On Prismatic and Torsional Actuation for Running Legged Robots

Bruce D. Miller, Jason M. Brown and Jonathan E. Clark

Abstract Among the challenges faced when developing dynamic, legged platforms are the manner and mechanisms utilized to modulate system energy. A great deal of success has been demonstrated by low degree of freedom platforms that rely on either pure torsion or thrusting to provide the requisite locomotive power. However, means of synergizing these approaches and the potential benefits thereof are not well understood. In this study, the effects of torsional and prismatic energy addition on running performance are investigated, both in isolation and as a hybrid approach. By allowing both mechanisms to be used in tandem, improvements to speed, stability and efficiency are noted. Additionally, these results suggest that rather than utilizing prismatic and torsional actuation to provide an even distribution of power, inhomogenous power generation may lead to futher performance benefits. This study not only examines the degree of actuator hybridization that leads to improved running, but also identifies the fundamental mechanisms by which these two approaches affect performance. These insights, in turn, provide physical intuition for the design of future legged platforms of more complex morphologies.

1 Introduction

Using legs, animals are able to dexterously negotiate a multitude of environments that often stymie conventional mobile robots. This has led to numerous studies aimed at understanding the fundamentals of legged locomotion (e.g. [6, 10, 13]) and developing robust and versatile technologies for application on robotic platforms (e.g. [23, 27]). Among the challenges facing these mechanical, legged systems is the manner by which they are actuated. Animals are able to leverage an over-actuated composition of controlled and passive degrees of freedom to produce effective locomotory behaviors utilizing a combination of highly-tuned joint compliance and coordinated

B.D. Miller · J.M. Brown · J.E. Clark (✉)
FAMU & FSU College of Engineering, 2003 Levy Avenue, Tallahassee, Fl, USA
e-mail: Jeclark@fsu.edu

B.D. Miller
e-mail: bdmiller@fsu.edu

M.A. Hsieh et al. (eds.), *Experimental Robotics*, Springer Tracts
in Advanced Robotics 109, DOI 10.1007/978-3-319-23778-7_2

muscle activation [15]. However, the implementation of similarly complex artificial systems, both from a mechanical design and a controls standpoint, poses a significant technological hurdle.

An alternate solution is to model the animal behaviors resulting from complex neuromusculoskeletal interactions with simple, reduced-order dynamical templates [8], which can in turn be anchored by low degree of freedom platforms. This approach has resulted in remarkable success, as evidenced by robots such as RHex [22] and iSprawl [14], along with many others. These platforms in particular epitomize two of the most common approaches for actuating legged runners, which can be categorized as *torsionally* and *prismatically* actuated systems. Torsional actuation, as demonstrated by the RHex-family, is characterized by incorporating locomotive energy via torque applied at the hips while linear motion between the hip and ground contact is passively regulated as a function of the tuned limb compliance. Conversely, prismatically-actuated platforms, such as the Sprawl-family, modulate system energy via extension and retraction of the nominal limb length while relying on tuned linear and rotational passive compliant elements to redirect the energy into stable, forward locomotion.

Both of these techniques have been utilized with a high degree of success. However, the particular advantages afforded by each method of actuation are not well understood. Preliminary investigations comparing these approaches have only considered particular instantiations of strictly prismatic or strictly torsional actuation [16]. Conversely, studies that examined hybrid systems have primarily utilized multi-variate optimization [21] or have limited consideration to particular coordination schemes [11]. Additionally, many applications intrinsically require the use of limbs with multiple controlled degrees-of-freedom (e.g. dexterous manipulation or reconfiguration) and an improved understanding of energy incorporation may facilitate hybrid actuation schemes that leverage the already available actuators. In this study, we explore the underlying effects of simple and feed-forward prismatic, torsional and hybrid actuation on the gait characteristics of running systems and aim to ascertain the mechanisms by which they improve or hinder performance. Furthermore, we present a novel, dynamical legged platform able to implement and investigate this hybrid approach on a physical system.

2 Modeling and Simulation

To investigate the effects of torsional and prismatic actuation on running, we turn to reduced-order templates. Such models provide a lens for exploring the dynamics of running while reducing the confounding couplings that arise from the additional free parameters and degrees of freedom in more complex models. In this work, attention is focused on the spring loaded inverted pendulum (SLIP) model. This model captures the sagittal plane dynamics of running [4] and has been shown to produce similar whole-body dynamics to biological [5, 7, 25] and robotic runners [2, 3, 20].

