Design Considerations for a Variable Stiffness Actuator in a Robot that Walks and Runs

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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.

Key Words: passive-dynamic, walking, running, variable stiffness

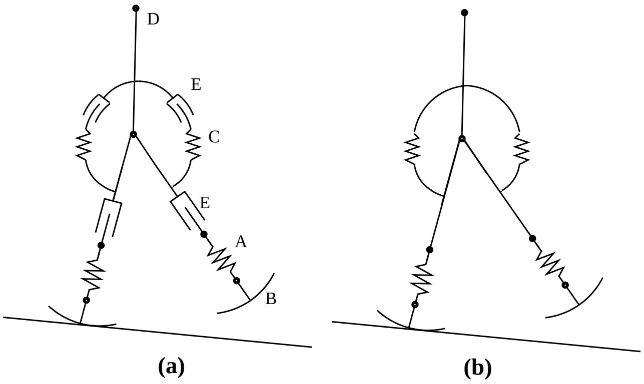
1. Introduction

Although robots which use the principles of passive dynamics to walk [14][25][6][7][27][8] or run [19][20][1] have been constructed, to the author's knowledge there does not exist a passive-dynamic robot capable of both running and walking stably without control. The objective of this research is to construct something close to such a robot, for the purpose of creating an efficient walking and running machine based on principles of passive-dynamic locomotion.

Restated another way, we seek to construct a practical robot which is as close as possible to the "pure" passive-dynamic robot. A pure passive-dynamic robot walks or runs down a gentle slope without control or actuation, and possesses a gait with a stable limit cycle for some range of system parameters and slopes. Research[6] has shown that robots based on passive-dynamic principles have energetic efficiencies much higher than those with control systems that specify position trajectories, for example as was used in the Asimo robot[23]. In a sense, we seek to construct the next generation of robots presented in [6], by increasing model complexity and adding actuation to bring the state-of-the-art of passive-dynamic legged machines one step closer to practicality.

Although a purely passive-dynamic machine can be built, reliable operation can be difficult to demonstrate [7], especially if the stable domain of the limit cycle is small. Therefore, to improve the chances of finding a suitably stable passive-dynamic limit cycle, we add additional complexity to the implementation (but not the model) in the form of variable-stiffness springs, as well as minimal actuation to deal with realistic engineering constraints.

The main goal of this paper is to present a novel, variable stiffness actuator well suited for use in passive-dynamic legged robots. This paper is organized as follows: section 2 justifies the selection of the biped model, section 3 describes the requirements for the novel variable-stiffness actuator, section 4 presents the overall topology of the actuator, and section 5 contains a brief description of the actuator that has been designed and prototyped.



(a) (b)

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

2. Discussion of Biped Model

The model we are studying is shown in Fig.1. In what follows, we mark the components of Fig.1 with (A), (B), (C), ... and justify the necessity of their inclusion in the model. Note that the springs shown in Fig.1 are generic linear springs, and the mechanical details of the spring will be discussed later in this paper.

(A). Leg Springs. The elegant, intuitive analysis of collisions by [22] and [24] in the context of walking and running suggest that collisions which resemble purely elastic collisions, regardless of how they arise, are energetically optimal. To make a biped efficient, and to minimize control and actuation, we should therefore include a spring element in the telescoping legs to allow this "pseudo-elastic collision" to occur via true passive-dynamics.[1]

(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

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[1] Indeed, to make a Honda humanoid robot run using the existing control and actuation system would require motors 28-56 times more powerful, without any change in weight [12]. Clearly, an elastic element is needed for running robots to be practical.

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. Note that the springs are actionally rotational in nature, but were drawn outside the hip in Fig.1 for purposes of clarity. Simple collisional mathematics applicable to all legged models [22] show that decreasing step size improves energetic efficiency because collisional losses are reduced. That is, for a given velocity, a robot with a hip spring takes shorter, faster steps than one without. Halving the step length reduces collisional loss per step to one fourth, so there are energetically beneficial reasons to include hip joint springs. 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]. It has been suggested that multiple oscillations, while perhaps permissible in a theoretical sense, have a smaller region of stability[26] than single up-down oscillation gaits. 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 torsoless designs[27].

(E). Actuation. Actuation is required for practical reasons, as will be discussed in detail in Section 3. 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. Motivation for Actuation and Variable Stiffness

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.

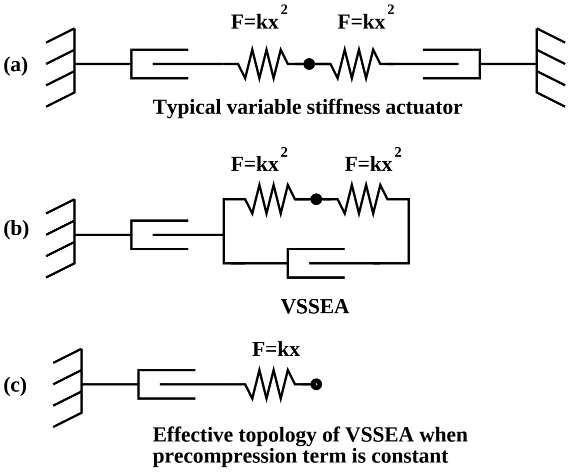

Fig.2 Comparison of typical variable stiffness topology (a), VSSEA topology (b), and the effective VSSEA topology when the stiffness is not being varied (c).

