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Experimental Investigations into the Role of Passive Variable Compliant Legs for Dynamic Robotic Locomotion

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Abstract— **Biomechanical studies suggest that animals' abilities to tune their effective leg compliance in response to changing terrain conditions plays an important role in their agile, robust locomotion. However, despite growing interest in leg compliance within the robotics literature, little experimental work has been reported on tunable passive leg compliance in running machines. In this paper we present an empirical study into the role of leg compliance using a composite tunable leg design implemented on our dynamic hexapod, EduBot, with gaits optimized for running speed using a range of leg stiffnesses, on two different surface stiffnesses, and with two different payload configurations (0 kg and 0.91 kg). We found that leg stiffness, surface compliance, and payload had a significant impact on the robot's final optimized speed and efficiency. These results document the value and efficacy of what we believe is the first autonomous dynamic legged robot capable of runtime leg stiffness adjustment.**

I. Introduction

Animals have a sophisticated high degree-of-freedom musculoskeletal system that is extremely difficult to duplicate with motors and gears. However, biomechanical studies suggest that in spite of this sophistication there are behaviors and responses that can be captured with simple mechanical models. One such response is that animals appear to adjust their leg stiffness when confronted with changes in speed, payload, and terrain [9] [8] [10] [11] [12]. We speculate that in order to close the performance gap between the two systems and thereby improve the utility of legged robots, tunable leg stiffness will play an integral part in future robotic systems.

Legged systems have typically been modeled in some fashion as a mass on top of spring which bounces like a pogo stick [6]. In one simulation, results suggest that for changes in a robot's body mass (i.e. payload changes) adjusting leg stiffness without changing the controller adapted for a particular set of physical parameters, gives stability results in general better than those obtained by optimizing the controller alone [23]. In another study, simulation results suggested that to achieve a large range of speeds and regions of stability, legs with adjustable joint stiffness are needed [18]. A monopod simulation by [16] suggested that active leg stiffness adjustment could be beneficial for maintaining energy efficient gaits in response to changes in speed, payload, or terrain.

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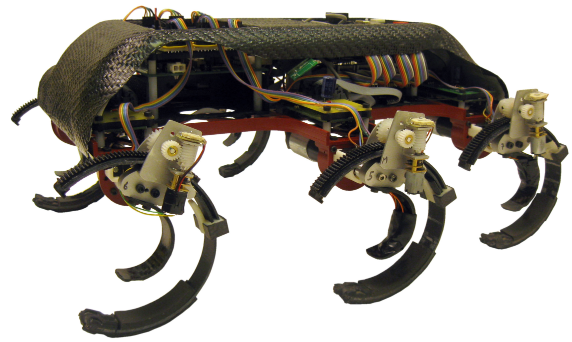

Fig. 1. An image of a fully assembled EduBot with tunable stiffness C-legs.

While simulations suggest tunable legs can add value to locomotion performance, little experimental work has been done to explore the role of mechanical leg compliance, especially tunable passive leg compliance, on a physical system. This is in part due to the fact that research in this arena requires access to a robust, dynamic legged robot of which very few exist. Of those that do, most leg development innovations have produced fixed stiffness passive compliant mechanisms [1], [3], [7], [24], and [25]. One of the limitations of fixed leg stiffness is a reduced adaptability of the final leg mechanism as it usually performs optimally for a small range of conditions such as running frequency or ground stiffness. Part of the difficulty in designing a tunable stiffness leg lies in the competing constraints of size, strength, flexibility, weight and final integration of the robotic appendage. Novel designs are required to meet these heretofore unmet stringent design requirements and to give robotic structures the kind of adaptability and robustness found in nature. Because analytical prescription of gait control parameters for passively compliant legs has only recently begun to advance to practice [20], [2], absent an experimental platform capable of running with variable passive stiffness, it remains impossible to understand how to apply the lessons from simple models and animals to improve the performance of legged robotic systems.

There are a only a few experimental studies that have suggested the value of mechanically adjusting leg stiffness for dynamic locomotion. For example, Raibert's Planar Biped featured an air spring in series with a hydraulic actuator which controlled the resonant bouncing motion, the air spring pressure (i.e. leg stiffness), and leg retraction. To our knowledge this platform demonstrated the earliest known implementation of robotic leg stiffness adjustment for a dynamic locomotor. Raibert et al. found that increasing the leg stiffness by increasing the air pressure in the legs allowed the robot to run faster [17]. It should be noted though that the Planar Biped was tethered to a compressed air source

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which is a rather inefficient method to pursue for leg stiffness adjustment in an autonomous vehicle.

