapshots from a live animal experiment. Top: The Rat Backpack mounted on the animal with the motors in home-position. 1-Waist coupling. 2-Ankle coupling. 3-Wires for the sensors and actuators. 4-Compliant elongation springs for partial weight support. Right: snapshots from the video recorded while the animal performed self-paced, forward locomotion. By design, the linkages on the manipulator do not touch the ground during locomotion.

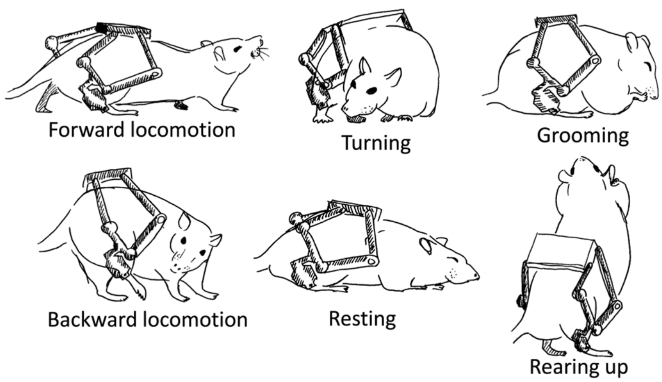

Fig. 7. Examples of movements commonly observed in this experiment.

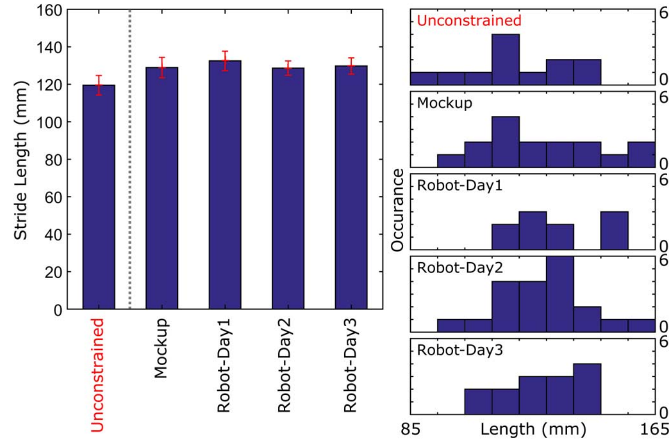

Fig. 8. Stride Length data. Left: Mean ± Standard Error. There is no significant difference between cases. Right: Data histograms.

TABLE I
STRIDE LENGTH DATA

	Stride Length [mm]		Jarque-Bera test (p)	Significance (p) vs. Unconstrained condition
	Mean ±STD	Number of samples		
Unconstrained	119.5 ±18.1	12	> 0.50	N/A
Mockup	128.9 ±21.7	16	0.27	0.23
Robot-Day1	132.5 ±16.3	10	0.39	0.09
Robot-Day2	128.7 ±17.0	20	> 0.50	0.16
Robot-Day3	129.8 ±16.3	14	0.30	0.14

suggested that the animal attached to the active Rat Backpack was as comfortable as when it was unconstrained.

2) Stride Length: The stride lengths measured are shown in Table I and Fig. 8. The distributions did not significantly differ from normal ($p > 0.05$) in all cases. Pairwise comparisons between the unconstrained dataset and mockup/Rat Backpack cases revealed $p > 0.05$ for all pairs, suggesting that the stride lengths in the mockup condition or in the active Rat Backpack condition did not significantly differ from the unconstrained normal case.

3) Stride Duration: Timing information was also determined from the video frames with a resolution of 0.033 s. Measured stride durations are shown in Table II. Unlike the stride length data, the unconstrained animal's stride duration was significantly shorter than when the mockup was attached and for the first two days when the active Rat Backpack was attached ($p \ll 0.05$). However, data collected on the third day with the active Rat Backpack attached showed no statistically significant difference from the unconstrained condition. Fig. 9 shows evidence that the animal adapted its stride duration to the kinematic constraint but did not adapt its stride length, as shown in Fig. 8. This trend is also seen in Fig. 9 where the peaks of the histograms of stride durations recorded during the three days when the constraint was attached (mockup or active Rat Backpack) apparently shifted towards the peak of the histogram recorded in the unconstrained case.

4) Swing Duration per Stride Duration (Duty Cycle): The ratio of swing duration per stride duration remained approximately constant across all conditions, as seen in Fig. 10. No statistical difference between any pair of data sets was found. Pairwise t-tests all resulted in $p > 0.05$.

