

# A Variable Stiffness Actuator for Use in Passive-Dynamic Robots

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## Abstract

A model of a passive-dynamic robot which is hypothesized to be capable of walking and running is presented. This model has been selected to match closely with a physical robot currently in construction, for the purpose of furthering the state-of-the-art in legged machines which locomote efficiently based on passive-dynamic principles. A novel actuator called the Variable Stiffness Series Elastic Actuator (VSSEA) is also introduced. Its design and advantages are briefly discussed.

## 1. What is the goal of the research?

- The objective of this research is to construct a robot that walks and runs efficiently, based on principles of passive-dynamic locomotion.
- A robot model currently under study that is believed to be capable of walking and running is shown in Fig. 1.

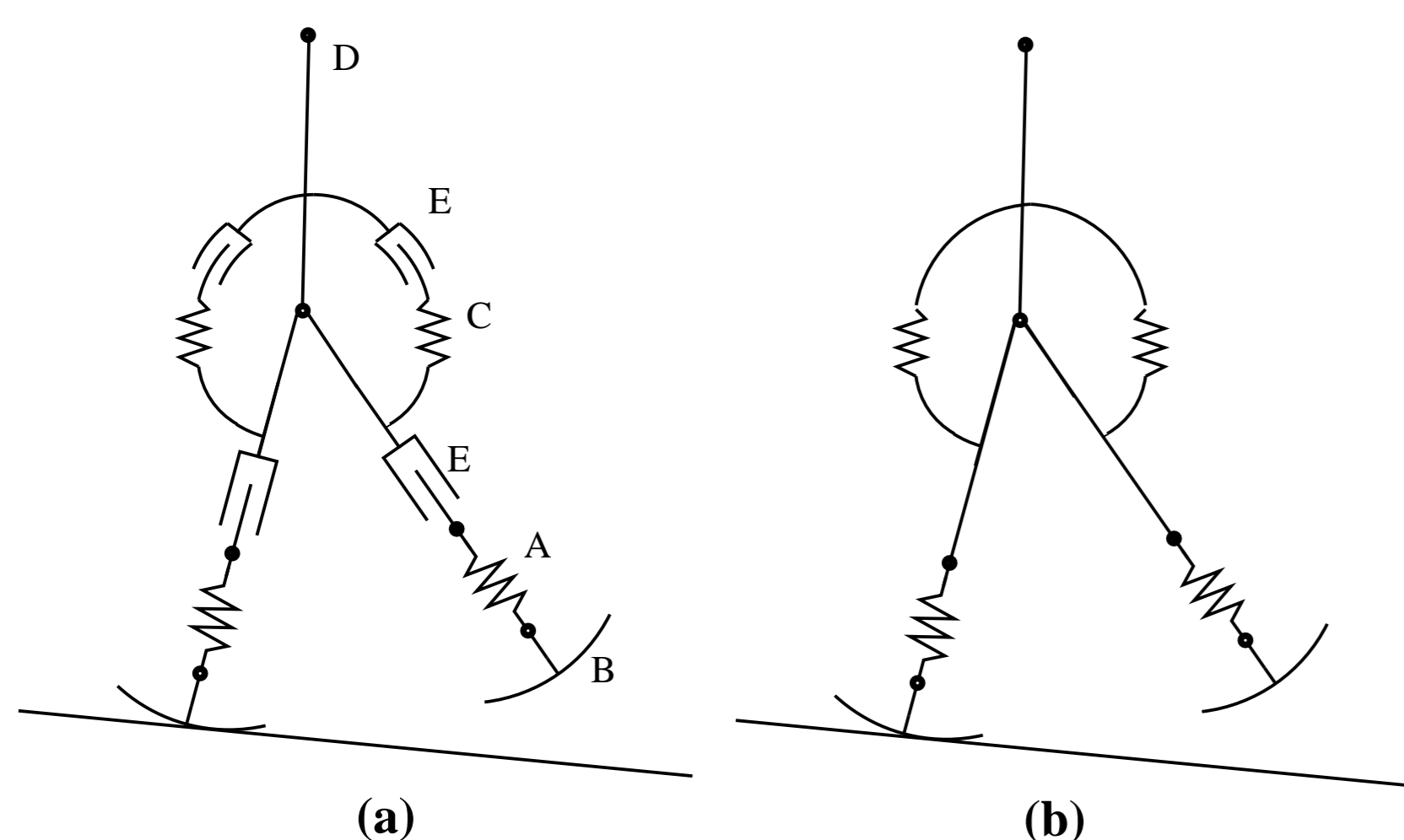


Figure 1: Model of the robot when being actuated (a), model of the robot when unactuated (b).