The necessity of actuating a passive-dynamic walker is motivated by practical considerations more than theoretical ones. Although many proof-of-concept passive-dynamic walkers are completely unactuated and walk stably down an inclined slope or on a treadmill, for practical use these robots are quite limited. Therefore, we follow an approach similar to [13], and instead of using gravity to add energy to the system, we use actuation and a minimal control system. This approach preserves the theoretical underpinning of passive-dynamic robots while opening possibilities for more practical applications.

More importantly, it is not yet known at the time of writing the size and stability of the model's limit cycles under realistic operating conditions. If the basin of attraction of the limit cycles are not sufficiently large enough for the physical robot to be passively stable in a walking or running gait, it will be necessary to stabilize the robot actively. However, section 2's arguments and their similarity to prior research suggest that for some range of spring, mass, and link length parameters, a stable limit cycle likely exists for the model in Fig.1b, allowing it to be capable of both walking and running motions without any control or actuation. A similar torsoless model under study by the author of [13] possesses stable limit cycles for walking and running [15]. Still, in the event that such a limit cycle is prohibitively small, we will need actuation to stabilize the robot. Including actuation is a way to reduce the risk of total failure to walk successfully.

Finally, adding linear actuators gives great versatility to the model. Many researchers[13][22] study reduced-complexity models, and thus only mention a few ways of adding energy to a biped model: hip-torque, and ankle-torque or "push-off". Another, less often mentioned way of adding energy to a passive-dynamic system is through pendular parametric excitation[3], the same principle at work when children use a playground swing. Therefore, one potential benefit of the proposed model is it is quite flexible and allows multiple energy-adding methods to be used, allowing experimental verification of their efficiencies and effect on stability.

4. Description of the Variable Stiffness Series Elastic Actuator (VSSEA)

The actuator presented in this paper 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. This can be shown as follows.

Assume we have an mass sandwiched between two antagonistic compression springs A and B. Let x be the displacement of the mass from the equilibrium point, and $F = K_n x^2$ be the resulting force from a spring, where K_n is the nonlinear stiffness constant for that spring in units of N/m^2. 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). We assume that the springs are always under compression, (i.e. that $l_0 \geq l_{eq}$, $x \leq l_0 - l_{eq}$). The force on the mass is then

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

We now define $K_{eff} = -4K(l_0 - l_{eq})$ 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. Notice that the effective stiffness K_{eff}, can be adjusted through the equilibrium precompression term $(l_0 - l_{eq})$.

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.

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. Graphically, the difference between the VSSEA and these other variable-stiffness mechanisms can be seen in Fig.2a and Fig.2b.

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.

We now return to the comment in the beginning of section 2 about the nature of the springs in Fig.1. For clarity, the complexity of the variable-stiffness mechanism was hidden in Fig.1, and instead of drawing Fig.2b at each actuated joint, we just drew Fig.2c.

The benefit of the VSSEA topology is that, without any mechanical changes, and assuming that the motors are non-back-drivable, a robot built with the VSSEA design could become a purely dynamic walker simply by removing power from the actuators (Fig.1b). 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.2c if the precompression motor is kept a constant length.

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.

5. Mechanical Description

A CAD representation of the actuator is in shown in Fig.3. A prototype has been manufactured and is under testing. The mechanical properties of the prototype are listed in Table 1.

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 "precompression" motor (D) and leadscrews(E). Two load cells (F) measure the compressive force acting on

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

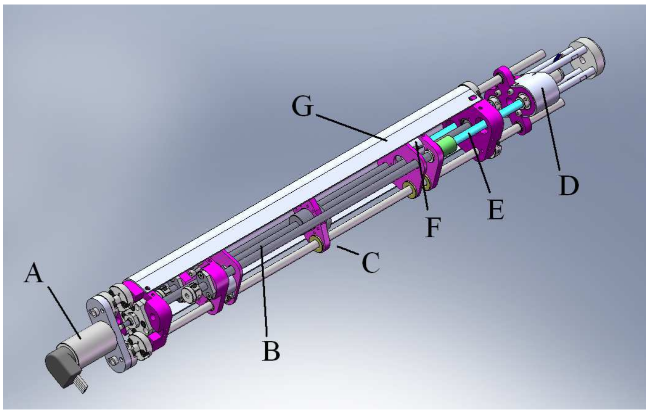

Fig.3 CAD rendering of the VSSEA.

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.

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.

6. 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. 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.

7. Acknowledgments

This work supported in part by the Japanese Government Monbukagakushou Research Student Scholarship.

References

[1] M. Ahmadi and M. Buehler. “Controlled Passive Dynamic Running Experiments with the ARL-Monopod II,” *IEEE Transactions on Robotics*, vol.22, no.5, October 2006, pp.974-986.

