Series Compliance for an Efficient Running Gait

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Lessons Learned from the Electric Cable Differential Leg

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Many robots excel at precise positioning and trajectory tracking using software control, and most successful robotic applications use this ability—examples include computer numeric control (CNC) machining, robotic welding, painting, and pick-and-place circuit board assembly. The mechanical design of these robots focuses on rigid transmissions and minimizing compliance in the structure so that the software controller can accurately track a desired position as a function of time, regardless of any disturbance forces. However, there is a class of tasks for which rigid actuation is not ideal: physical interaction with the world, especially interaction that involves an impact or kinetic energy transfer. Animals tend to excel at these tasks and far outperform the best robots. Examples include walking, running, catching a ball, gripping a piece of fruit firmly but without causing damage, and many types of assembly tasks.

For dynamic behaviors such as running, the performance limitations of a robot are often due to limitations of the mechanical design. A robot is an integrated system of electronics, software, and mechanisms, and each part of the system limits or enables the behavior of the whole. While some behaviors can easily be implemented through simple actuators and direct software control, a running machine requires a mechanical design that is specialized for the task. Among other things, physical springs are essential for a robust and efficient running gait, to store energy, provide high mechanical power, and overcome bandwidth limitations of traditional actuators. An ideal kinematic design, where the joints and links are perfectly sized and placed for the desired task, and motors that exceed the force and speed requirements of the task are not sufficient for successful dynamic interactions. Inertia, transmission friction, and other dynamic effects have a significant role on the behavior of a running robot.

We are building running and walking machines with a focus on the mechanical design to enable efficient and robust gaits. The defining characteristic of a running gait is spring-like behavior; all running animals, from small insects to large mammals, exhibit a center-of-mass motion that resembles a bouncing ball or a pogo stick. The spring-like behavior is implemented with the assistance of physical springy elements, such as tendons, and not entirely through software or neural control. Energy cycles back and forth between the ballistic trajectory of the body and the compression of the leg spring. To exhibit this behavior, our robots incorporate a mechanical spring that is tuned to absorb and release the energy of a running gait at the appropriate frequency. Electric motors act in series with this spring to add or remove energy from the cycle to modify or control the running gait.

Our first prototype machine is a single actuator mounted to a bench, called the actuator with mechanically adjustable series compliance (AMASC). The stiffness and the no-load position of the joint are mechanical configurations that can be independently adjusted using two separate motors, and it is a test platform to

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verify and refine several design ideas for leg joints of running and walking robots. After significant testing and design revision, we incorporated the ideas behind the AMASC into the design of a full bipedal robot, the biped with mechanically adjustable series compliance (BiMASC). A single leg prototype of the BiMASC was constructed and tested, and after some final revisions, we have built the electric cable differential (ECD) leg (Figure 1). The ECD leg derives its name from the construction—using electric motors, cable drives, and mechanical differentials to actuate the system. One ECD leg, named Thumper, was assembled as a monopod and installed in our laboratory at the Robotics Institute to study the role of compliance in running gaits. Two ECD legs were assembled as a biped named MABEL, which is installed in Prof. Jessy Grizzle's laboratory at the University of Michigan and will serve as a platform to explore an advanced feedback control theory for legged locomotion [31].

In this article, we discuss some earlier legged machines, explain some of the limitations of traditional actuation systems, and explain why mechanical springs are essential for a running gait. Not any arbitrary spring will help; the spring must be designed specifically for the task, and the "Tuned Spring: Stiffness Adjustment" section provides further details about the methods for creating a specific desired spring behavior that can be tuned as the environment changes. Finally, we discuss the lessons learned from the construction and testing of AMASC and BiMASC and explain the revisions to the final ECD leg, which eliminate the mechanically adjustable compliance.

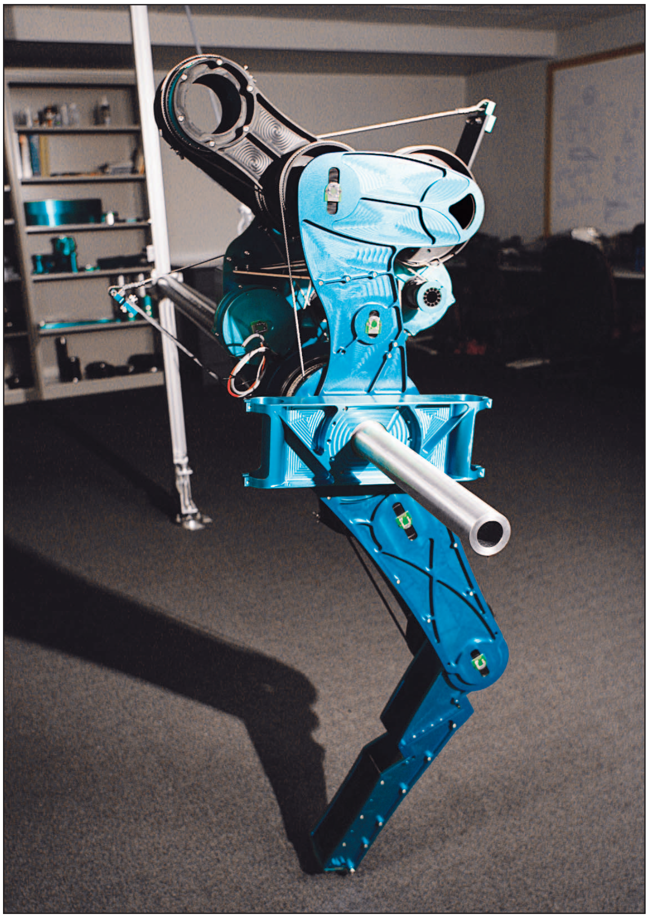

Figure 1. Thumper, the monopod ECD leg. Fiberglass bar springs are at the front and back of the body, but they act in series between the leg length motor and the actual leg length. A bipedal version, MABEL, is installed in Prof. Jessy Grizzle's laboratory at the University of Michigan.