## 2. Why is the model so complex?

- A robot that both walks and runs passively has many constraints, so the complexity is necessary to satisfy these constraints.
- Please note that when the actuators are locked, the model reduces to Fig. 1b.
- We now justify the inclusion of the labeled components in Fig. 1a.
- (A) *Leg Springs*. The analysis by [22] and [24] suggest that collisions which resemble purely elastic collisions, regardless of how they arise, are energetically optimal. We should therefore include a spring element in the telescoping legs to allow this "pseudo-elastic collision" to occur via true passive-dynamics.
- (B) *Arc Feet*. Ref [20]'s experiments with dynamically stable running robots show that, for some range of radii, arc feet can make a running robot self-stabilize. It has also been shown that passive-dynamic walker models which use semicircular, arc-shaped feet possess superior stability and efficiency compared to point-foot models[2][27]. Thus arc feet are beneficial to the efficiency and stability of both walking and running motions and should be included in a physical robot. Indeed, arc feet may be essential to make the basin of attraction of the limit cycle of a highly-dynamic running gait large enough to be realistically stable for a physical robot.
- (C) *Hip Joint Springs*. [22] show that decreasing step size improves energetic efficiency because collisional losses are reduced. Another reason to include hip springs is that simple calculations show that realistic running motions require a fairly stiff leg spring. Unfortunately, a realistic mass distribution means that the frequency of the pendular leg-swing is very low compared to the harmonic frequency of the body mass and the leg spring, resulting in multiple up-down oscillations of the center of mass during each step[9]. We can avoid this problem by adding hip springs to speed up the frequency of leg swing so that it is equal to some small multiple of the up-down bouncing period.
- (D) *Torso*. It is necessary to include a torso in the model, because realistic robots will likely require a torso for mechanical and practical reasons. The addition of

a torso does not present any significant disadvantages beyond one of complexity. In fact, torsos have been shown to have desirable stabilizing properties and also further energetic improvements compared to torso-less designs[27].

- (E) *Actuation*. Actuation is required for practical reasons, as is shown in the next question. Actuators maintain a constant length unless power is applied to them, so if no power is applied, the model reduces to just links and springs as shown in Fig.1b (i.e. a pure passive dynamic model).

## 3. Why is control required?

- Typically passive-dynamic machines do not have control systems.
- However, because there is no control, demonstrating reliable operation of a passive-dynamic machine is difficult[7], especially when the stable domain of the limit cycle is small. Adding control solves this problem by expanding the region of stability via an appropriate control law, and makes the machines able to be practically useful in the real world.

## 4. Why is force control required?

- Trajectory-control of passive-dynamic machines is not satisfactory in the case of passive-dynamic robots; precisely controlling the trajectory of the robot overwhelms the natural behavior of the machine and the machine will lose its passive-dynamic properties. Instead, we must control the energy of the system. Therefore, we need a force-controllable actuator capable of applying impulses of energy to the system.

## 5. What is the name of this actuator?

- The actuator is named the Variable Stiffness Series Elastic Actuator (VSSEA), because it is essentially similar to the standard Series Elastic Actuator (SEA) design of [21][18], but with the additional capability of variable stiffness. It uses two antagonistic nonlinear (quadratic) springs to effectively create a linear spring.

## 6. Why is this actuator special?

- It incorporates an energy storage mechanism (springs), variable compliance, and force control in a single package.
- Without any mechanical changes, and assuming that the motors are non-back-drivable, a robot built with the VSSEA design(Fig. 1a) could become a purely dynamic walker (Fig.1b) simply by removing power from the actuators.
- Another benefit of this topology is that control and analysis of the system are very close to linear, provided the stiffness is not changed quickly during operation, since the actuator model reduces to Fig.2d if the precompression motor is kept a constant length.

## 7. Why are springs needed?

- By measuring the deflection of the spring, you can accurately compute the force on the output mass.
- Springs reduce the output impedance of the actuator. Low output impedance is beneficial for force control.
- They provide a passive energy storage device.

## 8. Why is variable stiffness needed?

- Based upon other researchers' experience with real-world passive-dynamic bipedal robots[14][7], it seems common for the limit cycle of passive-dynamic robots to be relatively small, making their operation hard to reliably demonstrate by hand. It seems likely that despite accurate numerical simulations, building springs with the exact stiffness required for a robot based on the model in Fig.1 would be difficult. Hence, including a variable stiffness spring gives enough design flexibility to explore experimentally the range of the passive-dynamic limit cycle under realistic conditions.

