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Novel Variable Stiffness Spring Mechanism: Modulating Stiffness Independent of the Energy Stored by the Spring

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Abstract— **Theory suggests a linear relation between stiffness and the energy stored by a linear helical spring at constant deformation. This relation implies that increasing the stiffness of a helical spring upon deformation requires more energy at larger deformations. State-of-the-art variable stiffness spring actuators, used to drive robots and human assistive and augmentation devices, are characterized by a similar relation: increasing stiffness as the spring is deformed costs more energy as more energy is stored by the spring. This feature imposes an apparently fundamental limitation on variable stiffness spring actuation in demanding tasks, such as lifting more, jumping higher, or running faster, because, in all these tasks, the variable stiffness spring should store a considerable amount of energy and provide different stiffness to accommodate different weights in lifting, heights in jumping, and speeds in running. Here, we present an innovative variable stiffness spring design, where *the energy cost of changing stiffness is independent of the energy stored by the spring.* The key element of the new design is a novel floating spring which changes stiffness without changing the energy stored by the spring. Springs possessing the aforementioned feature could pave the way towards variable stiffness robot actuation and human augmentation using smaller motors and smaller battery packs.**

I. Introduction

A typical spring has constant stiffness that defines how much force it exerts upon deflection. The stiffness of a spring depends on the material, shape, and size of the spring. Variable stiffness springs are special types of springs, which change their shape or size in order to increase or decrease their stiffness, thereby, providing more or less force upon the same deformation. Variable stiffness springs enable a range of new capabilities compared to constant stiffness springs, including stable robot-environment interaction [1], safer human-robot interaction [2], [3], optimal resonance-based actuation [4], [5], [6], as well as advances in human performance augmentation [7], [8]. However, increasing the stiffness of a spring can be costly because the energy cost of increasing spring stiffness is higher as more energy is stored by the spring. For example, the energy required to increase the stiffness of a linear helical spring at a given deformation linearly increases with the energy stored by the spring at the same deformation.

State-of-the-art variable stiffness springs offer theoretically zero, and practically low energy cost stiffness modulation if the spring does not store energy [9], [10], [11], [12], [13] (theoretically zero energy cost stiffness modulation means that the cost to modulate stiffness is independent of the energy stored by the spring). Theoretically zero energy cost stiffness modulation may be achieved by shortening the active length of a helical spring [14], shortening the active length of a leaf spring [15], [16], [17], or changing the moment arm connected to a spring in a number of previous designs [18], [19], [10], [20] if the spring is at zero deflection and consequently does not store energy.

While all the aforementioned variable stiffness actuators and springs can be used to recycle, store and release energy, they require a significant amount of energy to change their stiffness during the middle of the task when the spring already stores a significant amount of energy. Changing stiffness when the spring stores energy is a typical requirement in a large class of tasks, including the pick-and-place task in industrial robots [21], the weight-lifting task in humans [22], [23], [24], as well as the jumping and running tasks considered in [7], [8]. In all these tasks, the force requirement has to be adapted when the robot engages a load at its end effector (pick-and-place), when a human aims to overcome load inertia (weight-lifting) or when the human interacts with the environment (jumping and running). Using a spring that can change its stiffness independent of how much energy it stores would be ideal for these tasks.

In this paper, we present a novel variable stiffness spring which allows stiffness modulation independent of the energy stored by the spring. The new design embodies a lockable floating spring which can change stiffness at theoretically zero energy cost regardless of the spring deflection. We present the mathematical model of the novel mechanism and present experimental data to confirm the theoretically predicted feature of the new spring design.

The proposed variable stiffness spring improves upon current variable stiffness spring technology by providing low-cost stiffness modulation while the spring stores energy at any deflection. Current variable stiffness designs enable energy input using low stiffness and energy release using high stiffness at the energy cost of changing stiffness proportional to the amount of energy stored by the spring. The proposed variable stiffness spring mechanism eliminates the energy cost of changing stiffness proportional to the amount of energy stored by the spring. We anticipate that the novel class of variable stiffness springs presented and investigated in this paper would enable low-cost force and stiffness augmentation at any spring deflection for a wider range of applications.