5) Interaction Force: Because the force transducers were coupled to the animal's hindlimb via semi-elastic string, the forces measured by the sensors were the projection onto the approximately para-sagittal plane of manipulator motion of the forces the animal exerted on the robot. In other words, they were the interaction forces required to back-drive the manipulators on the Rat Backpack in the directions in which it could be moved. They provided useful data to assess the back-drivability of the apparatus, as well as the animal's adaptation to it.

Fig. 11 shows the mean interaction force during sustained forward locomotion. Time windows containing only sustained forward locomotion of at least one stride (two steps) were gathered for each day. These time windows with different durations were combined to form a single time history of force for each day. The time-average of force is plotted in blue. In red is the value of the peak interaction force measured during the entire day.

The time-average of interaction force during movement was lower than 0.07 N (7 gram-force) on the right side, and lower than 0.13 N (13 gram-force) on the left side, approximately

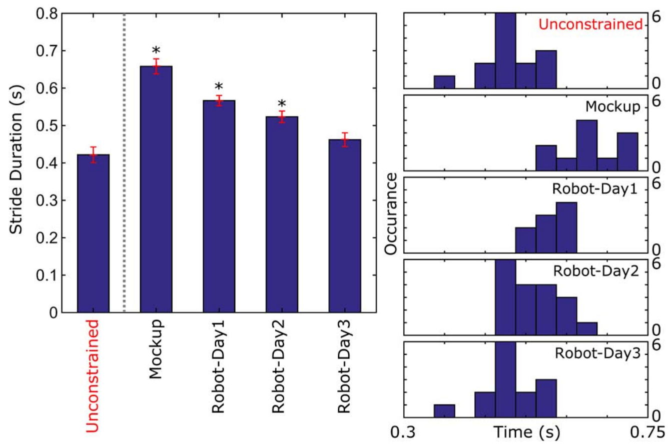

Fig. 9. Stride Duration data. Left: Mean $\pm$ Standard Error. Significant differences from the unconstrained case are marked with $^*(p < 0.05)$. Right: Data histograms. Note how the histograms progressively converge towards the unconstrained case.

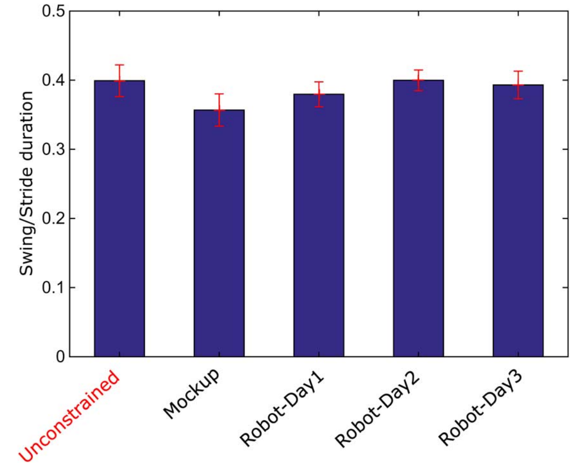

Fig. 10. Ratio of swing duration to stride duration (Mean $\pm$ Standard Error). No significant differences from the unconstrained case were observed.

TABLE II
STRIDE DURATION DATA

	Stride Duration [s]		Jarque-Bera test (p)	Significance (p) vs. Unconstrained condition
	Mean ±STD	Number of samples		
Unconstrained	0.42 ±0.072	12	> 0.50	N/A
Mockup	0.66 ±0.067	11	0.44	0.00
Robot-Day1	0.57 ±0.041	9	0.12	0.00
Robot-Day2	0.52 ±0.065	18	0.32	0.00
Robot-Day3	0.46 ±0.069	14	0.30	0.16

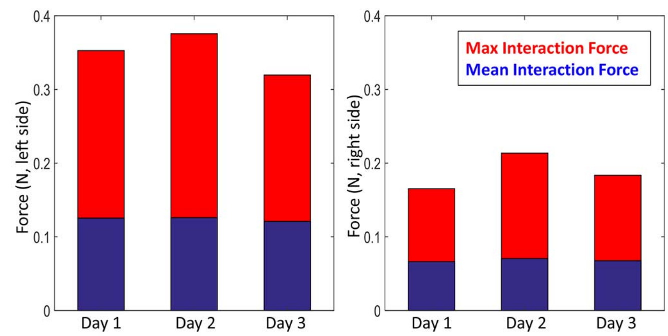

Fig. 11. Time-averages of interaction force magnitude during forward locomotion (blue), and the average peak interaction force. The left side showed larger interaction forces.