## 9. How is this actuator different from other variable-stiffness actuators?

- The difference in topology can be seen in Fig. 2a and Fig. 2b.
- Most researchers working on variable-stiffness mechanisms, such as [16][10][28][5], use actuators and quadratic springs in a different component topology than the VSSEA. They follow the principle that actuating antagonistic motors in common mode changes stiffness, and differential actuation changes position. In the VSSEA design, the stiffness and position are actuated independently.
- The reason for the different topology is due to a different goal. Most researchers desire for the stiffness of the actuator to be varied quickly and continuously throughout a motion, and use this stiffness change as an essential part of the control system (for, say, the purposes of safety [4][28] or for bio-mimetic reasons[16]). In contrast to this, when using the VSSEA actuator in passive-dynamic robot models such as the one presented in this paper, rather than *vary* the effective stiffness, we desire to *hold the stiffness close to some optimal value* corresponding to some stable, efficient limit cycle, while still being able to add energy to the system via actuation.

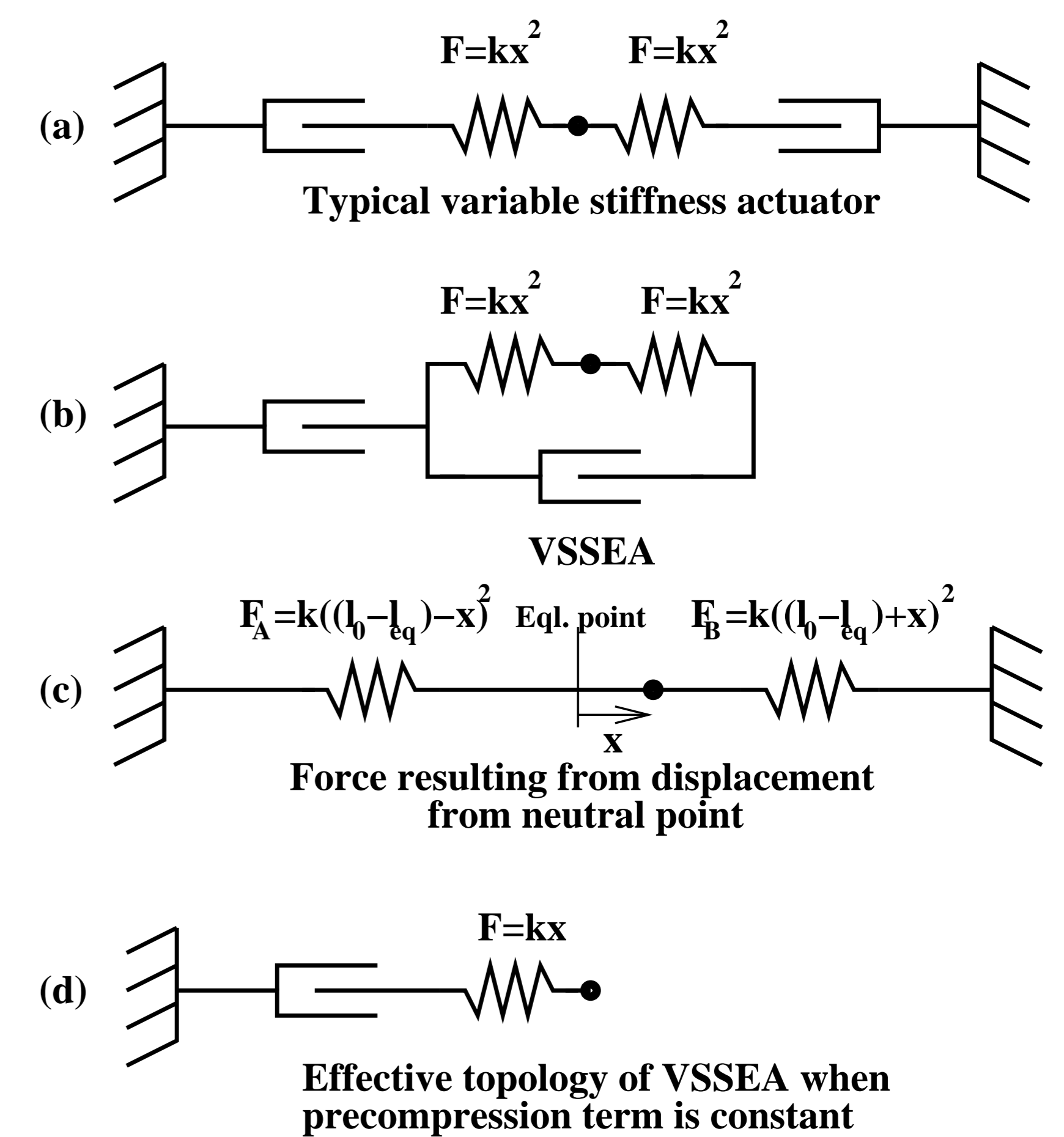


Figure 2: Comparison of typical variable stiffness topology (a), VSSEA topology (b), the force on the output mass when both actuators are locked (c), and the effective VSSEA topology when only the precompression actuator is locked (d).