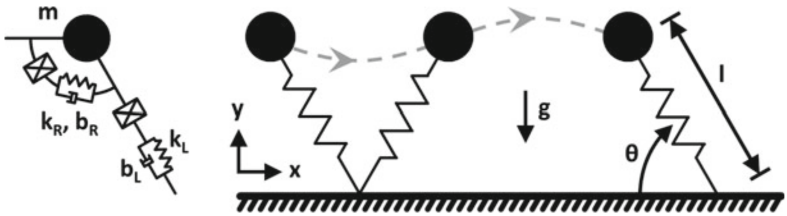

Fig. 1 Depiction of the SLIP model and the nominal trajectory that it follows over the course of a step. The parameters m, k_L, b_L, k_R, b_R and g correspond to the system mass, linear stiffness coefficient, linear damping coefficient, rotational stiffness coefficient, rotational damping coefficient and gravitational acceleration. The crossed boxes in series with the linear and rotational components represent the linear and rotational actuators driving the rest leg length l_{rest} and rest leg angle θ_{rest}, respectively. The variables x and y are the coordinates used for flight phase dynamics while l and θ are the coordinates used for stance phase dynamics

2.1 The Spring Loaded Inverted Pendulum Model

In its most basic form, the SLIP model is composed of two simple elements: a body, modeled as a point-mass, and a leg, modeled as a linear spring that is affixed to the body. A modified form of the model is utilized in this work that allows for both passive and active modulation of the system energy, as shown in Fig. 1. A damper element is added in parallel with the linear spring and a linear actuator is added in series to modulate energy along the leg axis. Additionally, a spring-damper element in series with a torsional actuator is added at the joint connecting the body and the leg. These extensions to the model provide both linear and rotational mechanisms to add or remove energy during locomotion.

The trajectory of the model progresses following the hybrid dynamics of stance and flight phases. Stance begins when the distal end of the unsprung leg contacting the running surface. This initiates a point-contact that acts as a pin joint about which the system rotates. As the body moves forward, the leg spring compresses and decompresses, redirecting the body and accelerating it to the point of lift-off. This event occurs when the ground reaction force at the leg-surface contact drops to zero. Following this occurrence, the system moves forward through the air following ballistic dynamics as the leg resets prior to the next touch-down event.

While the governing dynamics during flight can be simply described by

$$\begin{aligned} \ddot{x} &= 0, \\ \ddot{y} &= g, \end{aligned} \tag{1}$$

expressing the equations of motion that govern the stance behavior requires a more detailed examination of the SLIP model. Using the Euler-Lagrange approach, we begin by describing the kinetic and potential energies of the system

$$T = \frac{1}{2}m\dot{l}^2 + \frac{1}{2}m\left(l\dot{\theta}\right)^2,$$
$$V = \frac{1}{2}k_L\left(l_{rest} - l\right)^2 + \frac{1}{2}k_R\left(\theta_{rest} - \theta\right)^2 + mgl\sin\theta, \tag{2}$$

which can be used to calculate the Lagrangian

$$\begin{aligned}\mathscr{L} &= T - V,\\ &= \frac{1}{2}m\left(\dot{l}^2 + l^2\dot{\theta}^2\right) - \frac{1}{2}\left(k_L\left(l_{rest} - l\right)^2 + k_R\left(\theta_{rest} - \theta\right)^2\right) - mgl\sin\theta.\end{aligned} \tag{3}$$

Additionally, the nonconservative terms (i.e. damping) can be expressed as

$$\begin{aligned}Q_{nc_L} &= b_L\left(\dot{l}_{rest} - \dot{l}\right),\\ Q_{nc_R} &= b_R\left(\dot{\theta}_{rest} - \dot{\theta}\right).\end{aligned} \tag{4}$$

Substituting (3) and (4) into the Euler-Lagrange equations, the equations of motion governing the stance dynamics can be derived as

$$\begin{aligned}\ddot{l} &= l\dot{\theta}^2 + \frac{k_L}{m}\left(l_{rest} - l\right) - \frac{b_L}{m}\left(\dot{l}_{rest} - \dot{l}\right) - g\sin\theta,\\ \ddot{\theta} &= -\frac{2\dot{l}\dot{\theta}}{l} + \frac{k_R}{ml^2}\left(\theta_{rest} - \theta\right) - \frac{b_R}{ml^2}\left(\dot{\theta}_{rest} - \dot{\theta}\right) - \frac{g}{l}\cos\theta.\end{aligned} \tag{5}$$

2.2 Control

While the conservative, point-mass SLIP model (i.e. $\{b_L, k_R, b_R\} = 0$) can be self-stabilizing with appropriate parameter tuning and requires no actuation, the nonconservative analog necessitates a means of energy incorporation to offset the losses due to damping. Furthermore, both feedforward and feedback actuation have been shown to afford better stability than the model does on its own [1, 18, 19, 24].

In this study, we adopt feedforward controllers to drive both the prismatic and torsional actuators. This simplifies the control structure and reduces the computational requirements once instantiated on a physical system. An additional caveat for our controller is the assumption that the resulting platform is bipedal, rather than monopedal. This allows the results to be extended beyond single-legged, hopping systems and more readily apply to running platforms that have two sets of linked appendages (i.e. trotting pairs).[1]

[1]Without this assumption, all viable gaits require large aerial phases that are typically not desired as part of steady-state running.