In a more recent example, Thumper [16] is a segmented leg with fixed joint stiffness. Preliminary, tunable leg stiffness studies were conducted by physically removing its fiberglass spring and inserting ones of higher or lower stiffnesses back into the antagonistic arrangement. While only three different spring stiffnesses were tested, this monopod was able to experimentally demonstrate that adjusting spring stiffness could lead to energy efficient gaits. It should be noted that Thumper was attached to a boom and pivot point and constrained to run in circles.

In this paper we present an in depth experimental investigation into the role of leg compliance for dynamic locomotion. In particular we use our hexapod, EduBot (shown in Figure 1), to evaluate the role of leg stiffness, surface compliance and payload on the robot's overall speed and efficiency. The remainder of the paper describes this investigation in the following manner. In section II, we briefly review the mechanical design of the tunable stiffness C-leg. Section III covers the experimental set-up and the method by which running performance is measured. Section IV presents the experimental results with a discussion, and we offer concluding remarks in section V.

II. Tunable Leg Mechanical Design

The tunable stiffness legs used in our running experiments is a continuation of our earlier work [14] where we presented a composite tunable stiffness leg design that uses the method of structure-controlled stiffness to adjust the compliance of a C-shaped leg (see Figure 2). A self-locking actuation system was integrated into the leg to adjust the position of a compliant slider which serves as the tuning element to adjust the effective leg stiffness. A rotary sensor attached to the shaft of a small DC motor offers a means to detect the stiffness setting (i.e. the position of the compliant slider). Since our publication of this design, there have been two incremental improvements. First, a slip ring motor mount assembly was designed and implemented to electrically connect the robot body to the continuously rotating C-legs. This enables the robot to pass power to the DC motor on each tunable leg and to count revolutions of each rotary sensor. The particulars of the slip ring motor mount assembly can be found in [13]. In Figure 3, we present images of the actual tunable leg design where viewing the images from left to right, the leg compliance was commanded to increase. The second design improvement was the integration of a rigid, C-shaped mechanical stop (see Figure 2), which enables the robot to explore the role of lower stiffness legs that would otherwise fracture during uneven loading events. More information regarding the design and development of the composite tunable C-leg can be found in [13] and [14].

Lastly, it should be noted that leg stiffness adjustment can be performed during operation. In a simple set of walking experiments, EduBot was able to stop, change its leg stiffness, and continue walking. After performing these tests, we expect that in future developments EduBot should not have to stop, but instead could actively adjustment its leg stiffness while moving.

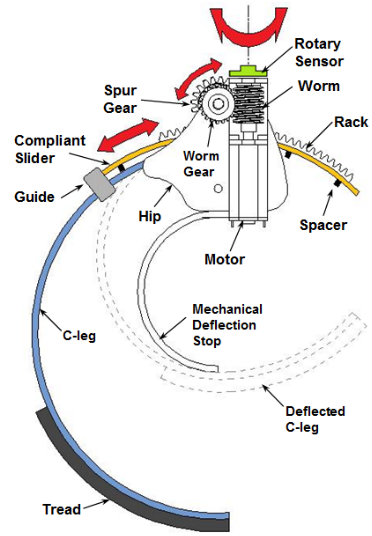

Fig. 2. A side view of tunable stiffness composite leg design. A small dc motor drivers a worm gear mechanism that controls the travel direction of the compliant slider. The compliant slider is the tuning element that ultimately increases or decreases the stiffness of the C-leg.

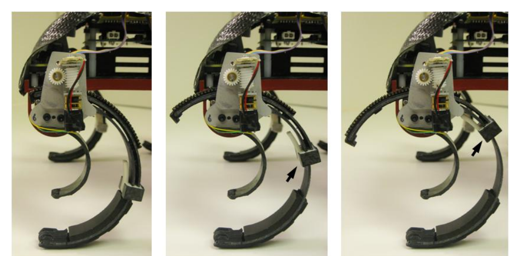

Fig. 3. Side view of the leg actively adjusting its leg stiffness where A) the leg is at its stiffest setting, B) the slider position moves up to a softer stiffness as indicated by the black arrow, C) the slider has traveled as far as possible where the leg is at its softest stiffness setting.