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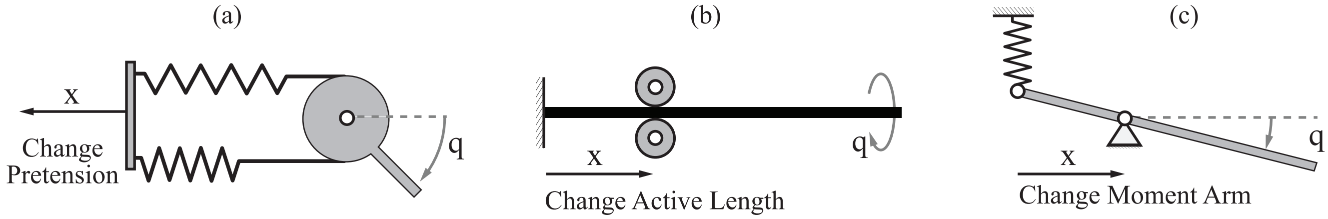

Fig. 1. (a) Pretension-based variable stiffness spring similar to agonist-antagonistic muscle pair in human joints. (b) Variable length torsional leaf spring. (c) Variable moment arm mechanism with movable pivot point.

II. Variable Stiffness Mechanisms

In this section, we examine the relation between stiffness and the energy stored in variable stiffness springs. We will consider the three common types of variable stiffness springs design using the spring-pretension, variable-length, and variable-moment-arm principles shown in Fig. 1(a)-(c). For each design, we will predict the minimum energy cost to increase stiffness when the spring is deflected from its equilibrium configuration, i.e. when it stores energy.

A. The ideal spring design

For the ideal variable stiffness spring, the energy stored by the spring V is independent of spring stiffness k for all deflections q:

$$V = V_{\text{ideal}}(q,k) \Rightarrow \forall q : \frac{\partial V}{\partial k} = 0. \tag{1}$$

The linear helical spring does not satisfy this condition, as the energy stored by the linear helical spring linearly depends on the stiffness of the spring:

$$V = V_{\text{helical}}(q,k) = \frac{1}{2}kq^2 \Rightarrow \frac{\partial V}{\partial k} = \frac{1}{2}q^2. \tag{2}$$

According to (2), the minimum amount of energy to increase the spring stiffness by Δk at a given deflection q is the extra energy added to the spring $\Delta V = \frac{1}{2}\Delta k q^2$. According to (2), the helical spring behaves like the ideal spring (1) only if it does not store energy $V_{\text{helical}}(q=0,k) = 0$.

Figure 1 shows three different non-ideal variable stiffness springs. The stiffness of these springs is adjusted by a motor while changing x:

$$k = k(x).$$

In what follows, we examine the relation between the energy storage and the stiffness of these springs.

B. The pretension-based spring design

Figure 1(a) shows a pretension-based variable stiffness mechanism. The potential energy of this mechanism is given in [11]:

$$V(q,k(x)) = \frac{1}{2}k(x)q^2 + \frac{1}{24}k(x)^3.$$

As we can observe, the potential energy increases if the stiffness of the spring increases:

$$\frac{\partial V}{\partial k} = \frac{1}{2}q^2 + \frac{1}{8}k(x)^2.$$

This example shows why energy is required to increase stiffness in pretension-based variable stiffness spring mechanisms.

C. Variable length and variable moment-arm designs

Figure 1(b) shows a variable-length spring where the stiffness is changed by modulating the active length of the spring, for example, a torsional leaf spring where $k(x) \propto x^{-1}$ [17]. Figure 1(c) shows a variable-moment-arm based spring design, where the stiffness is changed by modulating the moment arm. Here, the stiffness is a quadratic function of the moment arm $k(x) \propto x^2$ [25]. Regardless of which design is considered, the potential energy of these variable stiffness spring is given by:

$$V(q,k(x)) = \frac{1}{2}k(x)q^2. \tag{3}$$

This potential energy increases with increasing stiffness, similar to what has been predicted for the helical spring (2):

$$\frac{\partial V}{\partial k} = \frac{1}{2}q^2. \tag{4}$$

The congruence of (4) and (2) shows that neither of the aforementioned designs satisfy condition (1).

