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Human Driven Compliant Transmission Mechanism

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***Abstract*— Energetically-passive robot exoskeletons, mimicking the function of the bicycle, could enable humans to reach previously unprecedented mobility. However, energetically-passive robot exoskeletons require a sophisticated mechanism to enable the human to supply energy, similar to what is enabled by the variable gear transmission mechanism of the bicycle. In this work, we present a new type of *human-driven compliant transmission mechanism* that could enable humans to supply energy when the leg is in the air, store the supplied energy, and release the stored energy when the leg is on the ground, in order to amplify the leg force and power. The compliant transmission mechanism presented in this paper is the first prototype and key component of a future human-driven artificial limb that aims to augment human mobility without using external energy.**

I. Introduction

Recent theoretical studies have shown that humans could jump 100 % higher [1] and run 50 % faster [2] using conceptual spring-leg exoskeletons. These exoskeletons were envisioned similar to lever-arms and catapults that amplify the force and power of human limbs without external energy. The example of the bicycle shows that human peak performance can be greatly improved with energetically passive devices, if the device allows the human to effectively supply energy, and if the supplied energy can be effectively utilized to bypass the biological limitations of human mobility. However, an energetically passive spring-leg that can amplify human limb force and power has yet to be developed.

Experimental studies have shown that the limitation of human peak performance mainly comes from the force-velocity relation inherent to muscles [3]–[6]. Similar to electric motors, muscles can produce large force at low speeds, low force at high speeds, and maximal power with moderate force at nominal speeds. Using the crank-pedal and gear-shift mechanisms, the bicycle mitigates the force-velocity limitation as it enables cyclists to move their legs at the most optimal speed, thereby maximizing the power output of the limbs independent of the cycling speed [7], [8]. World-class cyclists can generate 19 W/kg continuous power [8], [9] enough to nearly double the top speed of running. However, legged locomotion – jumping, fast walking with a backpack, and running – requires explosive power during the short ground contact time, which cannot be generated using the rigid transmission mechanisms of the bicycle [10]–[14].

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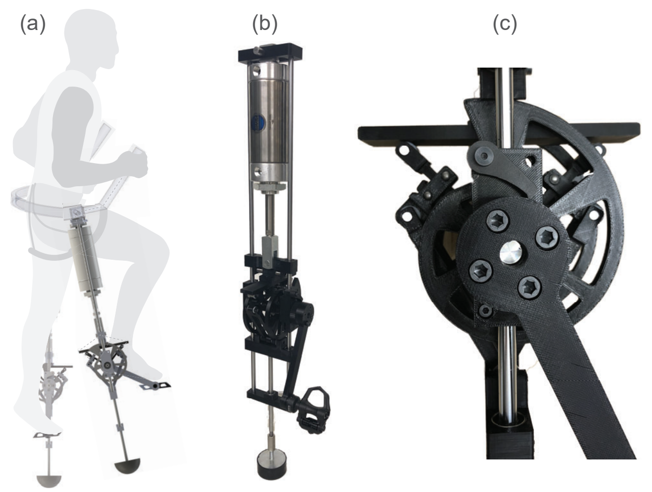

Fig. 1. (a) Conceptual design of a human-driven spring-leg exoskeleton. (b) Prototype of the spring-leg. (c) Compliant transmission mechanism. The human-driven compliant transmission mechanism can amplify the force and power of the biological limb. The new design generalizes the rigid transmission mechanism of the bicycle.

In order to provide explosive power for jumping higher, walking with a heavy backpack, or running faster, a temporary energy reservoir – spring – is needed [15]–[17]. A spring attached to the legs could enable the human to supply energy during the aerial phase of the legs during jumping, walking, and running, similar to when pedaling the bicycle. Subsequently, the energy in the spring could be released as it contacts the ground to accelerate the body upwards in jumping [1] or forward in running [2] (Figure 1a,b). However, a stiff spring could not be compressed by the legs to supply energy, while a compliant spring cannot provide enough force to accelerate the body when pushing against the ground. A sophisticated human-driven variable stiffness spring may accommodate the aforementioned requirements.