III. Experimental Set-up

Creating a useful model for this dynamic running hexapod is complicated by a high dimensional gait space, non-linear leg springs, and environmental conditions such as friction coefficients and ground-body interactions [22]. In particular the gait space used to control this system is composed of six parameters namely the 1) the stride period which specifies the rotation frequency, 2) the stance phase (or stance sweep angle) which is a portion of the leg rotation that is slowed to allow the leg to store and return strain energy, 3) the duty factor which is a percentage of the stride period that specifies the rotation frequency during the stance phase, 4) the leg offset angle specifies the angular position of the stance phase during a leg rotation, 5) the proportional gain, and 6) the derivative gain at each of the six motors. More details of the gait parameters can be found in [19] [22]. Careful tuning of all these parameters can lead to very fast and efficient locomotion and impressive performance on even the roughest terrains. As reviewed in the introduction, despite longstanding analytical efforts [2] and a growing body of theoretically informed numerical [4] and empirical [20] study, no body of theory yet exists that can predict the effect of controller gains and body and leg mechanics on locomotion performance.

Hence gait development and performance evaluation requires that experimentation be conducted on the actual robot.

Locomotion experiments were conducted using an automated optimization routine similar to the method used to optimize gaits for RHex, EduBot's predecessor [21]. More specifically, a Nelder-Mead optimization routine was used which is a non-linear technique that can find a locally optimum solution for systems with several variables. In [21], Nelder-Mead was employed to optimize RHex gaits and was able to identify gait parameters that enabled a nearly 3x increase in forward velocity over the best hand tuned gait. EduBot gait tuning relied on a Vicon motion capture system to control the robot during all aspects of the experiment. Reflective tracking markers mounted to the robot shell allowed the controller to accurately and repeatably steer the robot from one end of the test arena, known as an *end zone*, to the other. The length of each run measured approximately 7.6 meters (25 feet) with the first 35% reserved for acceleration, and the last 5% reserved for deceleration. The robot's center of mass was tracked with sub-millimeter precision at a frequency up to 120 Hz. During each trial (i.e. running from one end zone to the other), the average power and average velocity were recorded. These values were used to calculate the specific resistance, f_{sr}, which is a dimensionless parameter that characterizes energy efficiency as the ratio of average power in over average power out. It has become a useful metric for comparing the energetic performance across a range of locomotion platforms including legged ones [1]. Specific resistance is typically written as

$$f_{sr} = \frac{P_{avg}}{mgv_{avg}} \tag{1}$$

where P_{avg} is the average power consumed, m is the mass of the robot (EduBot weighs 3.3 kg), g is gravity, and v_{avg} is the average velocity recorded for a given set of gait parameters. It should be noted that for all of the running experiments P_{avg} is measured from the battery and therefore includes the power needed to run the microprocessor as well as the motors. The power consumed by an idle EduBot (i.e. no motor actuation) is approximately 10.7 Watts.

For situations in which we want to identify fast running gaits a useful velocity weighted version of specific resistance [21] can be represented as

$$f_v = \frac{P_{avg}}{mgv_{avg}^3} \tag{2}$$

We experimentally found that Nelder-Mead optimizations with f_{sr} as a cost function typically converge to dynamic, though relatively slower gaits on the order of 1 – 1.2 m/s. Optimizations with f_v as a cost function converge to faster gaits on the order of 1.6–2.6 m/s depending on leg stiffness and payload. As one would expect [15], these faster gaits tend to be more unstable to perturbations at higher speeds. We corroborate past empirical observation [22], [21] that low f_{sr} and f_v values are the signature of a relatively stable gait. An unstable gait is energetically wasteful with high f_{sr} and f_v values. Visually this takes the form of excessive body pitching and rolling with considerable slipping. In the following sets of experiments we are interested in fast gaits, and therefore used f_v as a cost function; however, perfomance is reported in terms of specific resistance, f_{sr}, to promote standard comparison within the robot locomotion literature previously cited.