D. Summary

According to the definition of the ideal spring (1), the only way to enable stiffness modulation independent of the energy stored by the spring is to keep the potential energy of the spring constant while stiffness is modulated. In the aforementioned designs, keeping the potential energy constant implies:

$$\frac{1}{2}k_1 q_1^2 = \frac{1}{2}k_2 q_2^2. \tag{5}$$

This condition can only be satisfied if q changes based on the stiffness k. This is why none of the aforementioned designs that use a single input x to change the stiffness $k = k(x)$, can provide stiffness modulation independent of q and the energy stored by the spring.

Next, we show that by using *redundant stiffness modulation* – using two inputs (x_1, x_2) to change stiffness $k = k(x_1, x_2)$ – and a *lockable spring*, we can provide zero energy cost stiffness modulation independent of q and the energy stored by the spring.

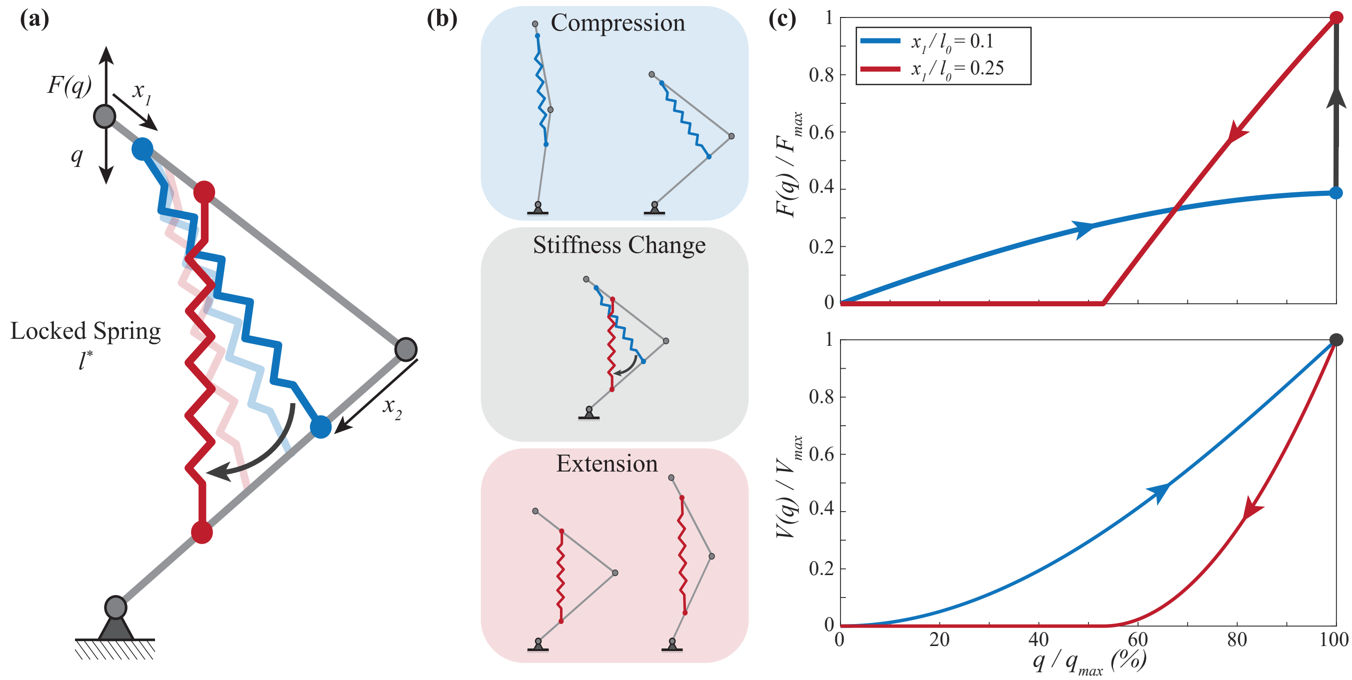

Fig. 2. Floating spring variable stiffness mechanism. (a) Input positions, x_1 and x_2, along the links change the stiffness when the length of the constant stiffness spring is locked, $l = l^*$. The deflection of the mechanism is q while the output force is $F(q)$. (b) Work-cycle: The mechanism is compressed in a low stiffness configuration (blue). After compression, the stiffness is increased by moving the ends of the spring to a high stiffness configuration (red). Finally, the mechanism extends in the high stiffness configuration. (c) Top: Force deflection characteristic of the mechanism during the work-cycle shown in (b). Bottom: Energy stored versus deflection of the mechanism during the work-cycle shown in (b). The output force $F(q)/F_{\max}$, deflection $q/q_{\max}$, and potential energy $V(q)/V_{\max}$ are normalized using their respective maximum values.