The feedforward trajectories for the prismatic and torsional actuators were selected to sinusoidally adjust the rest leg length and leg angle. These trajectories can be described by

$$\begin{aligned} l_{rest_k} &= l_{nom} + l_d \sin\left(2\pi\left(\omega t + \phi_a + \phi_b + 0.5k\right)\right), \\ \theta_{rest_k} &= \theta_{nom} + \frac{\theta_d}{2}\left(1 - \cos\left(2\pi\left(\omega t + \phi_b + 0.5k\right)\right)\right), \end{aligned} \quad (6)$$

where l_{nom} is the nominal length of the prismatic actuator, θ_{nom} is the nominal touch-down angle of the torsional actuator, l_d is the stroke length prismatic actuator, θ_d is sweep angle of the torsional actuator, ω is the actuator frequency, ϕ_a is the phase offset between the actuators, ϕ_b is the phase offset of the torsional actuator from the touch-down event, and k is a counting parameter that switches between 0 and 1 with each successive step.

2.3 Simulation

Due to the intractability of an exact analytical solution to the SLIP model, a numerical simulation was utilized to explore and characterize the model behavior. The simulation was developed in MATLAB 2013b (Mathworks, Inc.) and employs the built-in Runga-Kutta numerical integrator *ode45* with absolute and relative tolerances of 10^{-10}. A Newton-Raphson fixed point search was implemented to find periodic orbits of the model with a tolerance of 10^{-8}. Additional scripts were written and utilized to capture the energetics and stability of the model for various parameter settings and initial conditions.[2]

3 Simulation Experiments

3.1 Simulation Setup

To examine the effects of prismatic and torsional actuation on running performance, a simulation study was conducted. Using the SLIP model and MATLAB implementation described in Sect. 2.3, a parameter sweep the energy incorporation parameters was performed. This allowed for the quantification of the effects of varying torsional and prismatic actuation on the locomotion speed, stability and efficiency.

[2]Energetics was quantified by prismatic and torsional actuator power. Stability was determined as the maximum eigenvalue of the Jacobian at the Poincaré section coinciding with the touch-down event. Additional details are found in Sect. 3.1.

Table 1 Parameter settings for SLIP parameter sweeps

Parameter	Model values
Mass (m)	0.3 kg
Nominal leg length (l_{nom})	0.03 m
Nominal leg angle (θ_{nom})	30°, 70°and110°
Linear stiffness (k_L)	1200 N m^{-1}
Rotational stiffness (k_R)	3 N m rad^{-1}
Linear damping (b_L)	3.95 N s m^{-1}
Rotational damping (b_R)	0.1 N m s rad^{-1}
Prismatic actuator stroke length (l_d)	0–0.03 m
Torsional actuator sweep angle (θ_d)	0°–125°
Actuator frequency (ω)	3.5 Hz
Actuator phase offset (ϕ_a)	0.75

Parameter values for the simulation were selected to correlate to the future instantiation of a physical platform (see Sect. 5). A mass of 0.3 kg and a nominal leg length of 0.03 m were chosen based on physical measurements. Leg stiffness, both linear and rotational were calculated to allow for resonant running when actuated at 5 Hz [26]. Linear and rotational damping were computed such that the damping ratio was 0.1.

Nominal values for control parameters needed to be determined as well. The actuator displacements l_d and θ_d were the primary parameters considered in the sweep. A range of 0–0.03 m for l_d and 0 °–125° for θ_d were chosen, as values less than zero are not physically meaningful and above these upper limits, stable gaits could not be found. Multiple values of the nominal leg angle θ_{nom} also had to be investigated, as using a steeper or shallower nominal leg angle was found to strongly skew results towards increased prismatic or rotational actuation, respectively. With this in mind, parameter sweeps were performed on three nominal leg angles, 110°, 70° and 30°. Additional control parameters include ω, ϕ_a and ϕ_b. ω was chosen to be 3.5 Hz and ϕ_a was set to 0.75. However, ϕ_b was found to be gait dependent and was determined as part of the Newton-Raphson search. A list of all physical and control parameters is tabulated in Table 1.

To quantify the running performance of the SLIP model under the various conditions of the parameter sweep, several performance indicators were computed. Mean fore-aft velocity $\bar{v}$ was calculated from the fore-aft distance traveled and the stride period. Though this measure is dimensional, and thus subject to the effects of scale, the nominal leg length remained consistent for all parameter settings so normalization is not required. The second measure of running performance was stability, which was quantified for small perturbations by the maximum eigenvalue λ_{max} of the Jacobian of the linearized return map [12]. As the maximum eigenvalue correlates to the rate at which the system returns to steady-state, small values for λ_{max} equate to better stability than large ones. The third measure, efficiency, was expressed by the specific resistance SR, describing the ratio of mean actuator power to the locomotive