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Background and Previous Work

A common theme among all runners is spring-like behavior. Runners follow an approximate center-of-mass motion similar to that of a bouncing ball. Spring-mass models such as the spring-loaded inverted pendulum (SLIP) model have been developed as a tool to describe this center-of-mass motion [1]–[3]. Our spring-mass model is shown in Figure 2.

All running animals, and most running robots, store mechanical spring energy during a running gait [4]–[7]. The basic definition of running is linked to the use of leg springs, as depicted in the SLIP model—energy is transferred from kinetic energy in the flight phase to spring energy in the stance phase and vice versa [8].

Many robots have been built for the purpose of walking and running. There are generally two classes: robots that use mechanical springs to store and release kinetic energy during

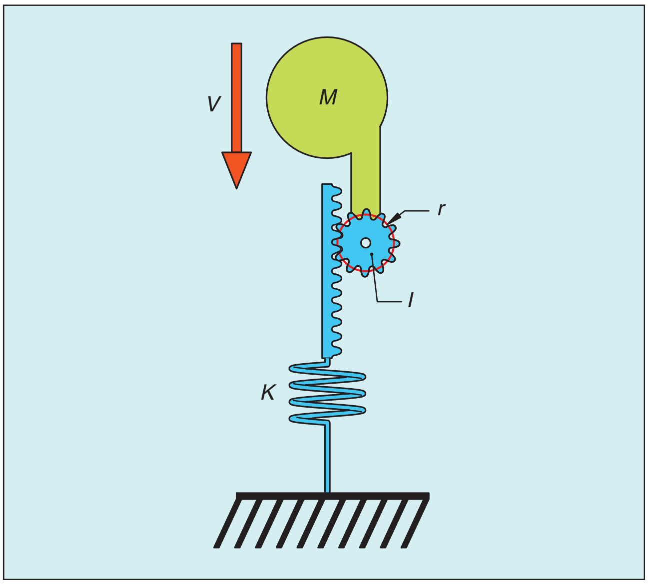

Figure 2. Our spring-mass model for running, similar to the SLIP model, but incorporating physically realistic actuator dynamics such as motor inertia. The motor, with inertia I and speed reduction r, can actuate the spring to excite a regular vertical oscillation to hop off the ground, much like a person on a pogo stick.

Runners follow an approximate center-of-mass motion similar to that of a bouncing ball.

a running gait, much like animals, and robots that rely on software control to implement all behaviors. The planar biped, built at the Leg Laboratory during its Carnegie Mellon days, is an example of a spring-mass robot, using air springs for energy storage [9]. This robot could also adjust the preload of air pressure in the cylinder that affects the leg stiffness. [Marc Raibert founded the Leg Laboratory at Carnegie Mellon University in 1979–1980. Raibert and the Leg Laboratory moved to Massachusetts Institute of Technology (MIT) in 1986.] The planar biped was capable of high-performance behavior such as front flips, because it was tethered to a large hydraulic compressor and air compressor. In contrast to the high power of many of the Leg Laboratory machines, both the Bowleg Hopper from Carnegie Mellon University and the ARL Monopod II from McGill University have defensible claims to being the most efficient running robots [10], [11]. Both gain their efficiency by using leg springs to effectively store and release energy during each stride, and so the electric motors do relatively little work during a normal running gait.

The MIT Leg Laboratory's Spring Flamingo does use springs but not for energy storage. The springs on the MIT-series elastic actuator (MIT-SEA) are primarily for force sensing and mechanical filtering purposes [12], [13]. The springs of an MIT-SEA are essentially a soft load cell, acting as a force sensor for the low-level controller. At low frequencies, the MIT-SEA acts as a more sensitive and robust force actuator than a gear motor and a load cell.

Recent bipeds that can change the stiffness of their joints have also been constructed [14], [15]. They have successfully walked, but they are not designed for running and are similar to the MIT-SEA in that they do not store significant amounts of energy in their springs. Additionally, when using pneumatic actuators for the joint stiffness control [15], the resulting system can be difficult to model and control precisely.

Robots with rigid transmissions, such as RABBIT and Asimo, do not use springs and are examples of machines that attempt to create all dynamics through software control [16], [17]. This is an important difference. If these robots are capable of an aerial phase, it is only at the expense of great motor power output and high energetic cost, with relatively unpredictable dynamic behavior at ground impact. Furthermore, the response of such machines to a disturbance, such as a slightly raised or lowered ground surface, will vary dramatically from that of an animal due to the fundamental mechanical differences.

Actuators for Running

While a general-purpose actuator would provide ideal flexibility for software controller development on a running robot, all actuators have natural dynamics that can limit the authority of the software controller. The mechanical system, unlike the software controller, cannot be easily modified and changed once it is built. Therefore, the best approach is to begin the robot design with a specification for the dynamic behavior of the machine. In other words, many aspects of the control should be designed before any mechanical system is created so that the natural dynamics of the actuator can assist and enable the behavior of the machine rather than impose hard limits.