In this paper, we present a new type of human-driven compliant transmission mechanism (Figure 1c) – energetically-passive variable stiffness spring – that can capture, store, and release the energy supplied by the human, at the desired rate, to provide force and power beyond the capability of the biological limb. The mechanism combines a “lever” and a “catapult”, and consists of three key components: (i) a pedal-crank-cam mechanism that mitigates the force-velocity limitation while taking into account the configuration-dependent force [18]–[20] of the biological limb, (ii) a spring with sufficient energy storage capacity to store the energy supplied by the limbs during locomotion – enabling the legs to supply energy in the air, and (iii) an adjustable lever to modify the

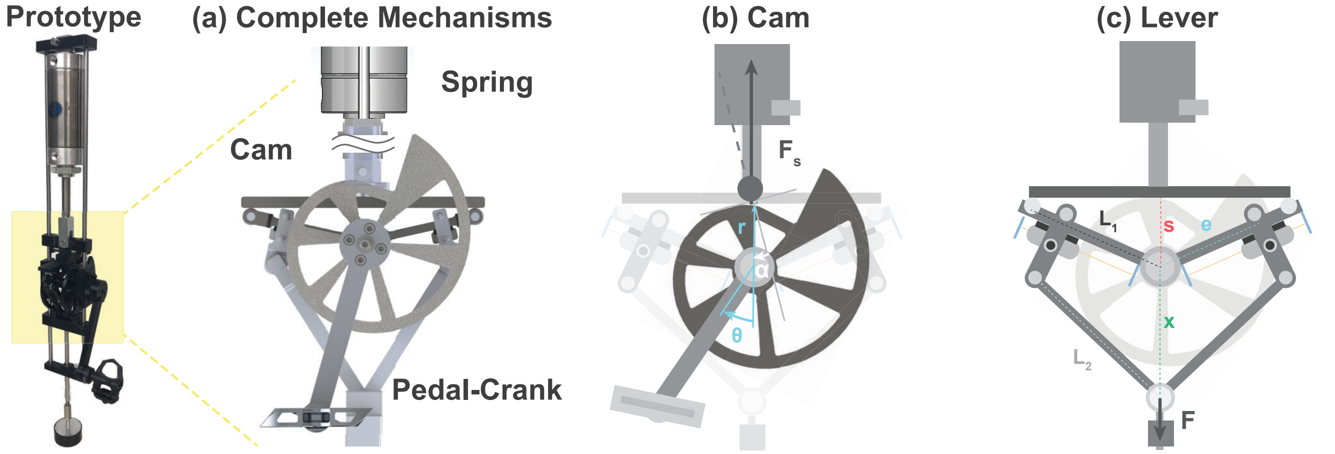

Fig. 2. Prototype of the human-driven adaptable-stiffness-spring artificial limb. The cam represents the variable-length lever driven by the pedal-crank mechanism. The air spring represents the elastic element that stores energy. The rotational lever arm at the output represents the slider-crank mechanism that can amplify force and stiffness. The slider-crank mechanism is composed of the primary rotational arm of length L_1 and the secondary rotational arm of length L_2. The distance measured from the slider to the shaft is e. The brake pad prevents the relative motion between the slider and the primary arm when the spring releases energy.

force, and stiffness provided by the spring-leg, as required to accelerate the body beyond what is possible by the biological limb.

The new mechanism extends existing compliant actuation concepts that promote motor-driven variable stiffness springs, to a new human augmentation concept that promotes human-driven variable stiffness springs. The mechanism generalizes the rigid transmission mechanism used for continuous energy supply in the bicycle, as it enables intermittent energy supply, energy storage, and controllable energy release that mitigates both the force-velocity and the configuration-dependent force limitation of the biological limb. The human-driven mechanism presented in this paper is the first prototype detailing key components of next-generation energetically passive human augmentation devices that could enhance human peak performance without large motors and heavy batteries that provide external energy.

II. Compliant Transmission Mechanism

In this section, we (i) present the conceptual design of a human-driven compliant transmission mechanism (Section II-A); (ii) develop the mathematical model of the transmission mechanism, predict the theoretical advantage of the proposed design under ideal conditions (Section II-B); and (iii) exemplify the working principle of the mechanism during assisted human running (Section II-C).