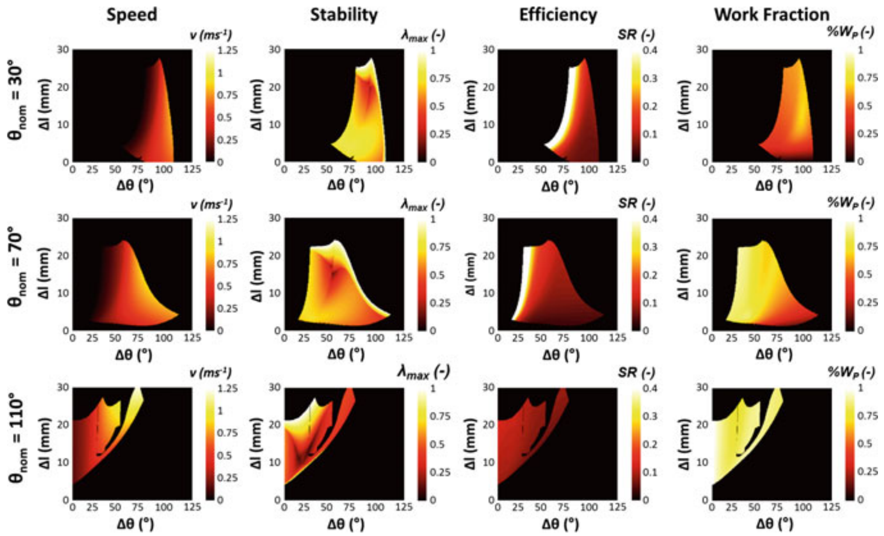

Fig. 2 Locomotive performance for the reduced-order running model as a function of the energy incorporation method. The plots (from *left* to *right*) show the speed, stability, efficiency and fractional work done by the linear actuator when running with varying degrees of prismatic and torsional energy input. *Black regions* around each plot show actuation settings for which stable gaits were not found

power required to move the system a given distance [9, 22]. As with λ_{max}, efficiency is maximized when SR is minimized. Additional measures, including the work done by the prismatic and torsional actuators and parasitic energy lost to the linear and rotational springs, were recorded as well.

3.2 Simulation Results

The calculated gait characteristics for each parameter set, speed, stability and efficiency, are shown in the left three columns of Fig. 2. Additionally, the work fraction, presented as the fractional work performed by the prismatic actuator, is included in the right column of Fig. 2. A review of these results can lead to the identification of several actuator-dependent effects.

As remarked on in the simulation setup, there is no nominal leg angle that can produce stable running gaits for both purely prismatic and purely torsional actuation. Furthermore, the range of fractional work performed by the actuators varies as a function of the nominal leg angle. This implies a significant coupling between the actuation approach and the parameters of the physical system and may merit the investigation of additional parameter couplings (e.g. linear/rotational stiffness and damping) in future studies. Additionally, it alludes to a challenge for generalized comparisons between prismatic and torsional actuation, for which results may be biased due to the choice of nominal system parameters. To overcome this, it is necessary to carefully consider the impacts of non-actuation system parameters and the couplings they may have to the actuation strategies.

When considering the effects of actuation on running speed, the most apparent trend is the strong correlation between the leg sweep angle and fore-aft velocity. Equally intriguing is the observation of a relatively weak coupling between fore-aft velocity and leg stroke length. These trends follow regardless of the nominal leg angle, indicative of a fundamental link between torsional actuation and running speed. However, it is worth noting that high-speed gaits are not devoid of prismatic energy incorporation, as at large nominal leg angles, the work fraction remains above 70 % prismatic even at the highest speed gaits.

While the leg stroke may only be weakly coupled to velocity, its effect on the stability is much more significant. Leg sweep is strongly coupled to the stability as well. It is also noteworthy that increasing or decreasing either actuation parameter does not have a monotonic effect on improving the stability, but rather peaks at an intermediate level. Additionally, the maximum eigenvalues are much smaller and the region for which the maximum eigenvalues remains small is much larger when utilizing a steep nominal leg angle.

Though speed and stability appear to correlate with the magnitudes of the leg sweep and leg stroke, efficiency demonstrates a stronger relationship to the ratio between the two. Aside from the extremely inefficient left edge seen at $\theta_{nom} = 30°$ and 70°,[3] the specific resistance closely mirrors the work fraction rather than either actuation parameter independently, with more efficient gaits noted with a smaller prismatic work fraction (or, equivalently, larger torsional work fraction).

To provide insight into the energetic effects, the negative work done by the actuators and parasitic behaviors of the springs were considered and the results are presented in Fig. 3. The energetic losses have been scaled by the steady-state system energy to provide a means of normalization between dissimilar gait types. For the actuators in the two left columns, it appears that more negative work is done by the torsional actuator than by the prismatic actuator at high speeds, while the negative work done by the prismatic actuation peaks at low speed, high stroke length gaits. Additionally, for the prismatic actuator, a region is present for which it generates a negligible amount of negative work. Furthermore, this region tends to include a section of the maximally stable set of gaits.