Although several successful running and walking machines have used pneumatic and hydraulic power, most designers opt for the simplicity and robustness of electric motors [18], [19]. Pneumatics have limitations on the control rate due to small tubes and valves and limitations on the power supply, especially for untethered machines. However, we do not discuss the details of pneumatic actuators. Hydraulic actuators have many limitations similar to that of electric gearmotors, and also power supply limitations similar to that of the pneumatic actuators. Most of the discussion in this article can be applied to hydraulic actuators, but we discuss electric motors primarily.

Electric Gearmotors and Inelastic Collisions

A simple design for a legged robot would involve the use of an electric gear motor at each joint. Several groups have built bipedal robots using this design, and some intended to make the robots run as well as walk. The problem with this approach to running is that most of the kinetic and potential gait energy is lost, with each hop, to an inelastic collision with the ground.

A spring-free, gear motor-actuated running robot is represented in Figure 3(a). Because there is no physical spring, all behaviors of the leg must be exhibited by the software through the motor. The entire mass of the robot (including the mass of the motor) is represented by M, and the leg is assumed to be massless. However, the rotational inertia of the motor cannot be lumped into the overall mass of the robot; it is represented by the variable I, and after the rotational inertia of the motor is converted to linear inertia by the conversion ratio r, the overall reflected inertia at the joint of the robot is $\frac{I}{r^2}$. For a typical harmonic-drive gear motor on a humanoid robot, the resulting reflected motor inertia can approach that of the robot mass, M.

Because the rotor inertia and the robot mass are uncoupled, the robot leg may be moved to the ground without affecting the model, as shown in Figure 3(b). The rotor begins at rest, and after collision, acquires some speed that matches that of the mass. If the kinetic energy just prior to impact is represented as T_0, the rotor inertia is represented as I, the conversion from rotational to linear motion is represented by a fictional pulley radius r, and M is the robot's total mass, then the energy lost to an impact is

$$T_{\text{loss}} = \frac{I}{Mr^2+I} T_0$$

and the remaining energy, stored in the downward motion of the robot and the rotation of the motor is

$$T_{\text{final}} = \frac{Mr^2}{Mr^2 + I} T_0.$$

If the effective inertia of the motor rotor (I/r^2) is the same as the robot's mass, then half the kinetic energy from flight will be lost to the inelastic collision. This estimate is in the best of situations, assuming absolutely no friction or losses in the transmission. For a realistic system, any energy remaining after the collision must be converted through the motor and transmission inefficiencies, which are compounded when energy must pass into the system and then out. In effect, very little energy can be recovered.

Adding Series Springs

Minimizing the reflected inertia of the motor can reduce the energy lost to inelastic collisions, but it is difficult to create a motor with sufficiently low reflected inertia that can still apply sufficient torque. Alternatively, a series spring can be used to decouple the motor inertia and the load inertia, eliminating the inelastic collision and the associated energy loss during impacts. Both methods are used in force-control applications [20]–[23], which are similar in many ways to the implementation of a spring rate.

An SEA may be much more effective than a standard gear motor at creating spring-like behavior, even when the physical spring is of a different stiffness than that of the desired behavior. In this case, the software must control the motor so that the overall system exhibits the desired total spring rate. In the ideal scenario of an inertia-free rotor, a proportional controller will behave like a spring, creating two springs in series—a software spring and a physical spring, as shown in Figure 4(a). This is relatively simple to analyze and provides a conservative estimate of energy use and power output due to the assumption of no inertia. Therefore, for the sake of argument, further analysis will assume perfect force control of a massless rotor, providing an ideal software spring in series with a physical spring.

Power Density of a Series Spring System

In a cyclical system, such as a hopping spring-mass system, energy is transferred from external sources (kinetic energy of motion or potential energy of height) to internal sources (physical spring energy or chemical battery energy) and vice versa, repeatedly. This transfer of energy is represented in Figure 4(b), where the energy may go into and out of the physical spring as an energy storage element (compression and extension) or through the physical spring merely as a power-transmission element (the spring translating with no deflection). The power output will be divided between the software spring and the physical spring, depending on their stiffnesses.

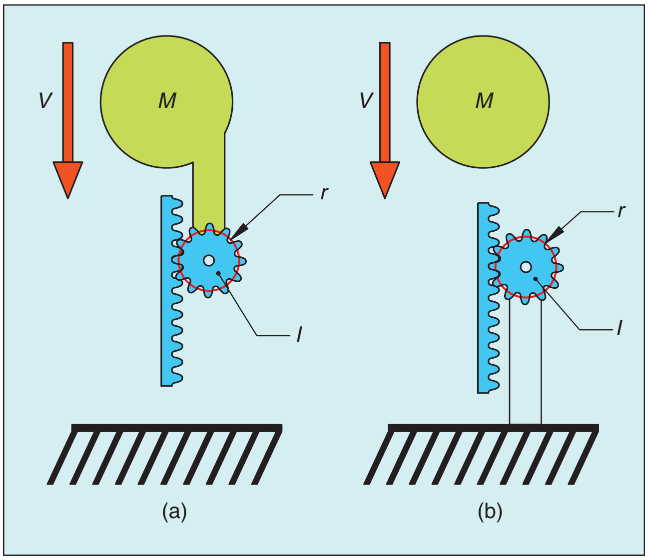

Figure 3. *Figures representing the mass-spring model, with the physical spring removed. The inertia of the motor is represented by I, the mass of the robot by M, the conversion from motor angular velocity to linear velocity by a fictional pulley radius r, and the velocity of the robot just before collision by V. (a) Mass-spring model without a spring. (b) The inertias separated but still in the same collision model.*