2.8% and 5.2%, respectively, of the animal's body weight. The occasional peaks of interaction force were around 0.15 to 0.2 N on the right side, and 0.3 to 0.4 N on the left side. While the left side exhibited larger interaction forces than the right side (due to large differences in the amount of static friction in the gearheads), there was no apparent trend or statistically significant difference between the data sets recorded during the three days when the active Rat Backpack was attached.

V. Discussion

This paper has presented the design of the Iron Rat system for rats and experiments for its initial evaluation. Like the apparatus presented by Nessler *et al.* [16] the Iron Rat permits direct interaction with the hindlimbs of the animal during locomotion. The two devices share design features such as having two 5-bar linkage mechanisms with two motors for each hindlimb, allowing only para-sagittal plane movements covering the workspace of the animal's ankle. The interaction force can be as low as 0.07 N (RMS value, present device) or 0.005 N (force control resolution, Nessler *et al.* [16]). However, a significant difference is that one allows overground movement and the other does not. This played a large role on the design choices in the two systems. While the system by Nessler *et al.* [16] could utilize mechanically grounded heavy motors with very low static friction, the Iron Rat system was built around miniature motors with gearheads and plastic linkages to reduce the size and weight of the wearable Rat Backpack. As a result the Iron Rat is capable of working directly with the hindlimbs of the animal while also permitting overground movement.

Although the apparatus was designed to interact with the hindlimbs of the animal while allowing it to move freely and voluntarily in an open area, the experiments were conducted using a 1D corridor shown in Fig. 5. The narrow 'hallway' was introduced solely to facilitate evaluation and is not an essential requirement for the use of this equipment. The animal quickly grew accustomed to the experiment including the preparation process of donning and doffing the Rat Backpack. The time required for two people to attach the active Rat Backpack to the rat was less than five minutes. Removing the apparatus from the animal required no more than two minutes.

The data obtained in this setup measure the similarity of spatial (stride length), temporal (stride duration) and cyclic (duty cycle) aspects of the gait with respect to unconstrained normal gait. After three days of exposure to the active Rat Backpack, the data measured during overground forward locomotion with the active Rat Backpack were not statistically different from those of unconstrained gait. Possible adaptation of stride duration occurred during the three days of the active Rat Backpack condition. The trend is even more visible if we consider the mockup condition as 'day-0' of the active Rat Backpack experiment, suggesting that the main cause of adaptation may be the kinematic constraint that required the two hindlimb ankles to move in approximately para-sagittal planes. While other possible causes of this phenomenon have not been ruled out, (such as the added inertia or the non-zero interaction force), it can be concluded that three days of 30-minute training with this apparatus were sufficient to achieve forward locomotion which approached that of a freely-moving rat, at least as indicated by these measures.

One remarkable observation was that Iron Rat allowed the stride duration to be as low as 0.4 seconds even with the active Rat Backpack attached (at an overground velocity of roughly 29 cm/s). Other studies using a treadmill-based device reported stride durations as long as 1.5 seconds [5] for animals similar to those used in this study (same strain, gender, age, weight and health condition). Note however that in [5] the treadmill speed was considerably slower (9 cm/s). Studies using healthy female Wistar rats of comparable size ($\sim$200 gram) walking on a treadmill with no constraint reported results comparable to those obtained here [25]. At 30 cm/s, the Wistar rats performed forward locomotion with stride duration of 0.432 ms and stride length of 141 mm, similar to our observations. The ratio of swing duration to stride duration during overground walking was reported to be 36% (28% while on treadmill), which is also quite comparable to almost 40% observed in our study.

On the other hand, for all three days when the animal was attached to the active Rat Backpack, it partially dragged its tail on the ground (Fig. 6). In contrast, during unconstrained locomotion the tail was constantly raised. The tail dragging did not disappear with further exposure to the apparatus. This phenomenon was also observed with the mockup, although the frequency of occurrence was lower. This may indicate a slight encumbrance due to the added inertia from the apparatus. However, factors such as the approximately sagittal plane constraint or the waist and ankle couplings may have also contributed to the tail dragging. Further investigation is required to discriminate among these possibilities. This observation suggests that the overall posture, especially that of the trunk, could be affected, even after the three days of adaptation. This could potentially alter the outcome of robotic gait training with this apparatus. Using the BBB Locomotor Rating Scale [21], the animal locomotion attached to the active Rat Backpack scored roughly 20.5 out of 21 (i.e. 98% of fully normal locomotion). However, this number must be interpreted with caution since the BBB scale was designed primarily to address rat locomotion during recovery from spinal cord injury rather than to assess impediments due to attached apparatus.