A. Conceptual Design

Figure 2 shows the schematic representation of the mechanism that consists of (i) the lever between the human limb and the artificial robot limb – represented by a pedal-crank-cam mechanism – (ii) the elastic energy storage element – represented by an air spring – and (iii) the lever between the energy storage element and the artificial limb – represented by an adaptable slider-crank mechanism. Below, we detail the main components of the design.

(i) *The pedal-crank-cam mechanism* (Fig. 2a) converts the cyclic leg motion to continuous rotation, similar to the pedal-crank mechanism of the bicycle. The cam establishes a kinematic coupling between the crank and the air spring. As the human turns the pedal, energy is continuously supplied while the cam is compressing the spring. Unlike the gear transmission of the bicycle, the cam accommodates the configuration-dependent leg force and thereby mitigates the limitation of the crank-pedal mechanism, as it allows the human to effectively supply energy independent of the crank angle. The same function does not exist on the bicycle as the variable-gear transmission can only mitigate the force-velocity limitation of human muscles between cycles, but cannot accommodate the configuration-dependent leg force within cycles. Although the pedal-crank-cam mechanism cannot mitigate the force-velocity limitation of the limb, the same can be done by changing the internal pressure of the air cylinder. This will be discussed next.

(ii) *The air spring* (Fig. 2b) stores the energy provided by the human while the cam compresses the spring. Pre-pressurized air springs have a superior mass-energy density, and can be used to bypass the trade-off between high stiffness and low energy storage capacity of mechanical springs [21]. The air spring is also used here to accommodate the force-velocity relation of the human limb. This can be done by modifying the internal pressure of the cylinder, as modifying the internal pressure is analogous to changing the stiffness of a helical spring by altering its effective length. As speed increases, with higher robot limb step frequency, the frequency of the human limb also increases as less time is available for a complete revolution, and lower resistance is desired for limb motion at higher frequencies. Therefore, the pressure in the air cylinder needs to be decreased. This can be achieved by switching on/off a valve for a certain amount of time similar to when moving the gear-shift nob in the bicycle.

(iii) *The adaptable slider-crank mechanism* (Fig. 2c) uses a variable lever arm to amplify the motion, force, and stiffness of the air spring to the motion, force, and stiffness of the robot limb. The amplified force and power enable the robot leg to simultaneously provide large force and explosive power – fast energy release – exceeding the limitations of the biological limb due to the force-velocity trade-off. Bypassing the force-velocity trade-off is crucial to augment humans for different tasks, such as jumping, walking with a heavy backpack, and running, with vastly different force and power requirements [6], [17], [22].

The artificial limb, takes any form of cyclic limb motion as input, captures energy like an advanced bicycle, stores the captured energy, and releases the stored energy like a variable stiffness spring catapult. The robot limb enables the human to supply energy at self-selected paces while storing and releasing the captured energy at variable and controllable rates with amplified force and power to augment human peak performance.

B. Mathematical Model

In this section, we derive the mathematical model of the mechanism shown in Fig. 2. The mechanism is divided into two functional units. The first unit is the *pedal-crank-cam mechanism connected to the air spring*; this unit is used by the human to supply energy. The second functional unit is the *air spring together with the variable lever mechanism*; this unit is used to amplify the leg force and release the energy stored by the spring. In the model below, we assume no energy loss due to friction, no transient thermodynamic effects, and we consider air to obey the ideal gas law.

(i) *Model of the pedal-crank-cam mechanism connected to the air spring:* The moment felt by the human limb M_h – or the resistive force felt by the human limb perpendicular to the pedal F_h – is given by:

$$M_h(\theta; p_0) = F_h(\theta; p_0)L_c = \frac{dr(\theta)}{d\theta}\frac{p_0}{p_0^*}F_s^*(s(\theta)) \tag{1}$$

where θ is the rotation angle of the crank, L_c is the crank length, r is the radius of the cam, F_s is the force of the air spring, s is the deflection of the spring, p_0 is the internal pressure while p_0^* is the nominal internal pressure of the air cylinder.