IV. Tunable Leg Experiments

A. *Optimizing Fixed Stiffness Legs for Speed on Carpet*

Previous optimization studies on RHex primarily focused on boosting robot performance through gait parameter adjustment [21]. A constant stiffness C-leg was used, and no other leg stiffnesses were explored. In preliminary optimization experiments, we sought to understand the role of leg compliance with EduBot, which has been shown to be geometrically and dynamically similar to RHex [13]. This topic was first explored using fixed stiffness C-legs so as to eliminate any effects a tunable leg might introduce. Five sets of C-legs were prepared with the stiffest leg being approximately 3.6x the stiffer than the most compliant leg. The legs were constructed from S2-6781 pre-preg fiberglass. The leg stiffness was set during manufacturing by either changing the number of layers of fiberglass or the leg width. The softest leg used 5 layers (5L) while the stiffest leg used 9 layers (9L). The leg labeled 6.5L is actually a 7 layer (7L) leg with a width that was reduced from 18 mm to 15 mm. This was done in order to quickly obtain a leg stiffness that fell in between a 6L and a 7L. To compare the stiffnesses of these legs, we use a scale called *relative leg stiffness* (RLS), where a 6L leg is used as a reference leg and has a RLS value of 1. Table I specifies the conversion of RLS to a radial stiffness value. This conversion is described in [5]. A Nelder-Mead descent was performed for each combination of leg stiffness and two different payloads: 0 kg and 0.91 kg. The payload was in the form of steel plates that were secured to the belly of the robot and positioned so as not to shift the robot's projected center of mass.

Fixed Stiffness C-leg					
Layers of Fiberglass	5L	6L	6.5L	7L	9L
Relative Leg Stiffness (RLS)	0.85	1	1.3	1.6	3.1
Radial Leg Stiffness (N/m)	1090	1280	1660	2050	3970

TABLE I
This table specifies the conversion from relative leg stiffness to radial leg stiffness for the variety of fixed stiffness C-legs.

EduBot typically converged to suitable gaits after 70+ trials. In most cases as the optimizer converged on suitable gaits minor adjustments were made to the gait parameters on successive runs. We therefore used these similar gaits to calculate the average and standard deviation of the measured specific resistance as well as the resulting forward speed.

It can be observed in Figure 4 that adding a payload results in a lower specific resistance; however, what is most revealing in Figures 4 and 5 is that increasing leg compliance

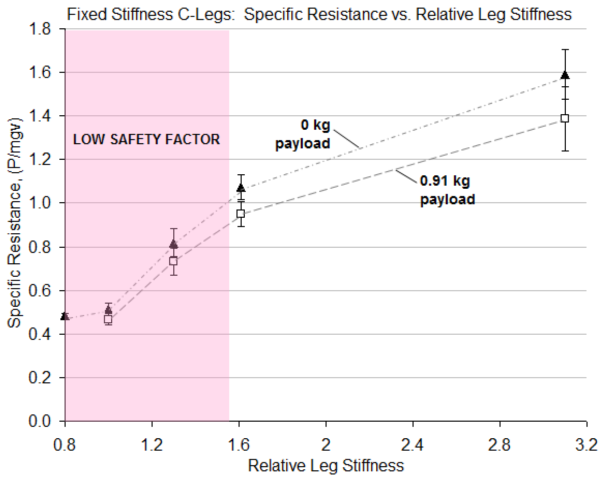

Fig. 4. Data from fixed stiffness C-leg optimization experiments with specific resistance plotted against relative leg stiffness for two payload configurations. The 6L leg is the reference leg stiffness with a relative leg stiffness value of one.

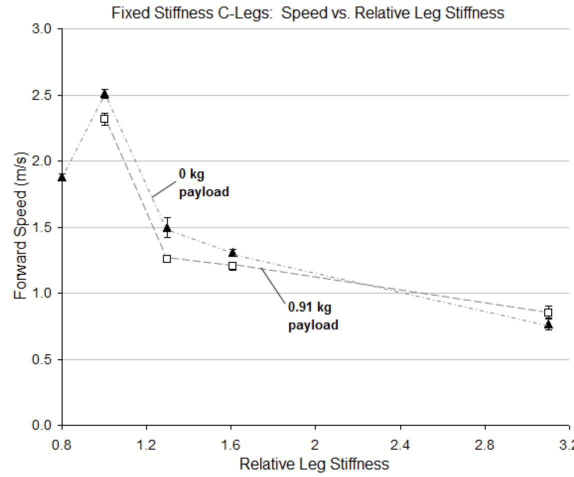

Fig. 5. Data from fixed stiffness C-leg optimization experiments with the resulting forward speed plotted against relative leg stiffness.

Tunable C-Leg				
Relative Leg Stiffness (RLS)	0.5	0.62	0.75	0.87
Radial Leg Stiffness (N/m)	640	800	960	1110

TABLE II

THIS TABLE SPECIFIES THE CONVERSION FROM RELATIVE LEG STIFFNESS TO RADIAL LEG STIFFNESS FOR THE TWO TUNABLE LEGS.

improved speed and efficiency up to a point. Figure 5 shows that the no-load average forward speed for a 9L, 7L, 6.5L, 6L, 5L is approximately 0.85, 1.31, 1.5, 2.51, and 1.9 m/s respectively. These results indicate that the value of tunable leg compliance likely exists near 1 RLS or lower where f_{sr} is lowest and achievable speed is highest.