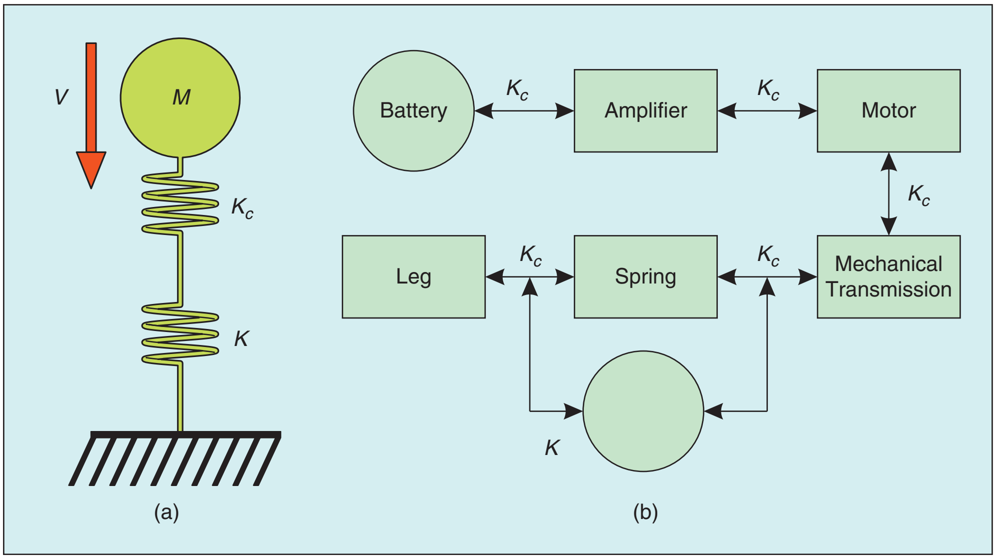

Figure 4. *Assuming an inertia-free actuator, the software controller can simulate a spring K_c. Acting in series with the physical spring K, the energy will flow into one or the other depending on the ratio of the stiffnesses. (a) Our spring-mass model, with software spring rate K_c and hardware spring rate K. (b) Energy flow diagram: K_c represents the energy path of the stiffness behavior implemented through software control; K represents the mechanical spring stiffness.*

A robot is a unified dynamic system comprising electronics, software, and mechanical components.

If the series spring system is deflecting at some rate, the power output attributed to the software spring, P_{K_c}, is

$$P_{K_c} = \frac{K}{K_c + K} P(t),$$

where $P(t)$ is the total power output of both springs in series, K_c is the proportional gain of the computer controller, and K is the physical spring constant. If the physical spring is perfectly tuned to match the desired stiffness, the software spring K_c becomes infinitely stiff, and it can be seen from the equation that the motor (exhibiting the software spring) exerts zero shaft power.

Because springs have higher power density than electric motors, it makes sense to design a system such that the physical spring transfers as high a proportion of the power as possible. A physical spring can have nearly infinite power density, depending on its stiffness; therefore, a comparison between the power density of a spring and that of a motor must be made in the context of an application. Choosing reasonable values for a hopping robot of leg stiffness $K = 5{,}000$ N/m, hopping height of $h = 0.25$ m, and robot mass of $m = 30$ kg, the highest power output during stance is approximately 1 kW (root mean square power is 680 W) and the maximum work stored is about 75 J. With an efficient fiberglass spring, such as those used on archery bows that have an energy capacity of around 1,000 J/kg, a 75-g spring can store the required energy and output the desired power. In contrast, a brushless motor that can output 600 W of continuous power (such as the Emoteq Quantum series 3401 [32]) weighs approximately 2.2 kg, almost 30 times the mass of the spring. Adding the necessary electronics and batteries would add to the mass considerably.

Based on this analysis, even ignoring the inertia of the rotor and the inefficiencies of the motor, it is clear that a spring has much higher power density than an electric motor in a cyclic system. This effect has been noticed in the biomechanics community, where experiments have shown that animals use their springy tendons to amplify the power output of their muscles for jumping and running [24], [25]. Recent work also uses the effect of tuned springs to amplify the power output of actuators for prosthetic limb designs [26].

Energy Efficiency of a Series Spring System

Although avoidance of inelastic collisions and power requirements are compelling reasons to use physical springs, the energetic efficiency of a cyclic system is also improved through the use of tuned physical springs. Again referring to Figure 4(b), energy can be stored and returned through the mechanical spring or through the batteries, which must first convert the mechanical energy to electrical, electrical to chemical, and back again. Assuming an overall efficiency of the spring energy storage e_k and an overall efficiency of energy storage through the motors and batteries of e_c, and given the previous assumptions of a perfect software spring K_c and an inertia-free rotor, spring constant K, and leg deflection x, the equation for energy returned is

$$E_{\text{ret}} = \frac{K_c}{2(K + K_c)} K x^2 e_k + \frac{K}{2(K + K_c)} K_c x^2 e_c.$$

Because springs can store and return energy more efficiently than an electric motor system, it makes sense for the physical spring stiffness to be as close to the desired spring stiffness as possible. If our assumption of zero rotor inertia is false, as in any real system, then the motor must transmit power to change the momentum of the rotor, and it will expend more energy than in this idealized example.

Tuned Spring: Stiffness Adjustment

For an oscillating mass-spring system, such as a running machine, matching the natural frequency of the mechanical system to the desired stride frequency will minimize the required motor power. In other words, a robot or animal of a particular size may have an optimal leg stiffness to minimize the amount of effort required to run. However, the optimal leg stiffness will change as the desired gait changes or as the environment changes. Observations from nature tell us that animals do adjust their leg stiffness in various situations, but we do not have a conclusive answer as to the specific strategy they use or how they do it.