The mean interaction force measured at the ankles during forward locomotion with the active Rat Backpack was below 0.07 N (7 gram-force) on the right hindlimb. While this is less than 3% of the animal's body weight, it is not zero and thus may affect features of locomotion not addressed in this study. For example, changes in muscle activation patterns may have occurred over time as the animal adapted to the equipment. Further investigation is required to assess the effect of non-zero interaction force during locomotion. Nonetheless, it is clear that the interaction force was sufficiently low to allow forward locomotion that is qualitatively similar to that of an unconstrained animal. When required by the experimenter, larger interaction forces may purposefully be applied to the animal depending on the design of experiments.

The passive weight support also provides force on the Rat Backpack and eventually on the rat through the waist coupling. The spring shown in Fig. 6 provides an approximately vertical force of 75 grams. However, video analysis showed that the tension can deviate from vertical for as much as 15 degrees posterior, generating forces up to 20 grams opposite to the direction of movement (where the vertical component deviated no more than 3 grams). Added to the inertial forces due to the Rat Backpack (which are small but non-zero) the anterior/posterior force component may alter the gait of the animal in a way not detected by measures such as stride length or stride duration. This highlights the performance of the Rat Backpack and its force feedback scheme in the presence of a less-than-ideal BWSS.

The coupling to the waist kept the base of the Rat Backpack on the lower back of the animal. While the attachment between the animal's fur and the Rat Backpack was sufficiently secure to prevent the Rat Backpack from falling off despite the animal's vigorous movements, any point on the animal's skin can move relative to the muscles and bones underneath it for as much as several centimeters. As the base of the Rat Backpack carried the motors and encoders, the skin movement prevented the encoder readings from representing the end-effector position with respect to a landmark on the animal's skeleton (e.g. the pelvis), or with respect to a global reference frame (for example, defined by the body-weight support robot). A better estimate of the end-effector position would be available with a more secure waist coupling, or from an external position measurement device. Nonetheless, the encoder data collected from the current evolution of the apparatus may potentially be used to detect the initiation of swing, touch-down, or left-right hindlimb coordination. This is a topic for future research.

While skin movement complicated the interpretation of the encoder data, it did not affect the force reading since the force transducer was connected in series with the animal's hindlimb such that the force was common to both. Also note that skin movement is less pronounced near the ankle joint [26], justifying the choice to couple the end-effector to the skin at the lower tibia close to the ankle joint.

The Iron Rat system developed in this work is by no means perfectly transparent—the Rat Backpack has non-zero inertia, non-zero interaction force, kinematic constraints and elastic couplings. Walking with such a device cannot be identical to walking with zero encumbrance. In fact, evidence showed that movement with the Rat Backpack was not perfectly natural. For example, the animal's locomotion with the Rat Backpack did not score 21 on the BBB scale. Also, stride duration data (Fig. 9) showed a possible adaptation occurring over three days, suggesting that on day 1 and 2, the animal may not have been fully accustomed to walking with the Rat Backpack. While these are measurable limitations, results such as stride length, stride duration, and duty cycle provide quantitative assessment of the naturalness of animal locomotion with a device that can directly alter or assist hindlimb gait. The data suggest that our apparatus enables animal movement analogous to unconstrained overground movement at least in these three measures, even with the manipulator arms attached to the ankles—a vast improvement over what is permitted by other hindlimb interaction devices such as the Rat Stepper [16]. Rat locomotion in this apparatus is remarkably close to natural overground locomotion. Moreover, compared to the treadmill alternatives, the range of possible movements is significantly greater overground. The apparatus in [20] offers similar or greater movement freedom but provides no control over the animal's hindlimbs.

The Iron Rat system described here enables interacting with the overground quadrupedal locomotion of rats in ways that were not previously possible. First, the apparatus allows a wide repertoire of overground movement (Fig. 7). Being ‘on the ground’ is a more natural state for the animal as opposed to being in often intimidating artificial conditions, such as inside a cage with a treadmill and subject to electric shock if it fails to move fast enough [27]. In the apparatus described in this work, the animal is allowed to choose its own movement unless the device is programmed to facilitate a specific movement. Adaptation to the device implies a possible alteration of posture during gait but the animal would have to adapt its movement to any physical device. In the apparatus presented here, the adapted movement was still quite comparable to the animal's natural movement. In other words, in future experiments, the base of comparison or ‘reference’ could be the unconstrained, natural movement of the animal in an open space, and not a constrained movement on a treadmill [16]. For example, since the widely-used BBB scale is for overground locomotion assessment, it can readily be applied in experiments using the Rat Backpack as demonstrated above. However, because overground movement is often not possible in early stages of recovery from injury, the Iron Rat system may be most suitable during the intermediate and final stages of locomotor training [18].