In the right two columns, the amount of elastic potential remaining in the springs at the point of lift-off can be observed. Parasitic losses to the linear spring are typically an order of magnitude or more smaller than the torsional. However, the amount of energy parasitically lost to both springs falls significantly at high-speed gaits and is indicative of a more efficient exchange of energy at these speeds. It is also notable

[3]For this region, the efficiency is actually worse than reported (up to and greater than 20) but has been limited to a maximum of 0.4 so the trends in the rest of the region is still discernible.

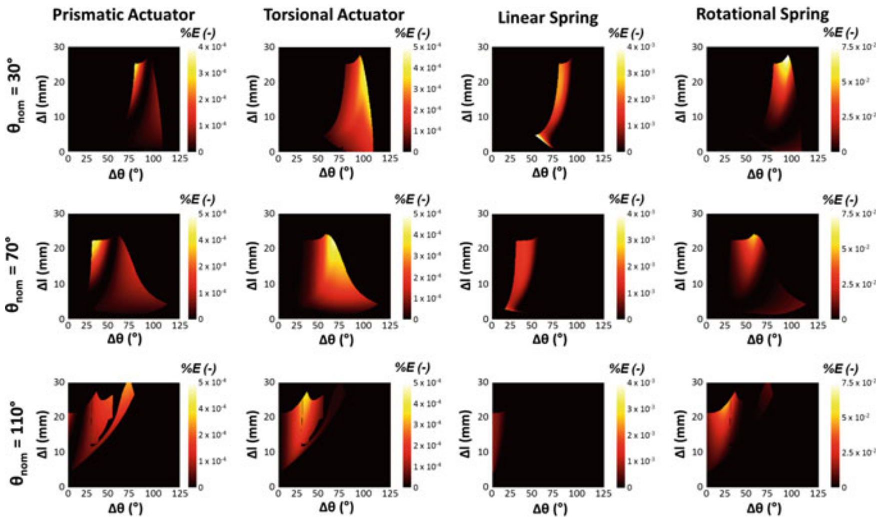

Fig. 3 Fractional sources of energetic losses during running. The two left columns show the amount of negative work done by the prismatic and torsional actuators. The two right columns depict the parasitic losses to the linear and torsional springs that arise due to lift-off occurring prior to the respective springs returning the elastic potential they have stored. All of the plots have been normalized to the steady-state system energy (i.e. kinetic and potential energy during the steady-state flight phase) and are expressed as the fraction of system energy

that the energetic losses due to the springs is considerably larger than for negative actuator work and that the drop in energetic losses coincides with the decrease in specific resistance.

4 Discussion

4.1 Prismatic, Torsional and Hybrid Actuation

In considering the independent and hybrid utilization of both prismatic and torsional actuation, it is evident that running performance is largely influenced by the total actuator input as well as the ratio of work provided by the prismatic and torsional actuators. It is clear that the entire spectrum, from purely prismatic to purely torsional actuation, is not available to produce viable gaits for any particular set of physical and control parameters. However, proper tuning of the ratio and magnitude of the actuator work can produce fast, stable and efficient behaviors at the nominal leg angles examined.

Perhaps the most striking result is that when utilizing a steep leg angle with a significant degree of hybridization ($\Delta L = 18$ mm, $\Delta\theta = 45°$ and $\theta_{nom} = 110°$), all three performance characteristics concurrently settle close to their ‘optimal’ values.

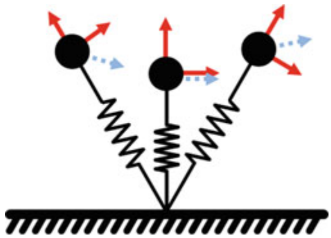

Fig. 4 Schematic depicting the hypothesized mechanism by which linear and prismatic actuator work contribute to running performance. The solid lines show the direction of the prismatic and torsional forces throughout stance; the dashes lines show the velocity heading

This result may be of import for several reasons. First, this suggests that few trade-offs may be necessary to optimize for any particular goal when properly tuned. Second, rather than settling at an evenly distributed work fraction, the 'optimal' point has a relative work distribution of 70 % prismatic/30 % torsional. This indicates that during actuator selection, inhomogeneous sets of prismatic and torsional actuators may allow for the best performance while maximizing specific power.

4.2 Mechanisms for Speed

As discussed in the simulation results, for a given nominal leg angle, running speed seems to correlate more strongly to leg sweep than to leg stroke. A likely mechanism for this behavior results from the orientation of the velocity vector with respect to the forces produced by the prismatic and torsional actuators, as depicted in Fig. 4. For prismatic actuation, extension of the leg during stance results in a force along the axis of the leg. For most nominal leg angles, this force is the negative direction immediately following touch-down and then progresses to accelerate the body forward after mid-stance. While still positive work, this method of energy input can results in slower speeds while increasing the apex height during flight. Conversely, the force produced by sweeping the leg is perpendicular to the leg axis and can accelerate the system throughout the stance phase. Thus, while increasing the leg stroke produces large decelerating forces in addition to accelerating ones, increasing leg sweep only increases accelerating forces (and potentially decreases decelerating ones, if present).