The force of the air cylinder at the nominal internal pressure is defined by:

$$F_s^*(s) = p_0^* A \frac{s_{\max}}{s_{\max} - s} \tag{2}$$

where A is the cross-sectional area of the air chamber while $s_{\max}$ is the height of the chamber.

Due to the kinematic coupling between the cam and the air spring, the deflection of the spring is defined by the cam radius at a given crank angle θ:

$$s(\theta) = r(\theta) - r_{\min} \tag{3}$$

where $r_{\min}$ is the minimum radius of the cam. The shape of the cam $r(\theta)$ is defined by:

$$r(0) = r_{\min} \text{ and } \frac{dr}{d\theta} = r\tan\alpha(\theta) \tag{4}$$

where $\alpha(\theta)$ is defined by the designer of the cam. For example, $\alpha(\theta) = 0$ leads to a circular cam that imposes no resistive force to the human according to (1), while $\alpha(\theta) = \theta$ would lead to a progressive cam (similar to Fig. 2b) that imposes more resistive force for larger rotation angles.

The key parameters of the pedal-crank-cam air spring unit are the cam-shape $r(\theta)$ and the internal pressure p_0 of the air cylinder. With a given cam-shape, higher internal pressure leads to more resistive force, creating an effect similar to higher-gear ratios in the bicycle. The preferred cam-shape could enable the legs to effectively supply energy given the configuration-dependent force limitation of the human limb. Assuming that the preferred configuration-dependent leg force is $M_H(\theta)$, the design of the cam can be formalized using (2) and (4). The following equation represents the moment balance between the crank-pedal and the cam:

$$r\tan\alpha(\theta) = \frac{M_H(\theta)}{F_s^*(r)}. \tag{5}$$

Figure 3a (blue line) shows the force-angle profile generated by the pedal-crank-cam mechanism; it resembles the force-angle profile of a cyclist [23]. Using such a pedal-crank-cam mechanism, the user would feel the same resistant force as in cycling, and could therefore continuously supply energy. Other customized force-angle profiles can also be used to achieve the maximal energy generation. Here, we choose the typical force-angle profile in cycling to demonstrate the working principle of our prototype mechanism. Figure 3a (grey lines) shows that increasing the internal pressure of the cylinder p_0 could be used to generate more resistive force and therefore store more energy inside the cylinder. Similarly, decreasing the internal pressure p_0 would require less effort and would result in less energy stored. In particular, the total energy stored (E_s) by the air cylinder after a full compression cycle is a linear function of p_0/p_0^*:

$$E_s = \frac{p_0}{p_0^*}E_s^* \tag{6}$$

where, the energy stored in the cylinder at the nominal internal pressure is:

$$E_s^* = p_0^* A s_{max} \ln\frac{s_{max}}{(s_{max} - r_{\max} + r_{\min})}. \tag{7}$$

Consequently, changing the initial pressure of the cylinder, changing p_0/p_0^*, is similar to shifting gears on the bicycle.

(ii) *Model of the variable moment-arm mechanism connected to the air spring:* The force of the spring leg is the force provided by the spring amplified by the variable lever mechanism. The spring is initially compressed by $r_{\max} - r_{\min}$ via the cam (Fig. 2b) while it subsequently expands as it moves the variable lever mechanism (Fig. 2c). The relation