III. Variable Stiffness Floating Spring

Figure 2(a) shows the schematic representation of the variable stiffness floating spring mechanism proposed in this paper. The mechanism is comprised of two rigid links (gray) connected with a cylindrical joint and a constant stiffness spring (blue/red). The end points of the spring can be moved along the rigid links – these points are denoted by x_1 and x_2 – while the length of the spring can be locked, $l = l^*$. Moving the endpoints of the springs from the upper to the lower configuration changes the force–deflection characteristic of the mechanism; it increases the output force F at the same output deflection q.

Figure 2(b) shows the working cycle of the spring mechanism. In the beginning of the cycle, the endpoints of the spring are locked to the mechanism, and the spring (blue) is compressed. As the output deflection q reaches its desired value, the length of the spring is locked, and the endpoints of the spring are moved to a new configuration (red). Because the length of the spring is locked, the spring cannot release the energy while it moves from the upper configuration to the middle configuration. When the spring reaches the middle configuration, the endpoints of the spring are again locked to the mechanism, while the length of the spring is unlocked. As a result, the spring extends.

Figure 2(c) shows that, during the extension, the spring returns the same amount of energy it stored upon compression, but with higher force and stiffness. Fig. 2(c) further shows that the mechanism can be used to change stiffness without changing the energy stored in the spring. Because the spring is locked when stiffness is changed, changing stiffness can be done by applying a small force to one of the sliding end points of the spring – for example x_1 – without being opposed by the large force in the precompressed spring. These features exist for any output position q, as required by the ideal spring condition (1).

The aforementioned three features characterize a new class of variable stiffness spring design, where the energy cost of stiffness modulation is independent of the energy stored by the spring and the output position.

A. Mathematical Model

In what follows, we will show that the floating spring in Fig. 2(a) can be used to modulate stiffness with theoretically zero energy cost, independent of the output position q, independent of the energy stored by the spring, and by using control forces that may only depend on the speed of stiffness modulation, and not on the energy stored by the spring.

The floating spring shown in Fig. 2(a) is described by the following potential energy function:

$$V = \frac{1}{2} k_{\mathrm{spr}} \Delta l(q, x_1, x_2)^2 \tag{6}$$

where k_{spr} is the stiffness of the spring, q is the output position, Δl is the change in spring length, and x_1 and x_2 are the locations of the endpoints of the spring.

The output force and the output stiffness are defined by:

$$F = -\frac{\partial V}{\partial q} = \underbrace{k_{\text{spr}}\Delta l(q,x_1,x_2)}_{F_{\text{spr}}}\frac{\partial \Delta l(q,x_1,x_2)}{\partial q} \quad (7)$$

and

$$k = \frac{\partial^2 V}{\partial q^2} = k_{\text{spr}}\left(\frac{\partial \Delta l(q,x_1,x_2)}{\partial q}\right)^2 + F_{\text{spr}}\frac{\partial^2 \Delta l(q,x_1,x_2)}{\partial q^2}. \quad (8)$$

The mathematical condition for keeping the energy stored by the spring unchanged for any given output deflection is:

$$\forall q: \delta V = \frac{\partial V}{\partial x_1}\delta x_1 + \frac{\partial V}{\partial x_2}\delta x_2 = 0 \quad (9)$$

while the mathematical condition for changing stiffness for any given output deflection is:

$$\forall q: \delta k = \frac{\partial k}{\partial x_1}\delta x_1 + \frac{\partial k}{\partial x_2}\delta x_2 \neq 0. \quad (10)$$

We aim to design a variable stiffness mechanism where the aforementioned two conditions can be maintained: the end points of the spring δx_1 and δx_2 can be adjusted to satisfy (9) and (10) simultaneously.