There are a variety of ways to create stiffness behavior in robotic systems, and a variety of ways to adjust the stiffness on the fly. The most common approach is to simulate spring behavior using an actuator and a feedback sensor, such as an electric motor or a hydraulic actuator with a force sensor. As discussed, this method has drawbacks with bandwidth limitations, power limitations, and energy efficiency for realistic actuators. In the absence of a perfect actuator free of all dynamics or limitations, the best way to create spring-like behavior is to use a physical spring in some way.

When designing an actuator that incorporates physical springs, there are several ways to adjust or tune the spring stiffness to suit a particular task. There are a range of mechanical solutions, which use linkages, transmissions, or clutches to adjust stiffness. Cocontraction of antagonistic springs is a biologically inspired approach and the basis for the AMASC and BiMASC designs. After extensive experimentation, we found that this method of stiffness adjustment has significant drawbacks for running gaits, mostly due to the additional mechanical complexity and the reduced energy storage capacity of the springs. More promising for this particular application is a hybrid active-passive approach, where a physical spring is tuned for the standard running gait, and a series motor actively adjusts the spring forces for gait changes or other nonstandard behaviors.

Cocontraction of Antagonistic Nonlinear Springs

A popular method of stiffness adjustment is the cocontraction of antagonistic springs as shown in Figure 5. Animals have this capability, and most robotic devices with variable stiffness use this method [9], [27], [28]. With two springs opposed across a single joint, the deflection of the joint, x, compresses one spring while relaxing the other. Cocontraction of the springs, p, compresses both springs. For the cocontraction to affect the joint stiffness, the springs must be nonlinear. For the simple example of quadratic springs, the force on each spring is

$$F_1 = K(p+x)^2$$
$$F_2 = K(p-x)^2,$$

and the combined force on the joint is

$$F = F_1 - F_2 = 4Kpx,$$

where the cocontraction can be considered as part of the spring constant that determines the resultant forces of a joint deflection x.

The obvious drawback for cocontraction is that two actuators are required for a single joint, and they must apply forces to hold a particular stiffness even if no work is done by the joint. This drawback can be minimized by using nonbackdrivable transmissions, mechanical differentials, brakes, and other mechanisms, such that joint work can be done by a large motor, and stiffness adjustment may be accomplished by a small motor with a holding brake. This is the idea behind our first prototype actuation system, the AMASC.

Adjusting Stiffness Behavior: Alternative Methods

Apart from cocontraction of antagonistic springs, the stiffness of a single spring can be adjusted by varying its effective length through some mechanical means. For example, a torsion bar can have a rigid base that rolls up and down the length, immobilizing a variable portion of the spring. A helical spring could have a rigid base that threads up and down the spring, immobilizing more or less of the coil [29], or many springs in parallel can be clutched in and out of the system in some way.

Because stiffness is essentially an energetically conservative force-distance relationship, a continually variable transmission (CVT) in series with a spring would be ideal; the forces could be changed arbitrarily for a particular energy transfer. The knee joint in a robot or animal leg can act as a constrained CVT, because the angle of the knee affects the mechanical advantage between the toe forces and the spring deflection. In effect, different knee angles can modify the force profile of the spring. It is not an ideal CVT, because the mechanical advantage cannot be changed arbitrarily, but mechanisms such as a knee can potentially be used to the advantage of a running gait or other dynamic behavior.

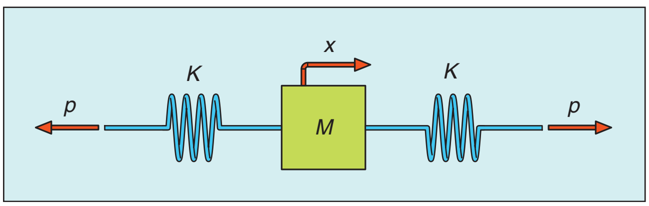

Figure 5. Two opposing springs in cocontraction across a single linear joint. Spring constant K, joint deflection x, joint load mass M, and cocontraction p.

One goal of a tuned leg stiffness is to minimize the amount of energy that the motor must use to maintain a constant gait cycle.

In many cases, the stiffness behavior of an actuator with series springs can be modified through active software control. In the example of a spring-mass running robot with a spring and motor in series, the spring undergoes a predictable trajectory based on the body mass and the leg stiffness, and so a preplanned motor trajectory or an other simple controller can be used to modify the overall leg stiffness. In the instance of an unexpected impact, only the passive behavior of the spring will contribute to the toe force, because the inertia of the motor prevents instantaneous acceleration. After the motor begins to accelerate and move, either relaxing or compressing the spring, it can add or remove energy and modify the force profile of the spring, effectively altering its stiffness. The force profile will not be a perfect simulation of a spring due to the inertia of the motor, but this may be of little consequence; it is certainly less problematic than the inelastic collision that exists with no physical spring in series with the motor. More importantly, any active modification of the natural spring oscillation will result in wasted energy by the gearmotor, and so this is a tradeoff to be considered.