We also suspect that the softer legs (5L and 6L legs) are better suited for maintaining robot stability especially in the face of an uneven tripod stance phase. For example, if a stiff leg touches down early (i.e. closer to the hip than to the toe) then the leg is essentially a rigid element absorbing little energy. The leg falls behind the desired leg position dictated by the PD controller, and consequently the robot inserts considerable torque in a short time interval. This has the effect of inserting poorly timed energy into the system which creates pitching and rolling moments of the robot body that cause instability on the next tripod stance phase. Therefore, the stiffer legs appear to narrow the region of stable gaits. Compliant legs on the other hand are more capable of deflecting and absorbing energy even if the leg touches down early, which minimizes the severity of ground reaction forces imparted to the body.

While the softer legs (especially the 5L and 6L) were the top performers, there was an increased occurrence of leg failure as the payload increased (see the shaded region labeled *low safety factor* in Figure 4). This is one of the drawbacks of the dual nature of passive compliant legs (i.e. as a structural support appendage and a spring). These results motivated the inclusion of the mechanical rigid C-shaped mechanical stop to protect these legs from failing.

B. Optimizing a Tunable Leg for Speed on Carpet

The fixed leg stiffness experiments suggest that EduBot runs fastest and most efficiently near 1 RLS or lower. For this reason, the tunable leg presented in Section II was assembled such that its relative stiffness range spanned 0.5 to 0.87 (Table II specifies the conversion to radial stiffness). Nelder-Mead optimizations were run on carpet at the two relative leg stiffness extremes with and without a payload of a 0.91 kg. Additional data were collected for 0.62 and 0.75 RLS with a 0.91 kg payload and for 0.75 RLS without a payload. Figure 6 is a plot of the mean and standard deviation of the top ten results from each optimization with specific resistance on the y-axis and forward speed on the x-axis. Here we assume good gaits occupy the bottom right hand corner of the graph where speed and efficiency are rewarded.

For the no payload configurations (see items A, B and C in Figure 6), the softest leg setting (A) converged to a slower gait while the stiffer leg settings (B and C) converged to faster gaits. We do observe though that specific resistance does not vary significantly between the gaits and their respective leg stiffnesses. This suggests that even though the robot runs slower at the softest leg setting it runs nearly as efficiently as a faster gaits with the stiffer leg settings. One will notice that the robot performed the best at 0.75 RLS, and not at 0.87 RLS as one would expect given the results from the fixed leg stiffness experiments. We suspect that this is due to a mechanical design oversight. The guide (see Figure 2), which holds the compliant slider against the C-leg, protrudes about 2 mm past the thickness of the tread and is likely interfering during touch down.

For the experiments carrying a 0.91 kg payload, we observed a wider separation in speed and efficiency between the leg stiffness extremes. For the higher leg stiffness experiments (E, F and G), adding a payload produces a significant improvement in efficiency with a very minor improvement in speed. For example, for the stiffest leg setting (0.87 RLS), we found a 24% increase in efficiency when the payload was added (see B and G in Figure 6).

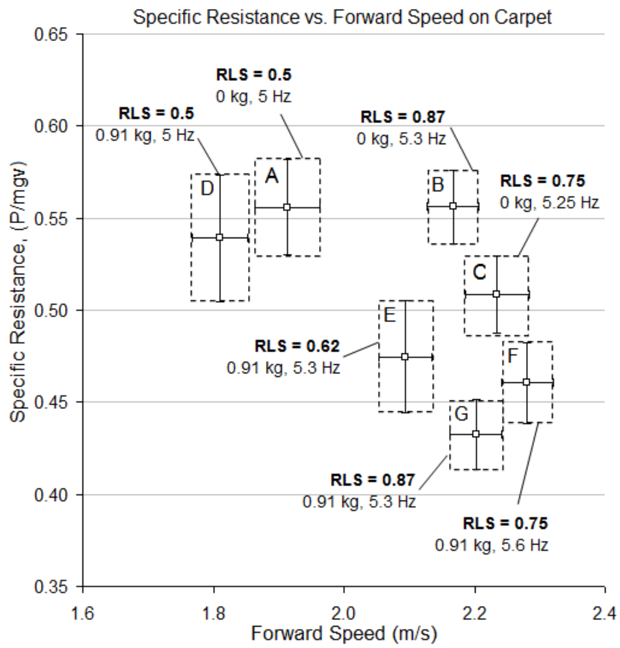

Fig. 6. Specific resistance vs. forward speed results for EduBot running on carpet.