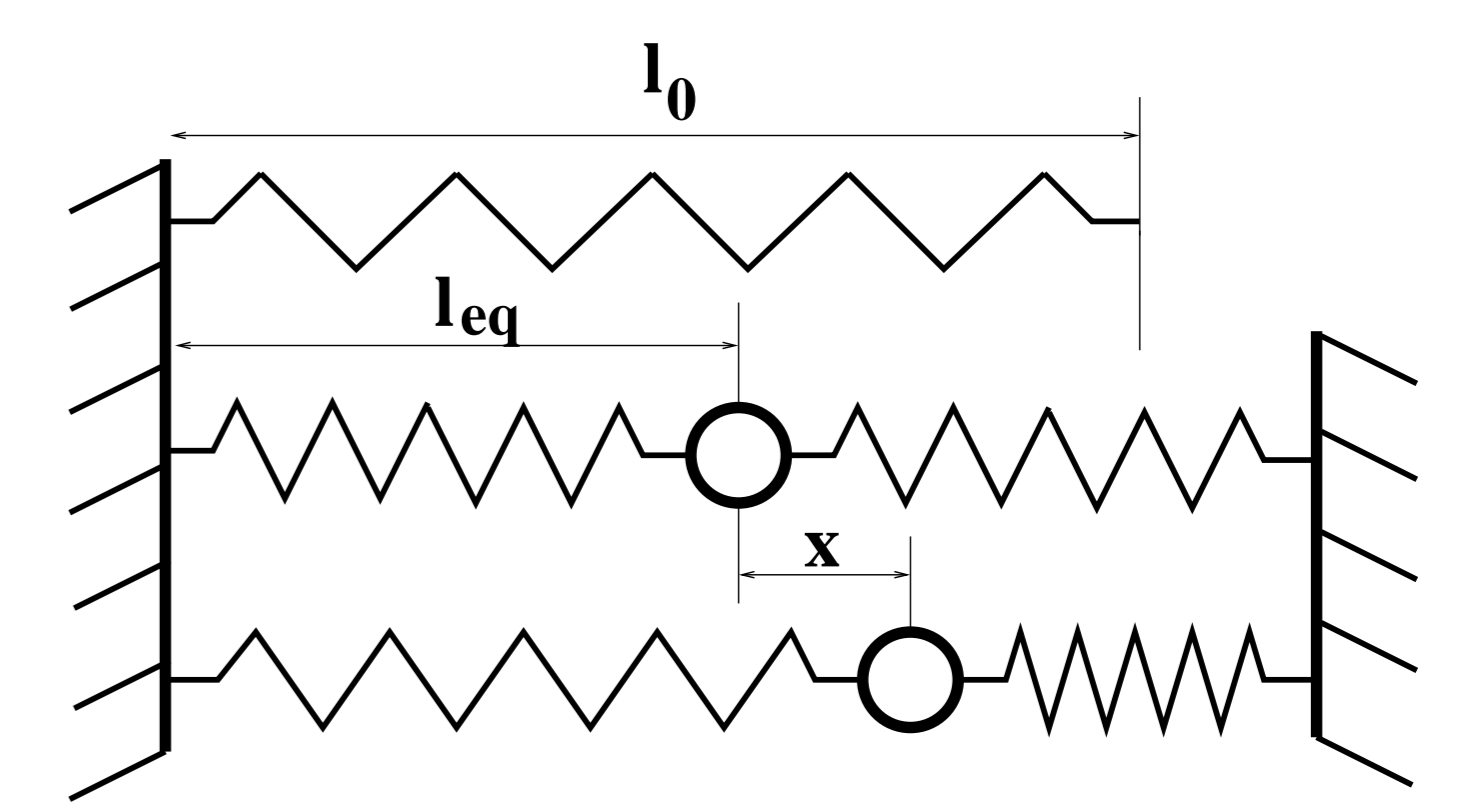


Figure 3: Mechanical configuration of two compression springs used in the VSSEA, emphasizing spring lengths.