Experimental Prototypes: AMASC and BiMASC

The AMASC, shown in Figure 6, was developed as a prototype leg for a running robot [30]. It is a single compliant joint, with two adjustable parameters and two corresponding

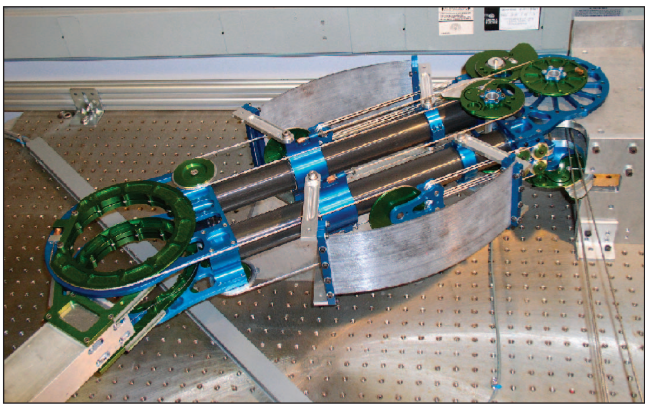

Figure 6. The AMASC is a prototype leg joint for a running robot.

motors: joint stiffness and no-load joint position. Two fiberglass springs act as an antagonistic pair, and a mechanical differential allows one small motor to adjust pretension, which corresponds to stiffness, and one large motor to control the no-load joint position. The mechanical system was designed specifically to behave in a dynamically simple manner, such that a basic mathematical model could predict the behavior of the AMASC. After testing through a range of frequencies and forces, the simulated model of the AMASC closely matched the dynamic behavior of the real device.

Based on ideas developed through the construction and simulation of the AMASC, we designed and built a single prototype leg of the BiMASC shown in Figure 7. The design has three degrees of freedom (DoF) per leg: the leg length, leg angle, and leg stiffness. The legs end in small hooves, and the motors are placed in the body to minimize leg mass and more closely emulate a simple SLIP running system. Similar to the AMASC prototype actuator, the BiMASC uses two antagonistic springs and a small braked motor to allow for joint stiffness adjustment. The springs act in series with a large motor, which controls the length of the leg. Another large motor controls the leg angle relative to the body.

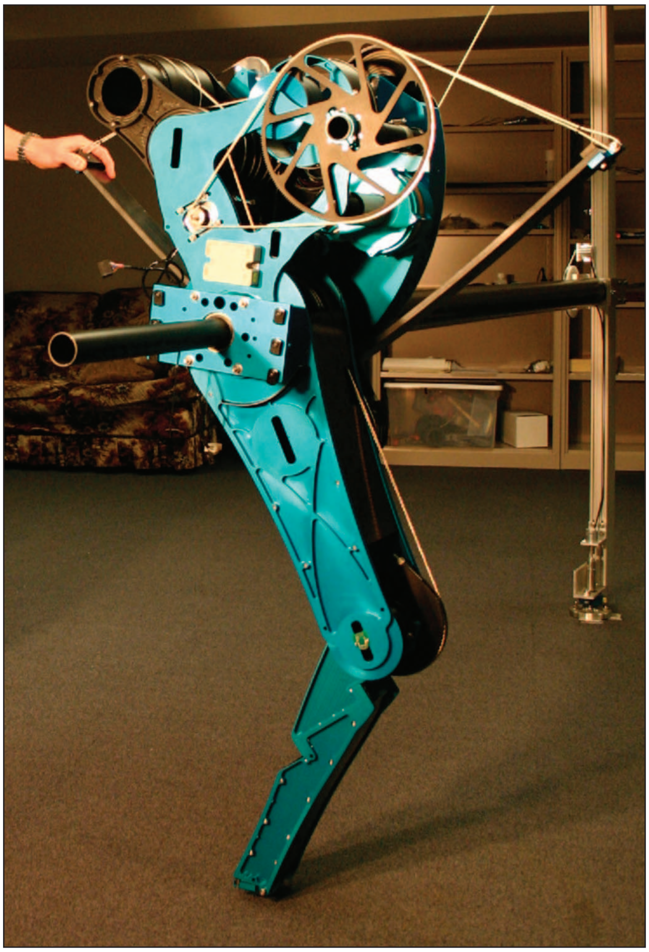

Figure 7. The initial prototype leg for BiMASC. This prototype used many of the same ideas from the AMASC, including cocontraction of antagonistic springs for stiffness adjustment. Based on the testing of BiMASC, the choice was made to eliminate the mechanically adjustable stiffness and instead use active methods for on-the-fly adjustment of the leg spring behavior on the ECD leg.

After initial construction of the prototype BiMASC leg, we tested some of the basic functionality. We moved all of the joints through their entire range of motion to verify whether there was any mechanical interference. We tested the robustness of the safety harness and the robot hard stops by lifting the machine in the air and throwing it toward the ground. We locked the motor shafts and manually bounced the robot in place. While most of the test results were encouraging and informative, it became apparent that antagonistic springs have significant tradeoffs. The springs, although physically large and capable of storing significant energy, did not store enough energy as an antagonistic pair to convincingly bounce the robot in the air.

As illustrated in our experiment, there are several effects that can reduce the energy storage capacity of antagonistic springs by nearly an order of magnitude over a single spring of the same size. First, only one of the springs is actually compressing when the joint compresses, halving the potential energy storage, and the other spring is actually relaxing and releasing energy into the compressing spring rather than into the joint. This effect accounts for approximately a factor of three. Additionally, the individual spring deflections are the sum of both the cocontraction and the joint deflection $(p + x)$, and so increasing the cocontraction will reduce the maximum allowable joint deflection if we assume an upper and lower limit on the spring deflection. If the joint stiffness is to be adjusted by a factor of three, for example, then the maximum joint deflection will be three times lower than the case where no stiffness adjustment is required. Combining these two effects, the energy storage capacity of the springs for this example is reduced by a factor of nine. Apart from the reduction in energy storage capacity, using antagonistic pairs of springs increases internal forces beyond the applied joint forces, which increases friction and requires stronger parts. There is also an extra actuator for stiffness adjustment and other additional parts, which add mass and complexity to the system.