4.3 Mechanisms for Stability

In contrast to speed, stability appears to be influenced significantly by both leg sweep and leg stroke. A closer examination of the most stable parameter settings reveals that gaits with improved stability demonstrate a trajectory phasing for which reaching the maximal stroke and sweep angle coincides with the end of stance. This may be a key factor in the underlying mechanism contributing to the stability of these running gaits.

We hypothesize that this stabilizing mechanism utilizes a two-step approach. The mechanism stabilizes the gait rapidly due to the change in actuator positions at touch-down in the step following a perturbation. This effectively reduces the stroke length and sweep angle for the step following a perturbation that increases the system energy while increasing the stroke and sweep if energy is depressed.

For example, when a perturbation increases the energy during one step, the vertical velocity at lift-off will be increased. This will result in a lengthened flight phase, during which the prismatic and torsional actuators will advance past their nominal touch-down conditions. In the following step, both the stroke and sweep of the leg will progress as normal; however, they will reach their maximal lengths prior to the end of stance due to the lag introduced by the increased flight phase. Thus, at the end of stance they will begin to retract, removing energy and bringing the system back to its nominal energy level.

This mechanism favors gaits in which the maximal leg extension and sweep coincide at the same time as lift-off. However, it will still allow for stabilization when this does not occur, albeit at a slower rate. Since a sinusoidal trajectory is followed, the rate at which the leg extends or sweeps slows as the maximum extension is reached. Thus, even if energy is not actively removed by the actuators at the end of stance, less energy will be added during a high-energy stride (and more will be added if the energy is low).

4.4 Mechanisms for Efficiency

Rather than being linked directly to the work done by either (or both) actuators, efficiency appears to be influenced by the ratio between the two. The mechanism to describe this effect may be closely related to that for fore-aft velocity. As discussed for that mechanism, the work done by the torsional actuator is primarily funneled into the speed of travel while a significant portion of the work done by the prismatic actuator contributes to the apex height as well. Thus, increasing the torsional work results in an analogous increase in speed. This contributes to a decrease in the specific resistance (or at the very least, maintains it at a constant value). However, when increasing prismatic work, a significant portion of the work done translates to vertical motion rather than fore-aft speed, and it follows that an increase in specific resistance should result.

5 Physical Platform

Analysis of the simulation study demonstrates the efficacy of the hybrid utilization of both prismatic and torsional actuators for running. This motivates the development of legged platforms that can employ both actuation strategies to leverage these

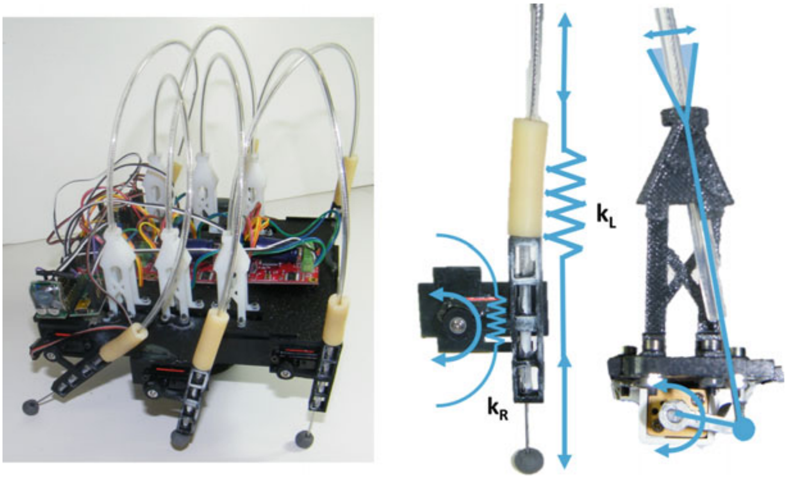

Fig. 5 Photograph of the hexapedal platform developed as a part of this study. This platform is designed to enable both prismatic and torsional actuation to improve performance and allow for modal transitions and limb reorientation in autonomous field operation

new-found insights. One particular application that dovetails with this finding are legged platforms designed for multi-modal running and climbing [17]. Purely prismatic actuation has shown to be effective at producing rapid and robust running and climbing behaviors. However, autonomous transitions between the disparate modalities are impossible without the presence of torsional, 'shape-changing' actuators to alter the limb morphology. Coupled with the simulation insights, we aim to develop a platform that can embed shape-changing actuators to allow for transitions, as well as employ them during steady-state behaviors for hybridly actuated gaits.