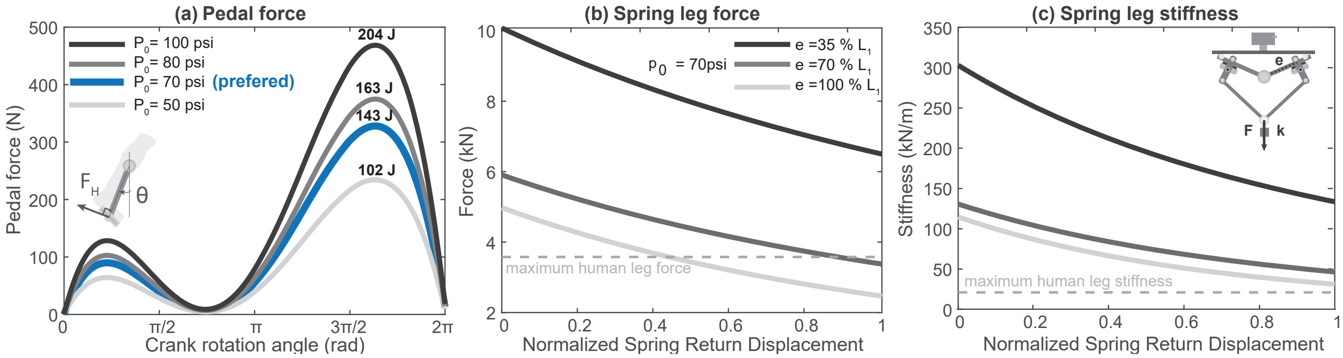

Fig. 3. Simulation results. The force-displacement curve of a subject cycling at 90 rpm and generating 280 W power [23] is used to find the cam profile via (5) and the following parameters of the cylinder and the slider-crank: $p_0 = 70\ psi; A = 7\ in^2; s_{\max} = 189\ mm; L_1 = 120\ mm; L_2 = 220\ mm$. (a) Force applied by the human F_h perpendicular to the pedal. (b) Force of the robotic leg F. (c) Stiffness of the robotic leg k. The spring return distance x is normalized by $x_{\max}$.

between the displacement of the spring leg x and the spring deflection s is given by:

$$s(x;e) = \frac{L_1 x}{2e}\left(\frac{L_2^2 - e^2}{x^2} - 1\right) - r_{\min} \tag{8}$$

where L_1 and L_2 denote the lengths of the lever arms while e is the changeable effective length of arm L_1 shown in Fig. 2c. The range of leg displacements (Fig. 2) is given by:

$$x \in [x_{\min}, x_{\max}) = [\sqrt{r_{\max}^2 - L_1^2 + L_2^2} - r_{\max}, L_2). \tag{9}$$

The force of the spring leg is given by:

$$F(x;e,p_0) = \frac{L_1}{2e}\left(\frac{L_2^2 - e^2}{x^2} + 1\right)\frac{p_0}{p_0^*}F_s^*(s(x;e)) \tag{10}$$

while the stiffness of the leg is:

$$k(x;e,p_0) = \frac{dF(x;e,p_0)}{dx}. \tag{11}$$

While deriving these formulas, we assumed that the offset between the links in the slider-crank mechanism is small and therefore negligible.

With a given nominal pressure of the air cylinder p_0/p_0^*, the key design parameter during the expansion phase is the effective lever arm e of the slider-crank mechanism (Fig. 2c). The force and stiffness of the leg can be simultaneously amplified by modifying the lever arm e (Fig. 2c); smaller e results in smaller leg displacement (9) but larger force (10) and stiffness (11). Larger stiffness means that the energy stored by the spring will be released faster (assuming the same body mass), as reducing e amplifies the force. This is similar to switching to higher gear ratios in the bicycle.

Figure 3b,c show the output force and stiffness of the robotic leg for different lever arm settings (different e in (10) and (11)); in the proposed mechanism, both force and stiffness increase as e decreases. We can also see that at $p_0 = 70$ psi, the maximum human leg force can be amplified over 2.5 times (Fig. 3b) while the maximum stiffness of the biological limb can be amplified up to 10 times (Fig. 3c). The amplification of the force and leg stiffness are both important as larger force is desired, and the same energy stored in the spring has to be released faster as the ground contact time is reduced in locomotion. Faster release of the same energy can be achieved by increasing the stiffness of the spring. Therefore, higher spring stiffness can generate the explosive power needed for locomotion tasks such as jumping and running.

C. A Potential Application

One of the potential applications (Figure 4) that motivates the conception and creation of compliant transmission mechanisms, is an energetically-passive human-driven artificial limb (Fig. 1). The design presented in this paper is the first implementation of the conceptual variable stiffness spring-leg envisioned in [2]. In what follows, we will illustrate the working cycle of the limb in human running.