## 10. Why are nonlinear springs needed?

- Refer to Fig. 2c and Fig. 3 for relevant measurements.
- Assume we have an output mass sandwiched between two antagonistic compression springs A and B. Let  $x$  be the displacement of the mass from the equilibrium point. Here  $l_0$  is the natural length of the spring, and  $l_{eq}$  is the length of the spring when in equilibrium with the antagonistic spring (at no-load conditions on the output mass). We assume that the springs are always under compression, (i.e. that  $l_0 \geq l_{eq}$ ,  $x \leq l_0 - l_{eq}$ ).

If the force-distance relationship for each spring when displaced from its natural length  $l_0$  by a distance  $d$  is equal to

$$F(x) = K_I d$$

where  $K_I$  is the linear stiffness constant for that spring in units of N/m, then the force on the output mass is

$$\begin{aligned} F &= F_A - F_B \\ &= K_I[(l_0 - l_{eq}) - x] - K_I[(l_0 - l_{eq}) + x] \\ &= -2K_I x \end{aligned}$$

The pretension term  $(l_0 - l_{eq})$  has no effect on the force the output mass sees, so a system which uses linear springs is not adjustable.

However, if the reactive force from the spring when displaced from its natural length  $l_0$  by a distance  $d$  is equal to

$$F = K_n d^2$$

where  $K_n$  is the nonlinear stiffness constant for that spring in units of N/m<sup>2</sup>, then the force on the output mass is

$$\begin{aligned} F &= F_A - F_B \\ &= K_n[(l_0 - l_{eq}) - x]^2 - K_n[(l_0 - l_{eq}) + x]^2 \\ &= K_n[l_0 - l_{eq} - x][l_0 - l_{eq} - x] \\ &\quad - K_n[l_0 - l_{eq} + x][l_0 - l_{eq} + x] \\ &= K_n[l_0^2 - 2l_0 l_{eq} - 2l_0 x + l_{eq}^2 + 2l_{eq} x + x^2] \\ &\quad - K_n[l_0^2 - 2l_0 l_{eq} + 2l_0 x + l_{eq}^2 - 2l_{eq} x + x^2] \\ &= K_n[-4l_0 x + 4l_{eq} x] \\ &= -4K_n[l_0 - l_{eq}]x \end{aligned}$$

Notice that the effective stiffness  $K_{eff}$ , can be adjusted through the equilibrium precompression term  $(l_0 - l_{eq})$ .

We now define  $K_{eff} = -4K_n(l_0 - l_{eq})$  to be the effective linear spring constant in units of N/m. This gives us  $F = K_{eff}x$ , which is a linear spring that obeys Hooke's Law.

In summary, the combination of two quadratic rate springs results effectively in a linear spring with a variable stiffness.

- This phenomenon seems well known by many other researchers investigating variable-stiffness mechanisms [11]. The maximum dynamic range of stiffness for two antagonistically paired quadratic springs is limited to a 2:1 ratio [5], but we believe this range to be sufficient for the purposes of tuning the dynamics of a passive-dynamic robot.

### 11. Aren't there other robots built which use similar principles?

- While other robots have been built using SEAs[17], unlike the approach presented in this paper, the mechanical design and control systems used on such robots did not generally focus on exploiting the great energetic efficiency found when operating near a passive-dynamic limit cycle.

### 12. What are other possible applications of the VSSEA?

- A VSSEA actuator would be useful in any situation where variable compliance is required. This includes peg-in-hole assembly tasks, safe human-robot interaction, cooperative robot mechanisms, low-energy control, and related problems.
- The design is also well suited to tuning and sustaining mechanical resonances for some narrow range of frequencies.

### 13. Mechanical Description

A CAD representation of the actuator is shown in Fig. 4 and Fig. 5. A prototype has been manufactured and is under testing. The mechanical properties of the prototype are listed in Table 1.