There are several ways to affect the stiffness behavior of a running machine, and cocontraction of antagonistic springs is only one method. After implementing the mechanical adjustment with sufficient energy storage for a running gait and observing the complexities of the real system, the costs seem to be higher than the benefits. Although improvements could certainly be made to the mechanical design, the fundamental issues of high internal forces and reduced spring energy storage cannot be overcome but present a useful piece of information for the design of variable stiffness mechanisms.

The ECD Leg

The ECD leg is the final revision of the BiMASC design. We created three copies of the ECD leg: the monopod named Thumper and the biped named MABEL. Similar to the earlier prototypes, the ECD leg uses electric motors, a cable drive transmission, and mechanical differentials to implement the desired relationships between motors and joints. However, the online stiffness adjustment can be achieved through active software control during the toe's ground contact time and through changes to the knee angle upon landing. The ECD leg has no antagonistic springs and cannot adjust its stiffness mechanically as do the BiMASC or AMASC. For experiments to determine the energy efficiency, the fiberglass springs were swapped between runs. The ECD leg has a lower mass and is mechanically simpler than the BiMASC, which we believe is a worthwhile tradeoff.

The ECD leg is designed to behave in a dynamic manner similar to that of the spring-mass model shown in Figure 1 so that the dynamic behaviors can be quantified and controlled. There are two motors—one to control the leg angle and another to control the leg length, with a large spring placed in series between the leg length motor and the actual leg length. The ECD leg has a knee joint, partly to enable human-like walking and partly to incorporate the CVT aspect of an adjustable mechanical advantage during running. The leg ends in a simple rounded hoof, with no articulation or actuation. Parameters and dimensions for the ECD leg are provided in Table 1. Thumper, the single ECD leg at Carnegie Mellon, can sustain a stable hopping gait as shown in Figure 8. We have tested the ability of varying the leg stiffness by actively controlling the set position of the spring as a function of its deflection or by changing leg length on touchdown to increase the mechanical advantage of the knee. Figure 9 shows the change in duty factor or the percent of the gait that the robot spends in the stance phase, as a function of physical leg stiffness or actively modified leg stiffness.

One goal of a tuned leg stiffness is to minimize the amount of energy that the motor must use to maintain a constant gait cycle. We measured the amount of mechanical steady-state work that must be inserted with each vertical hop and found that there is a leg stiffness that minimizes this motor work. In other words, the energetically optimal stiffness maximizes the spring restitution of the machine, as shown in Figure 10. We speculate that this is caused by a balance between energy losses from the inelastic collision of the toe, and energy losses from internal friction of the transmission. Stiffer springs will result in a more forceful impact on the ground and increased losses, whereas softer springs will result in greater spring deflection and correspondingly higher frictional losses through the mechanical transmission.

Table 1. Parameters for Thumper.

Leg length, fully extended	1 m
Leg length, fully retracted	0.5 m
Leg angle range	$\pm 45°$ from vertical
Robot mass	38 kg
Knee stiffness	512–585 Nm/rad
Motor peak torque	30 Nm
Speed reduction factor between motor and knee	31.5

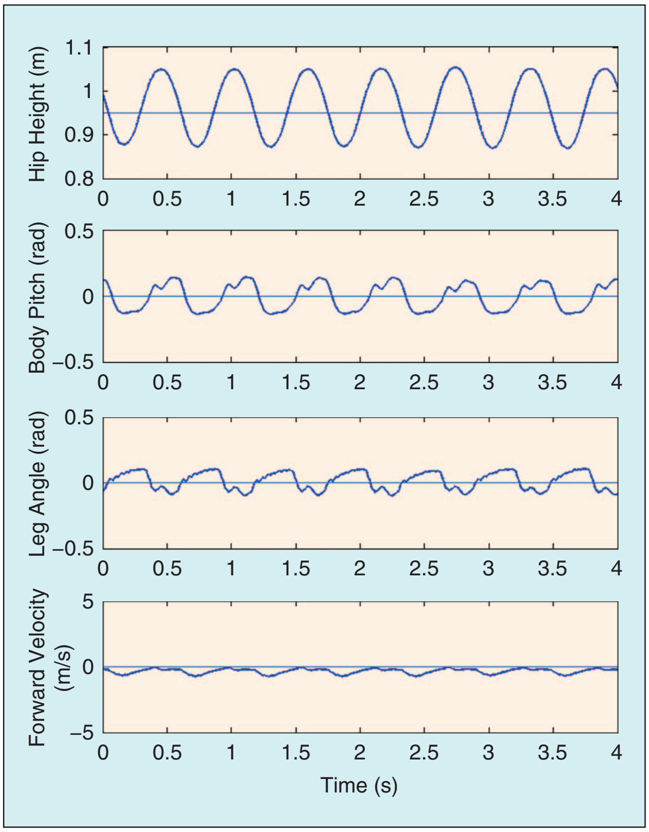

Figure 8. *Data recorded from Thumper, hopping with approximately zero forward velocity. A small time-section of the data has been plotted so that details of the motion are visible, but the rest of the dataset is similar. The length of the leg at full extension is 1 m, but the leg length at touchdown is held at 0.95 m for this experiment. Any values above 0.95 m are an aerial phase of running, while values below 0.95 m are stance phases. The knee stiffness in this experiment was 524 Nm/rad.*