Condition (9) is equivalent to doing no mechanical work when moving the endpoints of the spring $\delta V = -F_1\delta x_1 - F_2\delta x_2 = 0$. One way to satisfy this condition is not to move the end points of the spring $\delta x_1 = \delta x_2 = 0$, but in this way, stiffness cannot be changed, see (10). Another way to satisfy (9) is to use two motors for independently changing x_1 and x_2, and control the force exerted by both of these input motors to ensure that they do no net mechanical work [25]. However, not doing mechanical work does not imply no energy cost, as generating static force with electric motors requires energy. The third way to satisfy (9) is to ensure that the spring force is not transferred to the input motors [11]:

$$\forall q: F_{1,2} = 0 \quad (11)$$

We aim to design a variable stiffness mechanism where condition (11) is satisfied irrespective of the output position q. This condition is more restrictive than (9) as it not only ensures that the input motors do no net mechanical work, but also enables the use of small input motors – motors that can only generate low force – to perform stiffness modulation independent of the energy stored by the spring.

In our floating spring design, Fig. 2(a), conditions (9) and (11) can be satisfied by locking the length of the spring:

$$\forall q: \Delta l^* = \Delta l(q,x_1,x_2) \quad (12)$$

as locking the length of the spring leads to the following condition:

$$\forall q: \delta\Delta l^* = \frac{\partial \Delta l}{\partial x_1}\delta x_1 + \frac{\partial \Delta l}{\partial x_2}\delta x_2 = 0. \quad (13)$$

Because of (13), the potential energy stored by the spring will be constant, and therefore, independent of how q, x_1 and x_2 are changed

$$\forall q: V^*(q,x_1,x_2) = \frac{1}{2}k_{\text{spr}}\Delta l^{*2} = \text{const.} \quad (14)$$

while the stiffness can be changed by changing one of the input positions, for example δx_1, according to:

$$\forall q: \delta k = \left[\frac{\partial k}{\partial x_1} - \frac{\partial k}{\partial x_2}\left[\frac{\partial \Delta l}{\partial x_2}\right]^{-1}\frac{\partial \Delta l}{\partial x_1}\right]\delta x_1. \quad (15)$$

The latter condition ensures (10) if $[\partial k/\partial x_1 - \partial k/\partial x_2(\partial\Delta l/\partial x_2)^{-1}\partial\Delta l/\partial x_1] \neq 0$ which has been numerically verified for the floating spring design. In summary, the design in Fig. 2(a) satisfies the ideal variable stiffness spring condition given in (1).

IV. Experimental Validation

In this section, we present a prototype of the mechanism shown in Fig. 2(a), and provide experimental data to support the theoretical predictions derived in the previous section. The data is drawn from two experiments. The first experiment demonstrates the work-cycle of the spring shown in Fig. 2(b). The second experiment shows that the energy required to change the stiffness of the proposed mechanism is independent of the energy stored by the spring.

A. Prototype

The prototype of the floating spring mechanism is shown in Fig. 3(a). The mechanism consists of two linear rails affixed onto two aluminum bars of length $l_{1,2} = 370$ mm. The bars are connected with a cylindrical joint. Position lockable carriages that house the ends of the lockable spring, of equilibrium length $l_{\text{spr}} = 317.5$ mm and stiffness $k_{\text{spr}} = 2101$ N/m, travel along the linear rails to modulate the spring stiffness. The carriages hold their position with a friction brake. The length of the spring can be locked via metal cables routed through the end caps that hold the ends of the spring. The location of the carriages are determined by the two input positions x_1 and x_2. The deflection of the mechanism is defined by q while the output force of the mechanism is defined by F. The prototype closely resembles the model presented in Fig. 2(a). The prototype is used in the compression-extension experiment described in Section IV-B and a stiffness modulation experiment described in Section IV-C.