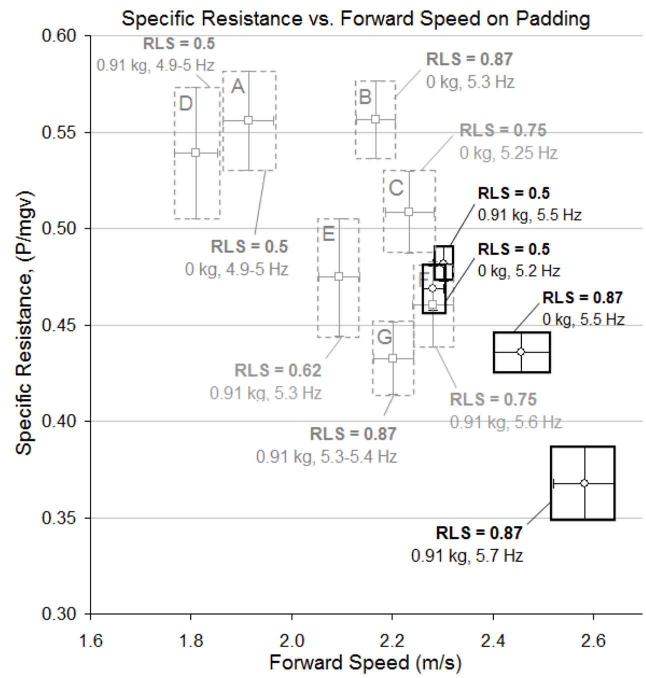

Fig. 7. Specific resistance vs. forward speed results for EduBot running on padding. The grayed portions of the graph offer a comparison of the results from running on carpet found in Figure 6. The data suggests that for a robot carrying no payload, soft legs (0.5 RLS) allow efficient locomotion albeit with a slower top speed. When a payload is added and/or the surface compliance increases stiffer legs offer better locomotion performance in both speed and efficiency.

The results also suggest that softer leg settings are speed limited. At the softest leg setting (see D in Figure 6), we find that the robot converged to a slower gait with a minor improvement in average efficiency. This response may be in part due to this particular leg design. The configuration with a soft leg setting and a payload caused the C-leg to deflect into the mechanical stop. This most certainly prevented leg failure; however, the leg's collision with the mechanical stop imparts poorly timed impulse forces to the body which contribute to unstable gaits at high speeds.

C. Optimizing a Tunable Leg for Speed on Padding

During previous operation with RHex it was noted that the hexapod seemed to run better on grass than on harder surfaces. To evaluate the influence of surface compliance on RHex-like locomotors with tunable legs, the optimization experiments were repeated on 12.7 mm (1/2") thick carpet foam padding. Samples of the carpet and padding were compressed in an Instron machine, and the force-deflection data revealed that the stiffness of the carpet was on the order of 20 kN/m while the stiffness of the padding was approximately 5 kN/m. This represents about a 4x change in surface stiffness. For the purpose of comparison, Figure 7 shows the speed and specific resistance results for running on carpet in gray.

The results in Figure 7 suggest that altering surface compliance can produce a significant shift in robot performance. For each leg stiffness and payload configuration EduBot ran faster and more efficiently on padding compared to the same configurations on carpet. For example, EduBot with a 0.87 RLS and a payload ran 14% more efficiently and approximately 17% faster on padding over the same configuration on carpet. Earlier stated trends also appear to hold where stiffer legs converge to faster gaits and softer legs appear to be speed limited. It can be observed in Figure 7 that the soft leg experiments (with and without a payload) converged to gaits of nearly the same speed and efficiency.

While the padding increased the surface compliance there are other inherent physical properties that can not be decoupled. For example, the padding material adds damping which may smooth out otherwise unstable gaits. Additionally, the leg can sink into the padding more than carpet, which we suspect increases contact area thereby improving traction. There is some evidence that the improved traction allowed the robot to run faster. A relatively fast gait (0.87 RLS, 4.79 Hz, duty factor = 0.397, leg offset angle = -0.330 rad, sweep angle = 1.473 rad, kp = 0.239, kd = 0.024) that was stable on carpet had an average forward speed of 1.75 m/s where as the same gait on padding achieved an average speed of 1.92 m/s. We speculate that since this gait was stable on carpet, the damping effects of the padding had a small contribution to the observed speed increase. Thus, improved traction may explain why the robot ran faster even at the softest leg stiffness setting.