Secondly, while the animal is on open ground, the apparatus allows physical interaction with hindlimb movement, affecting not only the kinematics but also the dynamics of overground locomotion. The two active manipulators with position and force sensors enable various form of forceful physical interaction to be programmed in software. For example, the novel locomotor training scheme developed in [6] may be implemented with this apparatus to assess its generalization to overground locomotion. Alternatively, the apparatus may be programmed to simulate an assistive device for overground hindlimb locomotion.

The Iron Rat system presented here may be used in conjunction with existing experimental arrangements such as an open area [1], 2D Mazes [2], [3], or a more complex 3D maze [4]. The apparatus can add an additional degree of control to these experiments, by providing preprogrammed perturbation and/or assistance as needed.

Despite the above advantages the system presented here also possesses notable drawbacks. Firstly, the current Rat Backpack is not readily adjustable to rats of various sizes and ages. This caused the design assessment experiments to be conducted on a particular rat which fit the Rat Backpack before the animal grew larger. Several sizes of manipulator arms on the Rat Backpack may be prepared in the future to address this issue. Even then, the system may be overly bulky to be used on smaller rodents such as mice. Another major weakness is the current BWSS. The robot shown in Fig. 3 operates with very low bandwidth ($<$10 Hz) and with position control only, requiring the use of tension springs between the BWSS and the Rat Backpack. This had minimal influence on the experiments with relatively constant forward locomotion velocity, which allowed manual compensation for the BWSS location (i.e. by pushing the cart). However, for future evolution of the system a real-time controllable BWSS is desired.

Although the apparatus developed in this work allows a wide range of overground movements, physical constraints imposed by the apparatus cannot be completely ignored. Future developments of the exoskeletal robot for overground rat locomotion may benefit from:

1) Reducing the number of wires between the Rat Backpack and the supporting hardware. Having too many wires encumbers the Rat Backpack and may also become problematic if the animal turns in place for multiple cycles, twisting the wire bundle. An early prototype of the apparatus attempted a fully wireless design but the communication lag was inadequate for real time control and the inertia and volume of the required onboard battery was excessive. Given recent improvements in wireless technology, it may be possible to reduce the number of wired connections between the Rat Backpack and the supporting hardware, although for power transmission wired connection may still be required.
2) The current waist coupling method is easy to put on and take off and simplifies animal preparation. However, it is not secure enough to prevent the Rat Backpack from shifting or tilting on the animal's body. An alternative waist coupling may use bone pins [7]—an invasive method which may complicate animal preparation. Nonetheless, that would greatly enhance the system's ability to track the position or force of the animal's ankle joint with respect to, for example, the hip joint. This would allow previously unavailable manipulations such as applying prescribed knee-hip joint torques, or a prescribed trajectory of the ankle joint with respect to the pelvic bone.
3) While the onboard encoders and force sensors provide useful information about rat locomotion, using dedicated external sensors may significantly improve the quality and volume of information. For example, the Vicon system used in [20] allowed the acquisition of individual hindlimb joint kinematics which was not available in this work. The video capture system used in the experiment is a simple illustration of an external kinematic sensor.
4) At the time of development, Maxon EC6 motor was the only actuator that satisfied the design requirements for size, weight and torque output. Future generations of actuators may improve the design of the Rat Backpack to be more compact and lightweight.

VI. Summary

The work reported here developed and demonstrated the Iron Rat, an exoskeletal robotic system that allowed free overground movement of a rat that appeared similar to unconstrained, voluntary movement, while also providing controlled physical interaction with the animal. The apparatus opens up a vast uncharted territory of possible experiments—far beyond those allowed by existing devices. We believe Iron Rat may enable research to pave the way for testing various robotic therapy protocols in rats, which will eventually translate to improving physical therapy provided to humans.

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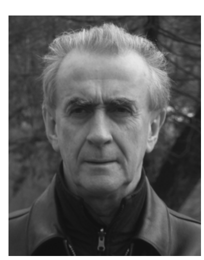

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