[2] F. Asano and Z. Luo. “On Energy-Efficient and High-Speed Dynamic Biped Locomotion with Semicircular Feet,” *Proc. of the IEEE/RSJ IROS*, 2006, pp.5901-5906.

[3] F. Asano, Z. Luo and S. Hyon. “Parametric Excitation Mechanisms for Dynamic Bipedal Walking,” *Proc. of ICRA*, 2005, pp.611-617.

[4] A. Bicchi, S. Rizzini and G. Tonietti. “Compliant design for intrinsic safety: General issues and preliminary design,” *Proc. of the IEEE/RSJ IROS*, vol.4, 2001, pp.1864-1869.

[5] A. Bicchi and G. Tonietti. “Fast and “Soft-Arm” Tactics,” *IEEE Robotics & Automation Magazine*, June 2004, pp.22-33.

[6] S. Collins, A. Ruina, R. Tedrake and M. Wisse. “Efficient Bipedal Robots Based on Passive-Dynamic Walkers,” *Science*, vol.307, 18 February 2005, pp.1082-1085.

[7] S. Collins and A. Ruina. “A Bipedal Walking Robot with Efficient and Human-like Gait,” *Proc. of ICRA*, 2005, pp.1983-1988.

[8] S. Collins, M. Wisse and A. Ruina. “A Three-Dimensional Passive-Dynamic Walking Robot with Two Legs and Knees,” *The International Journal of Robotics Research*, vol.20, no.7, 2001, pp.607-615.

[9] Y. Harata. “Kinematic Equations of a Biped Robot with Nonlinear Springs,” *Unpublished*, 2006.

[10] J. Hurst, J. Chestnutt and A. Rizzi. “An Actuator with Physically Variable Stiffness for Highly Dynamic Legged Locomotion,” *Proc. of ICRA*, 2004, pp.4662-4667.

[11] J. Hurst and A. Rizzi. “Physically Variable Compliance in Running,” *CLAWAR*, SPRINGER-VERLAG, www.springer-online.com, September, 2004.

[12] S. Kajita, T. Nagasaki, K. Yokoi, K. Kaneko and K. Tanie. “Running Pattern Generation for a Humanoid Robot,” *Proc. of ICRA*, 2002, pp.2755-2761.

[13] A. Kuo. “Energetics of Actively Powered Locomotion Using the Simplest Walking Model,” *Journal of Biomechanical Engineering*, vol.124, 2002, pp.113-120.

[14] T. McGeer. “Passive Dynamic Walking,” *The International Journal of Robotics Research*, vol.9, no.2, April 1990, pp.62-82.

[15] T. McGeer., personal communication, Jan 2006.

[16] S. Migliore, E. Brown and S. DeWeerth. “Biologically Inspired Joint Stiffness Control,” *Proc. of ICRA*, pp.4508-4513.

[17] J. Pratt and G. Pratt. “Intuitive Control of a Planar Bipedal Walking Robot,” *Proc. of ICRA*, 1998, pp.2014-2021.

[18] G. Pratt and M. Williamson. “Series Elastic Actuators,” *Proc. of the IEEE/RSJ IROS*, vol.1, 1995, pp.399-406.

[19] M. Raibert. “Legged Robots That Balance,” *MIT Press, Cambridge MA*, 1986.

[20] R. Ringrose. “Self-Stabilizing Running,” *Proc. of IEEE ICRA*, 1997, pp.487-493.

[21] D. Robinson. “Design and Analysis of Series Elasticity in Closed-loop Actuator Force Control,” *PhD Dissertation*, June 2000.

[22] A. Ruina, J. Bertram and M. Srinivasan. “A collisional model of the energetic cost of support work qualitatively explains leg sequencing in walking and galloping, pseudo-elastic leg behavior in running and the walk-to-run transition,” *Journal of Theoretical Biology*, vol.237, April 2005, pp.170-192.

[23] Y. Sakagami, R. Watanabe, C. Aoyama, S. Matsunaga, N. Higaki and K. Fujimura. “The Intelligent ASIMO: System overview and Integration,” *Proc. of the IEEE/RSJ IROS*, 2002, pp.2478-2483.

[24] M. Srinivasan. “Why Walk and Run: Energetic Costs and Energetic Optimality in Simple Mechanics-Based Models of a Bipedal Animal,” *PhD Dissertation*, May 2006.

[25] B. Vanderborght, B. Verrelst, R. Van Ham, M. Van Damme, D. Lefeber, B. Duran and P. Beyl. “Exploiting Natural Dynamics to Reduce Energy Consumption by Controlling the Compliance of Soft Actuators,” *The International Journal of Robotics Research.*, vol.25, no.4, April 2006, pp.343-358.

[26] R. van der Linde. “Active leg compliance for passive walking,” *Proc. of ICRA*, 1998, pp.2339-2344.

[27] M. Wisse. “Essentials of dynamic walking: Analysis and design of two-legged robots,” *PhD Dissertation, Technische Universiteit Delft*, 2004.

[28] M. Zinn, O. Khatib, B. Roth and J. Salisbury. “Playing It Safe,” *IEEE Robotics & Automation Magazine*, June 2004, pp.12-21.