D. Optimizing a Tunable Leg for Speed on Grass

In addition to running on man made surfaces, optimizations were also performed on a commonly encountered real world surface: grass. It is important to consider real world surfaces as there are generally interactions and behaviors that can not be produced in the lab with man made surfaces. To maintain consistency in our optimization methods, a sod track measuring 6 ft. x 25 ft. (1.82 m x 7.62 m), was assembled in the motion capture arena (see Figure 8). The grass had an approximate blade length of 3 inches with about 3/4" of

Fig. 8. Picture of EduBot on grass terrain.

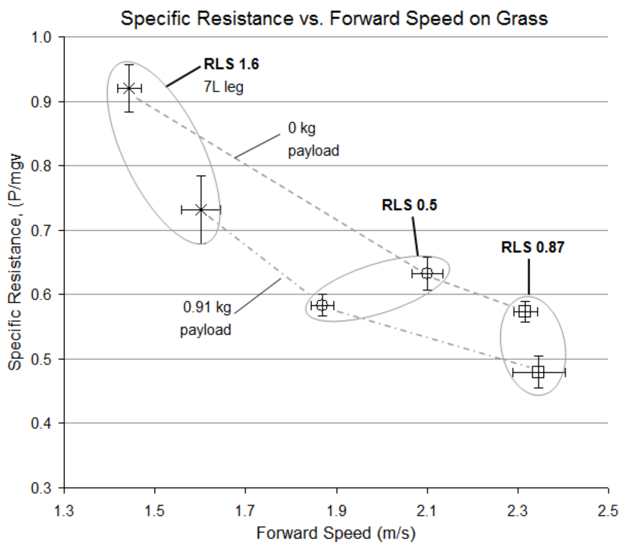

Fig. 9. Data from the optimization experiments showing that the stiffest tunable leg setting (RLS = 0.87) ran the fastest. Results from a fixed stiffness C-leg (1.6 RLS) further confirm that there is a limit to the value of increasing EduBot's leg stiffness.

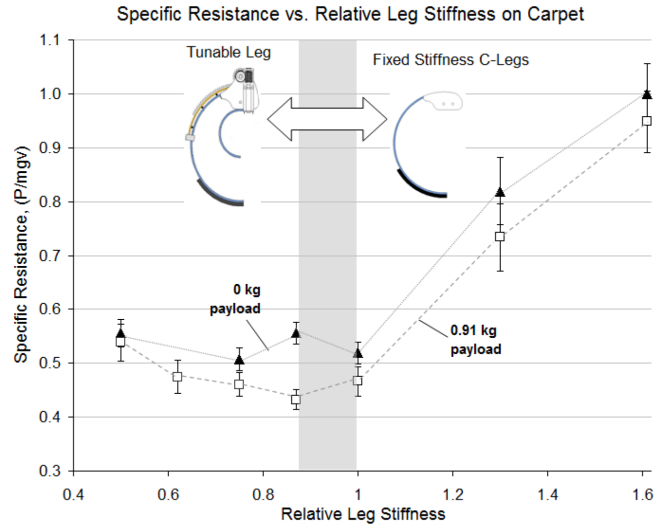

Fig. 10. Data from the optimization experiments showing specific resistance results from tunable leg and fixed stiffness leg optimizations on carpet.

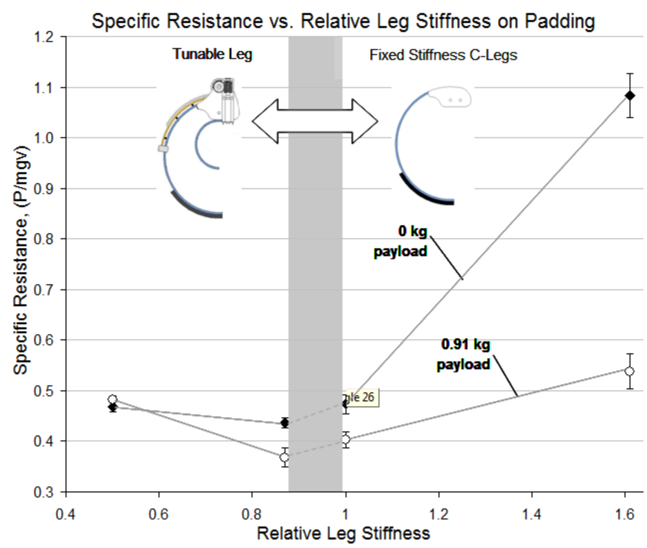

Fig. 11. Data from the optimization experiments showing specific resistance results from tunable leg and fixed stiffness leg optimizations on padding.

root and soil support. Tunable leg optimization experiments were run at the softest and stiffest leg settings with and without a payload (0.91 kg). An additional optimization was conducted with a 1.6 RLS fixed stiffness leg as well.