Table 1: Parameters of Prototype Actuator

Parameter	Value	Units
Max length	89	cm
Overall mass	4.5	kg
Spring stroke	20	cm
No-force stroke	>10	cm
Max. $K_{eff}$	6400	N/m
Min. $K_{eff}$	3200	N/m
Main Motor	90	W
Precompression Motor	5	W
Max. Force	>320	N

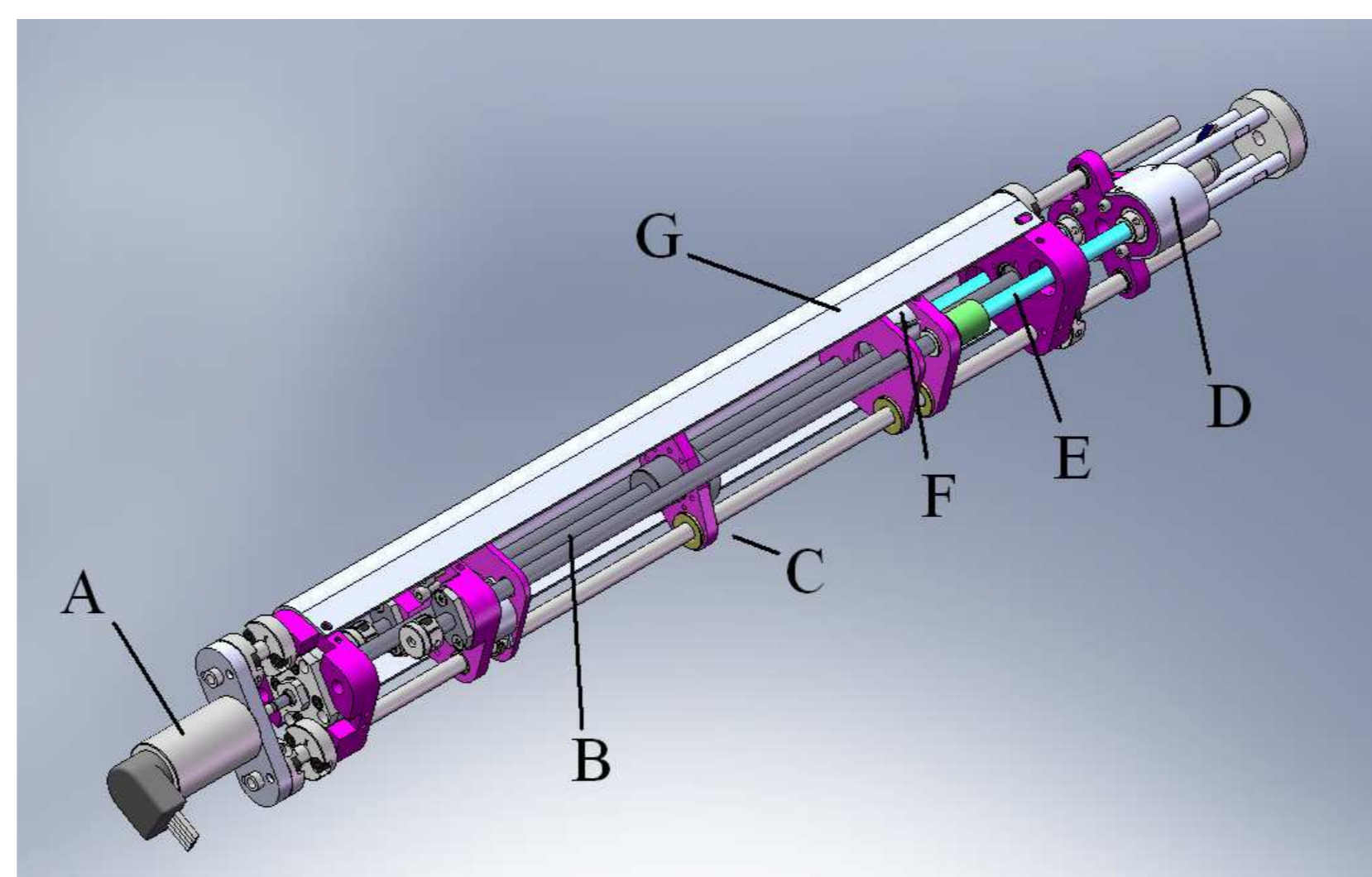


Figure 4: CAD rendering of the VSSEA.

At the heart of the actuator is the "main" motor (A) connected to a ballscrew (B). The ballscrew nut (C) is sandwiched between two variable-rate quadratic springs (not shown), which themselves are put under some variable amount of precompression by what we will call the "pre-compression" motor (D) and leadscrews (E). Two load cells (F) measure the compressive force acting on each spring. To determine the position of the output link (connected at D), length sensors (not shown) measure the length of each spring. The length sensors can also be used to double check the accuracy of the forces measured by the load cells, because the force-compression characteristics of the spring are known. A dust cover (G) keeps the actuator interior clean.