(i) *Human supplies energy* (Fig. 4a-d): Starting with toe-off in running (Fig. 4a), the swing leg turns the pedal-crank-cam as if standing on a bicycle. The work done by the leg to overcome the resistance of the air cylinder is stored as potential energy inside of the cylinder. As the leg continues the up-stroke motion (Fig. 4b), the cylinder keeps storing more energy. The runner finishes the down-stroke motion (Fig. 4c) right before the spring leg touches the ground, where all the energy generated by the runner in the preceding swing phase (Fig. 4d) is stored.

(ii) *Spring leg releases energy* (Fig. 4e-f): Assuming vertical leg touchdown as in high-speed running, the air cylinder will be disengaged from the cam (due to the discontinuity in the cam shape) and start to release all of its stored energy through the slider-crank mechanism (Fig. 4e). While the air cylinder releases energy, it applies force to the ground and thereby redirects the vertical motion and accelerates the body forward (Fig. 4f). When all energy is released from the cylinder, it engages with the cam again, and the entire cycle starts over.

(iii) *Adaptation between steps* (Fig. 4g): To mitigate the force-velocity relation of the human limb between cycles, the runner may use an effortless finger motion to switch on/off the pressure valve in the cylinder (Fig. 4f). Namely,

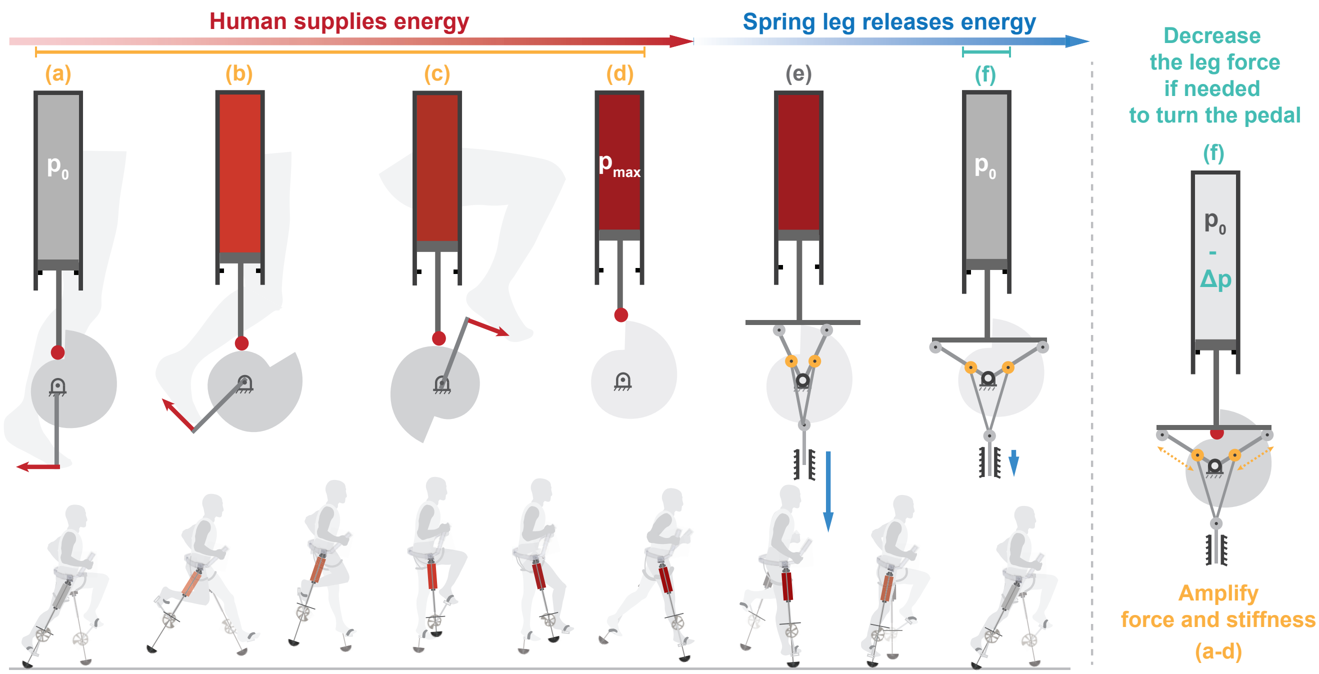

Fig. 4. The working principle of the human-driven compliant transmission mechanism in running.

releasing some of the air from the cylinder will lower the internal pressure p_0, which will consequently lower the force required for turning the crank (1) while the human supplies energy (Fig. 4a-d). Releasing the air pressure may be done while the resistive force on the pedal is low – at the end of the current step and beginning of the next step (Fig. 4f).

