Walking with Springs

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ABSTRACT

Developing bionic ankles poses great challenges due to the large moment, power, and energy that are required at the ankle. Researchers have added springs in series with a motor to reduce the peak power and energy requirements of a robotic ankle. We developed a "robotic tendon" that reduces the peak power by altering the required motor speed. By changing the required speed, the spring acts as a "load variable transmission." If a simple motor/gearbox solution is used, one walking step would require 38.8J and a peak motor power of 257 W. Using an optimized robotic tendon, the energy required is 21.2 J and the peak motor power is reduced to 96.6 W. We show that adding a passive spring in parallel with the robotic tendon reduces peak loads but the power and energy increase. Adding a passive spring in series with the robotic tendon reduces the energy requirements. We have built a prosthetic ankle SPARKy, Spring Ankle with Regenerative Kinetics, that allows a user to walk forwards, backwards, ascend and descend stairs, walk up and down slopes as well as jog.

Keywords: prosthetic ankle, spring, power, energy

1. INTRODUCTION

Within the US there are approximately 1.8 million people who have suffered limb loss, with about 100,000 new cases each year. Of those people affected, approximately 80% are lower limb amputees. Robotic technology offers great hope and promise to individuals coping with the lost functionality of a missing limb. Until recently, robotic technology for amputees has been limited, but functional, powered, walking-assistance devices have just begun to emerge.

Our mission is to develop a new generation of powered orthotic/prosthetic devices based on lightweight, energy storing springs that will create a natural, more functional gait. Very few researchers are addressing powered wearable robotic systems because they pose many crucial engineering challenges [1-7]. They must be lightweight, safe, compliant, and powerful, but also energy efficient. Engineers have struggled to meet all of these functional requirements in a single device. For example, the ankle poses a particularly difficult set of design parameters, including a very large power requirement (257W for an 80kg person) in addition to a very high cycle life (3 – 5 thousand steps daily translating to 44 to 73 million revolutions per year on our motor system).

Direct drive electric, hydraulic, and pneumatic systems have been proposed, but they are heavy [8, 9]. In contrast, we propose a radically different approach by storing and releasing energy in springs [4-6, 10-13]. A spring can have power to weight ratios of 300,000 W/kg versus 300 W/kg for DC motors. A small, lightweight, low power motor is used to adjust the position of the spring. A heavy, powerful motor is not necessary because it is not the "actuator". The actuator is a spring tuned and adjusted for an *individual*. Our robotic systems are a combination of safe, lightweight motors and powerful, compliant, energy storing helical springs.

The robotic tendon actuator is based on a helical spring that has shown significant results in supplying large power spikes using a low power motor [4, 5, 14]. Additionally, this actuator is optimized through the use of a unique, customized spring for each subject.

In section 2, a mathematical description of a lead screw actuator and a robotic tendon actuator will be presented. The main difference is that the varying load changes the input motor speed and input power in the robotic tendon actuator. In section 3, a description of the ankle position, moment and power during gait will be described. In section 4, models of the robotic tendon actuator with additional springs will be optimized to minimize input motor energy and a reduction of peak power.

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2. DESCRIPTION OF A ROBOTIC TENDON ACTUATOR

In a bionic ankle, an actuator system must convert the motor angular velocity and torque into a linear velocity and force. A standard lead screw model will be described first which will be used to highlight a motor/gearbox transmission. The robotic tendon actuator system will then be described which adds an additional spring at the end of the nut. In this system, the spring alters the input velocity and power.

2.1 Standard Model of a Lead/Ball Screw Actuator

In a lead screw or ball screw model, the motor rotates moving the nut position, *r*, inward and outward, Figure 1. To simplify the analysis, friction is not modeled. The output position, *x*, and force, *F*, describe the required movement and force to move the ankle during gait. In our research, standard gait data [15] is used to determine *x* and *F*.