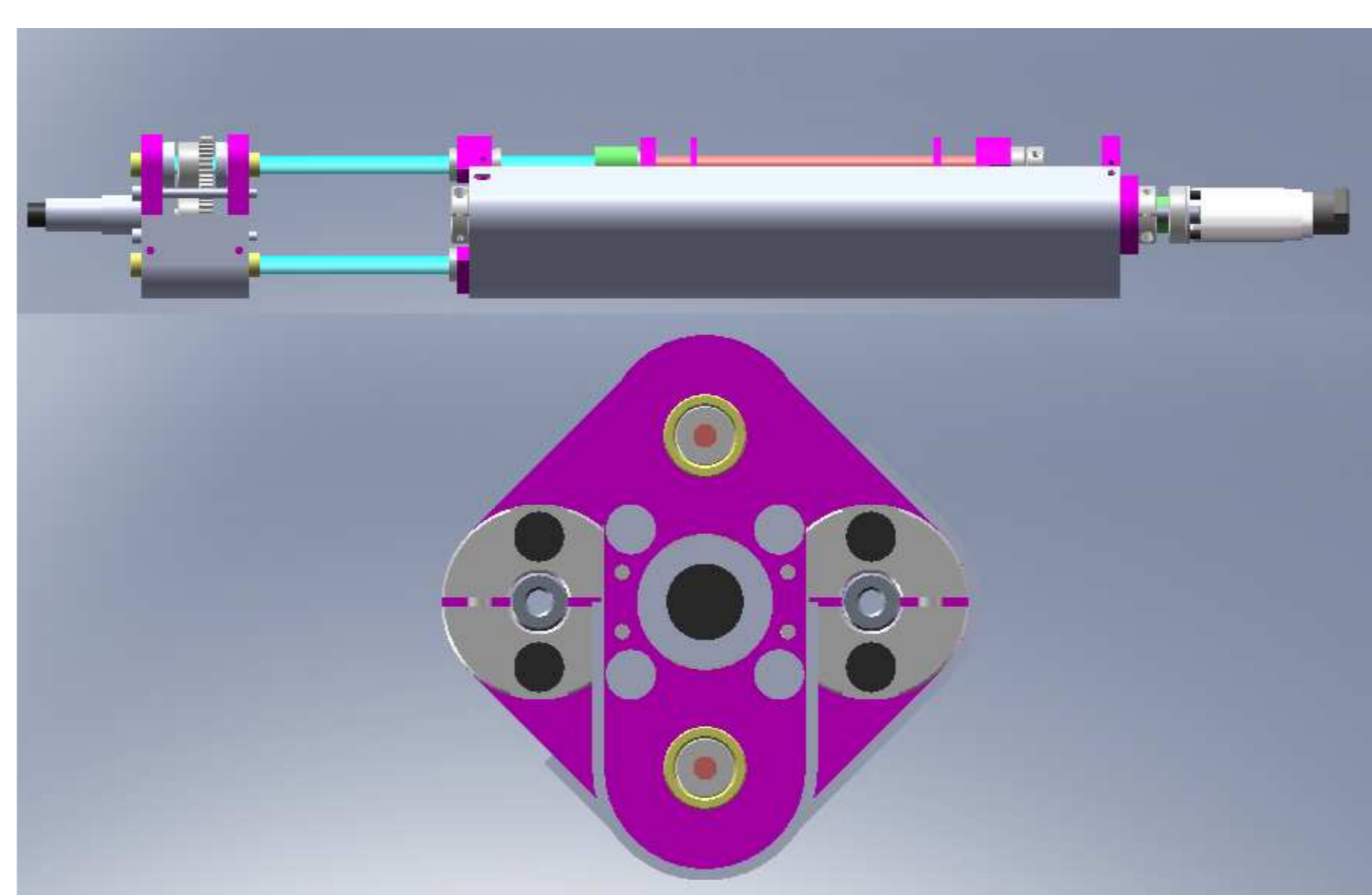


Figure 5: Another view of the VSSEA.

The prototype is composed mainly of aluminum, steel, and cast magnesium parts, but is not yet as lightweight as desired. Force-control is accomplished via a simple PD control rule implemented using feedback from quadrature encoders. Photos of the prototype are shown in Fig. 6 and Fig 7.