Several design criterion were considered in developing this physical platform, including: proximal location of the actuators to minimize leg inertia, a simple and robust transmission for prismatic and torsional actuation, readily tunable linear and rotational limb compliance, and an appropriate distribution of actuator power for both steady-state locomotion and transitional behaviors. The platform itself, shown in Fig. 5, draws substantial inspiration from iSprawl [14], as evidenced by the hexapedal morphology and cable-drive system. The cable drive, in particular, is beneficial as it allows the prismatic actuators to be situated on the central body rather than mounted on the individual legs. Thus, while the mass of each leg, including the actuators, is 33 g (∼8 % of the total platform mass), over half of the weight is affixed to the central body, significantly reducing the leg inertia.

To drive each leg, two actuators are utilized: a DC motor (Pololu, 75:1 Micro Metal Gearmotor HP), which extends and retracts the cable drive via a modified four-bar linkage, and a servo motor (PowerHD, DSM44 Digital Servo), mounted at the hip joint, which sweeps the leg. The modified four-bar uses a crank to directly drive the cable, eliminating the need for a separate coupler by allowing the joint at which the drive cable enters the sheath to rotate, as can be seen in the right panel of Fig. 5. Compliant elements are also readily incorporated into this design. A soft section of silicon tubing at the joint between the sheath and the leg provides linear compliance that can be adjusted by modifying the thickness and length of this element. Rotational compliance is incorporated by a shaft linking the hip and the leg, which acts as a cantilever beam.

With the presence of 12 active DoFs, it is necessary to utilize a robust control architecture that can handle this quantity of actuators. Since the control law itself is clock-based and feed-forward, minimal coordination is needed between the individual limbs. This allows for off-the-shelf components to be utilized that are capable of driving the actuators at fixed rates. Three dual motor controllers (Orion Robotics, 2 × 5A RoboClaw) are used to drive the leg stroke actuators. The DC motors are equipped with quadrature encoders to provide position feedback for the velocity PID controllers. The servos are connected to a controller (Pololu, Mini Maestro 12-Channel) that is capable of prescribing set positions and sweep rates for each servo. These components are connected to a Wixel microcontroller (Pololu) that serves as the on-board processor as well as a communication link, via wireless RF, to the human operator.

A final aspect of the design process related to the power distribution of the actuators. While chosen partially for the functionality they provided, the DC and servo motors also drew from the observation of inhomogeneous power generation in the simulation study. While a wide range of hybrid strategies demonstrated the capacity for high performance running, those at the 110° nominal leg angle showed the highest levels of speed and stability. Furthermore, a fairly consistent actuator work distribution of approximately 75 %\25 % prismatic to torsional was found for stable running gaits. This supports the motor selection for this platform, for which the drive motors (driving the four-bar linkage, i.e. prismatic actuators) can supply approximately 9.6 w apiece while the servo motors (rotating the hips, i.e. torsional actuators) can provide 4.2 w. This distribution of 69 %\31 % prismatic to torsional is in line with the observed simulation behavior.

6 Conclusion

In this work, we have investigated running with prismatic and torsional, as well as hybrid actuation to examine the effects of each strategy on the overall running performance. We used simulations of reduced-order models to investigate the variation in actuator parameters. From this study, we can determine 'optimal' degrees of hybridization for a given system. Furthermore, we considered the trends that effect the performance criterion to hypothesize several mechanisms that may govern the observed performance characteristics, including speed, stability and efficiency. Additionally, we developed and presented the design of a novel, hexapedal robot with the capacity to actuate prismatically, torsionally and using hybrid modes.

Future studies will extend these findings in a number of ways. First, the platform will be used to more extensively investigate how various degrees of hybridization affect the performance of a physical platform. Additionally, we will investigate how other parameters interact, as a significant parameter dependence was observed with regards to the nominal leg angles and hypothesized dependences to the leg and hip compliance are expected as well. These studies will enable the novel platform, as well as future legged system, both simple in nature and with more complex morphologies, to better leverage their on-board actuators for high performance locomotion.