To increase the force and stiffness of the spring leg as the runner picks up speed, the runner may also use an effortless finger motion to change the amplification ratio of the slider-crank mechanism (e in Fig. 4a-d). Increasing the force and stiffness are required to redirect the motion of the body and to release the same amount of energy stored by the air cylinder during shorter ground contact times as the running speed increases. The overall effect of changing the amplification ratio of the slider-crank mechanism e is similar to the effortless gear shifting on the bicycle.

III. Discussion and Conclusion

In this work, we introduced the concept of human-driven compliant transmission mechanisms that may be used to develop robotic exoskeletons driven by humans instead of motors. The mechanism uses cyclic limb motion to allow the human to supply energy while the legs are in the air. The mechanism accommodates the force-velocity trade-off and the configuration-dependent human leg force to enable the human to supply more energy. Finally, the mechanism amplifies human limb force and stiffness as it touches the ground, to extend human physical ability in tasks such as jumping, fast walking with a heavy backpack, or running.

During legged locomotion, humans can only supply energy while the leg is on the ground. When jumping higher, or walking and running faster, the ground contact time reduces, and therefore, less force and power can be generated, due to the force-velocity trade-off in human muscles [3], [4], [6], [17], [22], [24]. One way to bypass this limitation is to use energy storage elements, for example, tendons in humans. However, the energy storage capacity of human tendons is insufficient to increase jump height during repeated jumping [15]. Furthermore, tendons cannot be pre-loaded in the air to provide more force and power when the foot touches the ground. Bicycles mitigate the force-velocity trade-off in human muscles with a rigid transmission mechanism. However, a rigid mechanism cannot store energy, and therefore cannot generate the explosive power required to augment locomotion tasks. To augment human peak performance in jumping, fast walking with a heavy backpack, and running, a compliant transmission is needed. Furthermore, unlike the single variable gear transmission used in the bicycle, the proposed spring leg requires two separate mechanically adaptable mechanisms; (i) the pedal-crank-cam spring mechanism that accommodates the force-velocity trade-off and the configuration-dependent leg force, and (ii) the variable arm slider-crank mechanism that amplifies the force and the stiffness of the spring leg.

In the current phase of development, the prototype incorporates a number of innovative elements, and shows promise for future applications. However, future work is needed to ensure safety, stability, and improve user operation experience. Furthermore, one of the key limitations of the current design is the energy efficiency of the air cylinder which is expected to be less than 60%. This efficiency is low compared to the energy efficiency of a typical bicycle, 90 % [25]. Replacing the air cylinder with a composite spring that has adequate energy storage capacity could mitigate this limitation in addition to making the device lighter. If the spring could store 500 J of energy and would have the efficiency of 60 % (significantly below the efficiency of a modern bicycle), then it could augment human locomotion as no other previous invention [2].

Springs have been used to augment human performance for generations, with patents dating back to more than a hundred years [26]. However, springs have not been effectively used to augment human locomotion. This is because unlike bicycles with variable gear transmission, fixed stiffness springs cannot accommodate the force-velocity limitation of human muscles, and cannot provide more force and stiffness as the ground contact time reduces in event driven tasks, such as running. The human-driven compliant transmission mechanism is a novel energetically passive variable stiffness spring that can accommodate the aforementioned limitations. Compared to motor-driven energetically active compliant actuators [27], the proposed mechanism promotes the more recent concept of human-driven variable stiffness springs [21], [28]–[33]. Variable stiffness springs can potentially enhance event-driven tasks by emulating the function of a bicycle and a catapult, to exceed the biological limitations of the human limb. The same mechanism may be also combined with powered devices to reduce the energy consumption of motors and promote energy sustainability using human power.

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