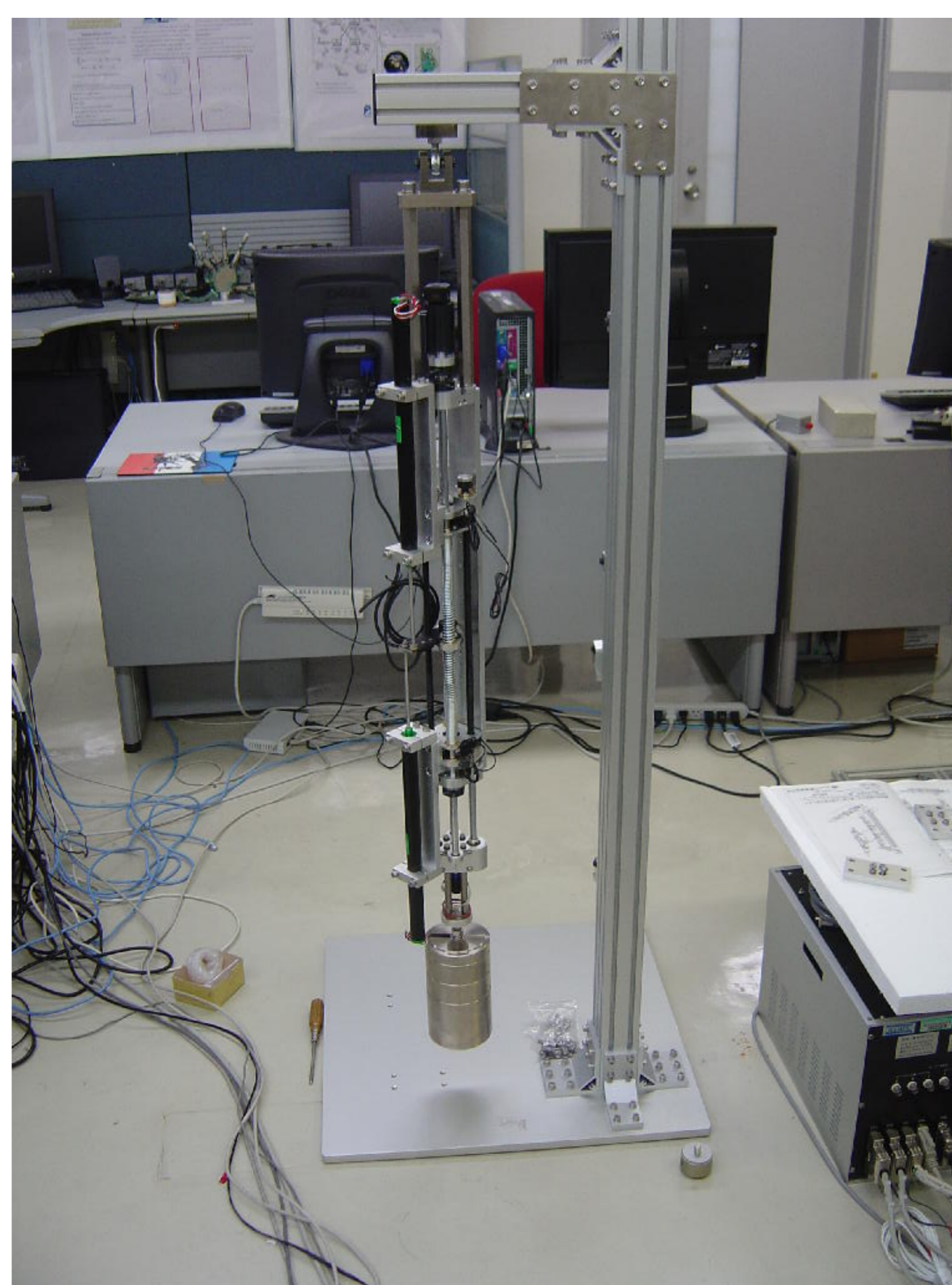


Figure 6: The VSSEA in a vertical-hang test configuration. Two other configurations are possible: horizontal and "hopping" modes.



Figure 7: The VSSEA on a table. Extra sensors have been fitted to the VSSEA for testing.

### 14. Conclusion and Future Work

We have presented motivation for studying the rather complex model shown in Fig.1, and introduced the necessity and benefits of using a novel actuator called the VSSEA. The VSSEA prototype has been manufactured, and after testing, four such actuators will be used to implement the biped model. We have also argued that this biped model is likely capable of both walking and running modes of operation. While the equations of motion corresponding to the biped model of Fig. 1 have been derived, a complete simulation including impact modeling and system stability has not yet been completed. In the future, we plan to study the limit cycle stability of the model, present prototype actuator test results, and examine experimental measurements of stability of a robot built with VSSEAs. It is hoped that the experimental results will verify the practicality of exploiting passive-dynamic limit cycles for energetically efficient legged locomotion.

### 15. Acknowledgments

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