B. Compression Experiment

To validate the theoretically predicted force-deflection behavior of the mechanism shown in Fig. 2, a controlled compression test was performed using an Instron 5944 testing apparatus, see Fig. 3. The prototype was vertically constrained with linear guides and secured at the base of the Instron machine, Fig. 3(a). A force transducer was used to measured the output force, as the device was compressed and as it subsequently extended. The device was vertically compressed 90 mm at 0.1 Hz at low initial stiffness ($k \approx 385$ N/m) Fig. 3(a) (d)-blue. Following the compression phase, the length of the spring was kept fixed with a metal cable, and the upper end of the spring was moved to a high stiffness configuration ($k \approx 1459$ N/m) Fig. 3(b) (d)-gray. Subsequently, the carriages were locked in place and

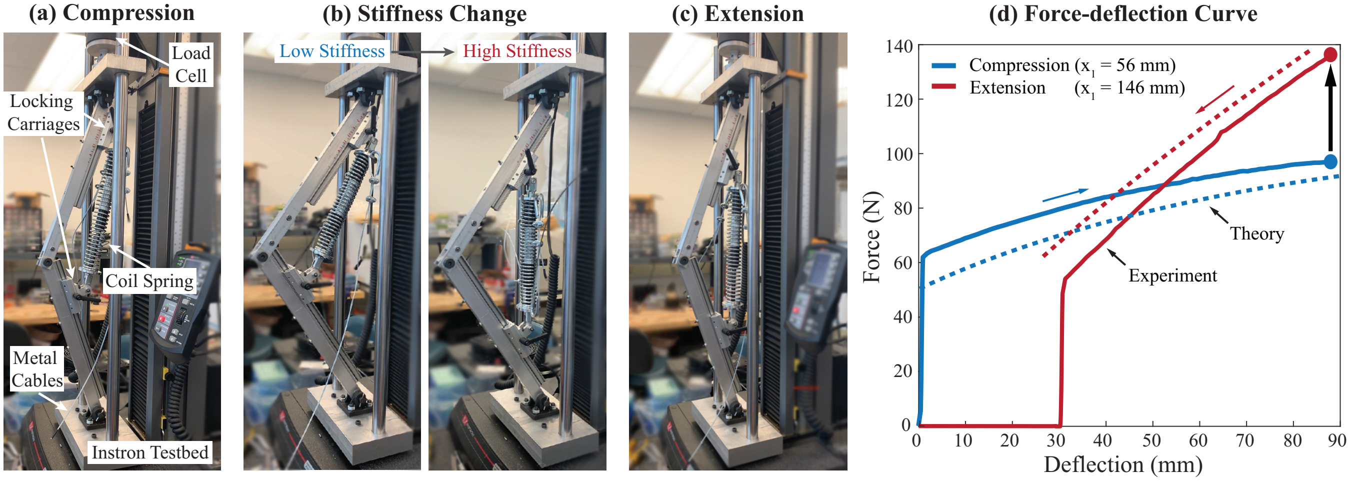

Fig. 3. Compression Experiment. (a) The mechanism is set to a low stiffness and the spring is compressed. (b) The stiffness of the mechanism is changed from low to high by moving the endpoints of the locked spring. (c) The spring releases its energy as it extends. (d) Measured force displacement data. The solid lines are the collected experimental data. The dashed lines represent the prediction of the model.

the mechanism extended back to its equilibrium configuration Fig. 3(c) (d)-red. The force-deflection data Fig. 3(d) (solid lines) show a strong resemblance to the theoretically predicted force-deflection curves, Fig. 3(d) (dashed lines). (The difference between Fig. 2(c) and Fig. 3(d) is due to the non-zero initial pre-compression of the spring in the prototype.) The video of the experiment can be found in the supplementary material.

C. Stiffness Modulation

In order to show that the energy cost of modulating the stiffness of the proposed mechanism does not depend on the energy stored by the spring, we have performed a stiffness modulation experiment using the setup shown in Fig. 4. The prototype was fixed onto a mechanical breadboard at a constant deflection q, and a simple pulley system, driven by a brushed DC motor, was used to move one of the carriages to adjust the stiffness of the device. The experiment of moving the spring from a low stiffness setting $x_1 = 0$ mm Fig. 4(a), to a high stiffness setting $x_1 = 75$ mm Fig. 4(b), was repeated for four different spring lengths $\Delta l \in \{0, 20, 40, 60\}$ mm (0-11 J). The same set of experiments was repeated at two different speeds $\dot{x}_{1\text{slow}} = 19$ mm/s and $\dot{x}_{1\text{fast}} = 188$ mm/s. The motor current and voltage were recorded during these experiments, and the power consumed by the motor was calculated.