These results (see Figure 9) show a resemblance to the results obtained from optimizing on carpet and padding. We find that EduBot runs fastest and most efficiently at 0.87 RLS with and without a payload. The robot runs slower with a marginal decrease in efficiency at 0.5 RLS. The results further support earlier evidence that 1.6 RLS legs are simply too stiff for EduBot and yield slow, inefficient gaits.

In these particular experiments, we observed that some gaits performed poorly because the worm gear mechanism became tangled in the matrix of dead grass near the soil surface, a problem to be remedied through the introduction of a cover in future design iterations.

E. Tunable Leg Optimization Discussion

We have shown that varying leg stiffness for a given payload and terrain can lead to gaits with a range of speeds and efficiencies. For the last part of this analysis we draw additional insights into the role of leg compliance by stitching together tunable leg and fixed stiffness leg experimental results. In Figures 10 – 12, the tunable leg results are plotted to the left of the gray divider and select fixed leg stiffness results are on the right. In Figures 10 and 12, one can see that the stiffness range of the tunable leg offers efficient locomotion for a range of fast speeds on carpet and that extending the leg stiffness much beyond 1 RLS will result in slower and less efficient gaits. For the padding experiments, one can see in Figure 12 that EduBot is capable of running faster at every tested leg stiffness setting where speed is maximized near 1 RLS.

V. Future Work & Conclusion

A topic that requires further investigation is the role of leg compliance for EduBot's slow to intermediate speeds

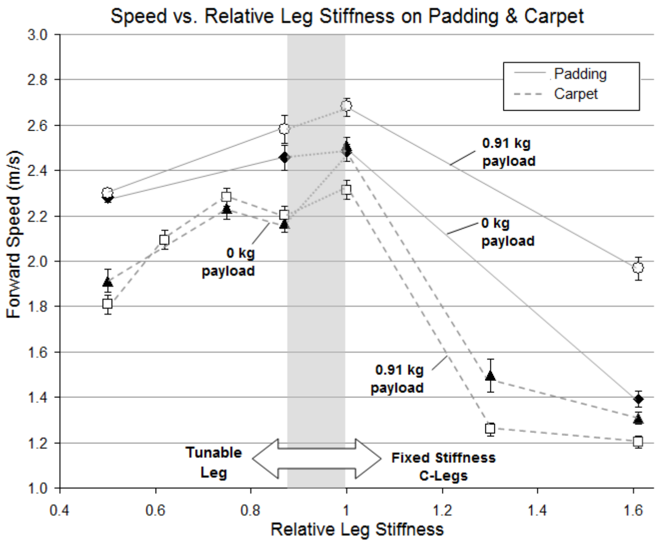

Fig. 12. Data from the optimization experiments showing forward speed results from tunable leg and fixed stiffness leg optimizations on carpet and padding.

(1.2 – 1.8 m/s). In our experiments, we optimized for speed resulting in gaits with forward speeds of 1.8 – 2.6 m/s. From these experiments we found that softer legs would not allow the robot to run as fast as stiffer legs, however their specific resistance values were not significantly different even though they were running slower. This and preliminary results presented in [13] suggests that lower stiffness legs may allow the robot to locomote more efficiently at intermediate speeds than stiffer legs. Intuitively this makes sense as one would expect a lower leg stiffness to be better suited at lower driving frequencies.

In this work, we have presented empirical results which suggest that passive variable stiffness legs can improve the performance of a dynamic running robot. The results from thousands of running experiments revealed that a RLS $\approx$ 1 allowed EduBot to run fast and efficiently. Increasing leg stiffness much beyond this point produced slower and energetically wasteful locomotion. On stiffer terrains (with no mass added), a softer (0.5 RLS) leg (item A in Figure 6) appears to be nearly as efficient as stiffer legs (items B and C in Figure 6) albeit with a slower top speed. However, on softer terrain or with an added payload, the results suggest that stiffer (0.87 RLS) legs enable faster and more efficient locomotion than softer (0.5 RLS) legs–showing that having adaptive leg compliance can improve locomotion speed and efficiency for changing terrains and payloads. To our knowledge, this is the first experimental evidence demonstrating the utility of tunable leg compliance on an autonomous dynamic running robot.

VI. ACKNOWLEDGMENTS

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