References

1. Altendorfer, R., Koditschek, D.E., Holmes, P.: Stability analysis of a clock-driven rigid-body SLIP model for RHex. Int. J. Robot. Res. **23**, 1001–1012 (2004)
2. Altendorfer, R., Saranli, U., Komsuo?lu, H., Koditschek, D., Brown Jr, H.B., Buehler, M., Moore, N., McMordie, D., Full, R.: Evidence for spring loaded inverted pendulum running in a hexapod robot. In: Rus, D., Singh, S. (eds.) Experimental Robotics VII. Lecture Notes in Control and Information Sciences, vol. 271, pp. 291–302. Springer, Berlin Heidelberg (2001)
3. Birkmeyer, P., Peterson, K., Fearing, R.S.: DASH: a dynamic 16g hexapedal robot. In: IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), St. Louis, MO (2009), pp. 2683–2689
4. Blickhan, R.: The spring-mass model for running and hopping. J. Biomech. **22**, 1217–1227 (1989)
5. Blickhan, R., Full, R.J.: Similarity in multilegged locomotion: bouncing like a monopode. J. Comp. Physiol. A: Sens. Neural Behav. Physiol. **173**, 509–517 (1993)
6. Dickinson, M.H., Farley, C.T., Full, R.J., Koehl, M.A.R., Kram, R., Lehman, S.: How animals move: an integrative view. Science **288**, 100–106 (2000)
7. Farley, C.T., Glasheen, J., McMahon, T.A.: Running springs: speed and animal size. J. Exp. Biol. **185**, 71–86 (1993)
8. Full, R.J., Koditschek, D.E.: Templates and anchors: neuromechanical hypotheses of legged locomotion on land. J. Exp. Biol. **202**, 3325–3332 (1999)
9. Gabrielli, G., von Kármán, T.: What price speed? specific power requirements for propulsion of vehicles. Mech. Eng. **72**, 775–781 (1950)
10. Geyer, H., Seyfarth, A., Blickhan, R.: Compliant leg behavior explains basic dynamics of walking and running. Proc. R. Soc. B: Biol. Sci. **273**, 2861–2867 (2006)
11. Görner, M., Albu-Schäffer, A.: A robust sagittal plan hexapedal running model with serial elastic actuation and simple periodic feedforward control. In: IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Tokyo, Japan (2013), pp. 5586–5592
12. Guckenheimer, J., Holmes, P.: Nonlinear oscillations, dynamical systems, and bifurcations of vector fields. Springer (1983)
13. Holmes, P., Full, R.J., Koditschek, D., Guckenheimer, J.: The dynamics of legged locomotion: models, analyses, and challenges. SIAM Rev. **48**, 207–304 (2006)
14. Kim, S., Clark, J.E., Cutkosky, M.R.: iSprawl: design and tuning for high-speed autonomous open-loop running. Int. J. Robot. Res. **25**, 903–912 (2006)
15. Koditschek, D.E., Full, R.J., Buehler, M.: Mechanical aspects of legged locomotion control. Arthropod Struct. Dev. **33**, 251–272 (2004)
16. Larson, P., Seipel, J.: A spring-loaded inverted pendulum locomotion model with radial forcing. In: ASME International Design Engineering Tecnical Conferences & Computers and Information in Engineering Conference (IDETC/CIE). vol. 4, Chicago, IL (2012), pp. 877–883
17. Miller, B., Darnell, A., Clark, J.: Running in the horizontal plane with a multi-modal dynamical robot. In: IEEE International Conference on Robotics and Automation (ICRA) (2013)

18. Poulakakis, I., Grizzle, J.W.: The spring loaded inverted pendulum as the hybrid zero dynamics of an asymmetric hopper. IEEE Trans. Autom. Control **54**, 1779–1793 (2009)
19. Raibert, M.: Hopping in legged systems - modeling and simulation for the two-dimensional one-legged case. In: IEEE Transactions on Systems, Man and Cybernetics **SMC-14** (1984), pp. 451–463
20. Raibert, M.H., Chepponis, M., Brown Jr, H.B.: Running on four legs as though they were one. IEEE J. Robot. Autom. **2**, 70–82 (1986)
21. Remy, C.D., Buffinton, K., Siegwart, R.: Comparison of cost functions for electrically driven running robots. In: IEEE International Conference on Robotics and Automation (ICRA), Saint Paul, MN (2012), pp. 2343–2350
22. Saranli, U., Buehler, M., Koditschek, D.E.: RHex: a simple and highly mobile hexapod robot. Int. J. Robot. Res. **20**, 616–631 (2001)
23. Sayyad, A., Seth, B., Seshu, P.: Single-legged hopping robotics research - a review. Robotica **25**, 587–613 (2007)
24. Schmitt, J., Clark, J.: Modeling posture-dependent leg actuation in sagittal plane locomotion. Bioinspiration Biomimetics **4** (2009) 046005 (17)
25. Srinivasan, M., Holmes, P.: How well can spring-mass-like telescoping leg models fit multi-pedal sagittal-plane locomotion data? J. Theoretical Biol. **255**, 1–7 (2008)
26. Thompson, C.M., Raibert, M.H.: Passive dynamic running. In: Hawyward, V., Khatib, O. (eds.) Experimental Robotics I. Lecture Note in Control and Information Sciences, vol. 139, pp. 74–83. Springer, Berlin Heidelberg (1990)
27. Zhou, X., Bi, S.: A survey of bio-inspired compliant legged robot designs. Bioinspiration Biomimetics **7** (2012) 041001 (20)

http://www.springer.com/978-3-319-23777-0

Experimental Robotics
The 14th International Symposium on Experimental Robotics
Hsieh, M.A.; Khatib, O.; Kumar, V. (Eds.)
2016, XIV, 927 p. 497 illus., 65 illus. in color., Hardcover
ISBN: 978-3-319-23777-0