Figure 4(c) shows the average motor power required to move the endpoints of the spring to modulate the stiffness for different amounts of energy stored by the spring (different compressed spring lengths) and different speeds. We observed a negligible difference in the motor power when the spring did not store any energy $\Delta l = 0$ mm (0 J) but also when it stored a significant amount of energy $\Delta l = 60$ mm (11 J). On the other hand, we observed a significant difference in the motor power required to modulate stiffness at low and high speeds, although in both cases average power was below 5 W. Therefore, consistent with what has been predicted by our theoretical analysis, the motor power required to change stiffness is only dependent on the speed to

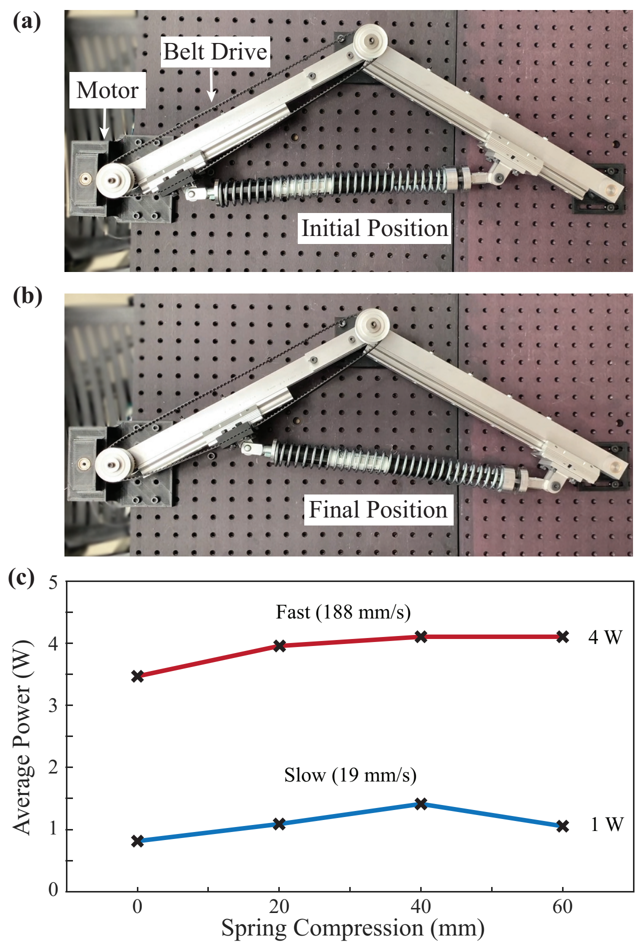

Fig. 4. Stiffness modulation experiment. (a) Mechanism in the low stiffness setting at the beginning of the motion. (b) Mechanism in the high stiffness setting at the end of the motion. (c) Estimated motor power. The video of the experiment is provided in the supplementary material.

change stiffness while it is independent of the energy stored by the spring, see Fig. 4(c).

We note that the prototype used in the aforementioned experiments presents practical limitations as the design of lockable springs Fig. 3 and lockable carriages Fig. 4 is not explored in this paper. Our future work will address these limitations and demonstrate the use of the lockable floating spring concept in human augmentation.

V. Conclusion

In this work, we introduced a novel variable stiffness floating lockable spring design that enables stiffness modulation independent of the energy stored by the spring. The mathematical model of the novel spring was presented, a prototype of the mechanism was created, and the theoretically predicted features of the prototype were experimentally confirmed. Although further work can be done to improve upon the implementation of the variable stiffness floating spring mechanism, the experiments have confirmed the key novelty of the proposed design: it enables stiffness modulation at any spring deflection with an energy cost independent of the energy stored by the spring.

The proposed actuation concept may find applications in the design of robot limbs, quasi-passive limb prosthesis, and spring leg exoskeletons. In all these limb designs, the mechanism may be used in a weight lifting task, where the force required to move with a weight downwards is lower (see Fig. 2 and Fig. 3 blue) than the force required to move the weight upwards (see Fig. 2 and Fig. 3 red). A variable stiffness spring that can change from low to high stiffness as the spring stores energy could effectively help ease the mechanical requirement of a weight lifting task. Together with this simple example, the novel mechanism introduced in this paper may motivate the design of new generation variable stiffness spring leg robots.

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