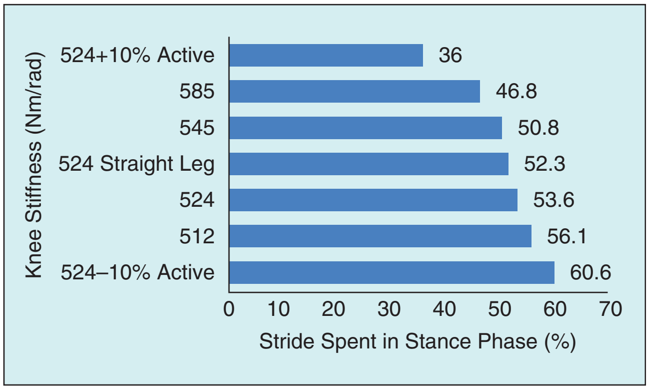

Figure 9. *The duty factor, or percent of gait cycle spent on the ground, as a function of knee stiffness. Although the physical spring acts in the direction of the leg length and is not strictly acting at the knee joint, it is a reasonable simplification. We have chosen to report stiffness in terms of the linear torsional knee spring, because the leg spring is affected by the mechanical advantage of the knee joint and becomes nonlinear.*

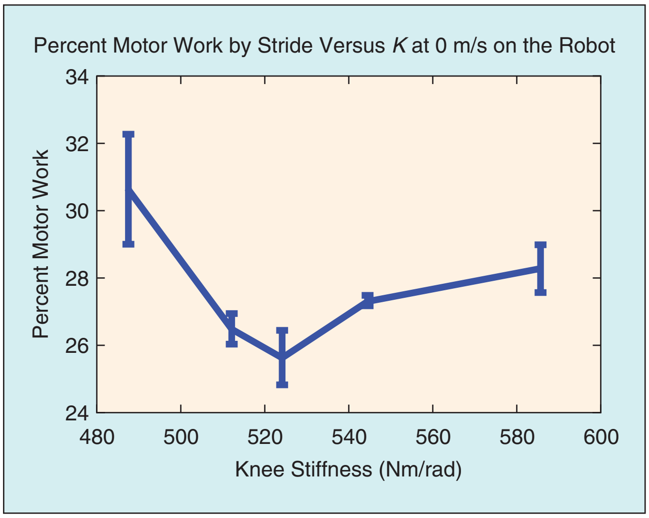

Figure 10. *The percent of mechanical work done by the electric motor during a stance phase, as a function of leg stiffness, while hopping in place. The goal is to minimize this value, which means that the spring is doing the maximum amount of work. Data points in this plot are calculated from ten averaged hops for each knee stiffness, with the standard deviation shown by error bars.*

Discussion

In choosing to remove the adjustable stiffness capability of the BiMASC and the AMASC for the ECD leg revision, we made a subjective engineering decision. The internal forces of the antagonistic springs, along with the additional mechanism associated with our implementation, seemed to have greater costs than the benefits could warrant. Because different engineering implementations may achieve better performance than ours, we cannot conclude that the variable stiffness mechanism is not worthwhile. Our experiments have illustrated some energetic effects of different leg stiffnesses in a real system, and future work could show greater effects for running at speed.

When choosing the leg springs for testing the energy use on Thumper, we first calculated the necessary energy storage capacity based on the mass and the hopping height and verified whether our springs would be physically large enough. After construction of the robot, we tried various different springs to find the one that provided the best subjective running gait. We then ran experiments with springs that were slightly softer and slightly stiffer. The very soft springs resulted in long leg deflections that neared the limits of leg deflection, while very stiff springs resulted in harsh ground impacts that destabilized the gait. We do not believe that it is coincidental that the subjective best leg stiffness also resulted in the best spring restitution for the robot, although the influence of leg stiffness on spring restitution was somewhat weak. The curve in Figure 10 might be much more pronounced for significant forward velocities.

The energy insertion is calculated by measuring the deflection of the motor at each millisecond, and the deflection of the spring at that point in time, which corresponds to the applied force at the motor shaft. By measuring only the mechanical work, we avoid the effects of the motor technology, such as inertia or stall inefficiencies, and the results of our experiments can be compared more easily to robots using other actuation technologies. We also avoid the consideration of a software controller in the calculation of work insertion; the energy can be inserted in a way that is electrically inefficient, using high torques and accelerations, without affecting the results of our experiment. This way, we are certain that the energy savings come from some mechanical effect, such as collision losses or frictional losses.

Thumper has an unexpected preference for running backwards, assuming that the forward direction is a human-like knee bend. In addition, Thumper has some difficulty running very fast, because the leg swing causes a significant body pitch, which destabilizes the machine. In recent experiments, we have added a long bar to increase the rotational inertia of the torso. This modification dramatically improved the Thumper's running performance, allowing as forward running speed of approximately 1.5 m/s. It is our hope that MABEL will be better suited for running without an added torso inertia bar, because the two legs can counter each other's inertia and keep the body relatively stable.

Conclusions

The important message to take from this article is that a robot is a unified dynamic system comprising electronics, software, and mechanical components, and for certain tasks such as running, a significant portion of the behavior is best exhibited through natural dynamics of the mechanism. Therefore, the mechanical system must be specialized for the task and designed with the same care for dynamic control as the software control system.

In constructing the ECD leg, we have attempted to follow this philosophy and design the mechanical system for the specific tasks of walking and running. The prototype actuator, with dynamics verified by testing, exhibited behavior that enabled running in simulation. The ECD leg builds on design revisions from the BiMASC prototype, and the successful experiments with Thumper hopping around the laboratory have proven the ideas and engineering behind the design. Prof. Grizzle's group at the University of Michigan has already demonstrated tentative walking with MABEL, and we expect to demonstrate robust and efficient walking and running gaits in the near future.

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Keywords

Legged locomotion, actuation, series compliance.

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