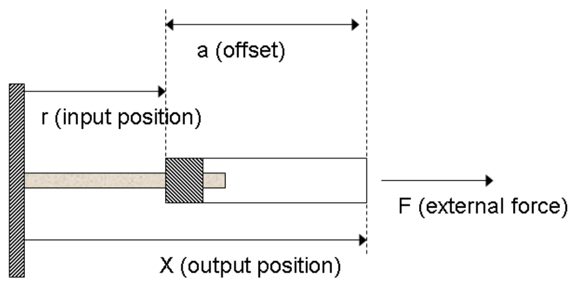

Figure 1. In a lead/ball screw model, the motor turns moving a nut inward or outward adjusting, *r*. The external force, *F*, and position, *x*, describe the desired outputs. The offset distance, *a*, is fixed.

In a quasi static analysis, the external force determines the toque on the lead screw where *l* describes the lead:

$$\tau = \frac{Fl}{2\pi} \tag{1}$$

The input position, *r*, is determined by the number of revolutions, *n*, that the motor spins and the lead, *l*:

$$r = l \cdot n \tag{2}$$

The output position, *x*, is determined by *r* and the constant offset *a*:

$$x = r + a \tag{3}$$

The input velocity is given by differentiating (2) and assuming the lead, *l*, is fixed:

$$\dot{r} = l \cdot \dot{n} \tag{4}$$

The output velocity is given by differentiating (3):

$$\dot{x} = \dot{r} \tag{5}$$

The motor angular velocity is given by:

$$\begin{gathered} \omega = \dot{\theta} = 2\pi \cdot \dot{n} \\ \dot{\theta} = \frac{2\pi \cdot \dot{r}}{l} \end{gathered} \tag{6}$$

The input power is determined by multiplying the input torque and angular velocity. In this simple case, the input power equals the output power. The lead, *l,* can be used to adjust the motor speed and torque to fit the motor operating specifications. Typically a gearbox and a small lead are both needed to achieve the slow speeds and high torques needed at the ankle. The problem with this method is that a large motor and gearbox combination is needed [6, 11, 16]. To be consistent with the standard gait literature, the power curves will be inverted and a negative sign is added.

$$\tau\dot{\theta} = -F \cdot \dot{r} = -F \cdot \dot{x} \tag{7}$$

2.2 Model of a Robotic Tendon Actuator

In a robotic tendon model, the motor rotates moving the nut position, *r*, inward and outward, Figure 2. The output position, *x*, and force, *F*, describe the required movement and force to move the ankle during gait. In this model, a spring with stiffness, *K*, is placed between the nut and the external force. The spring is a buffer which can store and release energy altering the power relationships.

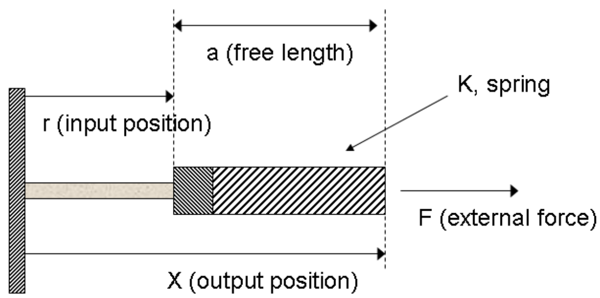

Figure 2. In a robotic tendon model, the motor turns moving a nut inward or outward adjusting, *r*. The external force, *F*, and position, *x*, describe the desired outputs. A spring is placed in between the nut and the external force. The free length of the spring is given by, *a*.

In a quasi static analysis ignoring friction, the external force determines the torque on the lead screw where *l* describes the lead. Ignoring acceleration or inertia at the output position by assuming they are both small, the external force is balanced by the spring force. We have modeled inertias in a separate model [5].

$$\tau = \frac{Fl}{2\pi} \tag{8}$$

$$F = K(x - r - a) \tag{9}$$

The input position, *r*, is determined by the number of revolutions, *n*, that the motor spins and the lead, *l*:

$$r = l \cdot n \tag{10}$$

The output position, *x*, is determined by *r*, *F*, and the constant offset *a*:

$$x = r + a + \frac{F}{K} \tag{11}$$

The input velocity is given by differentiating (10) and assuming the lead, *l*, is fixed:

$$\dot{r} = l \cdot \dot{n} \tag{12}$$

The output velocity is given by differentiating (11) assuming the spring stiffness is constant:

$$\begin{aligned} \dot{x} &= \dot{r} + \frac{\dot{F}}{K} \\ \dot{r} &= \dot{x} - \frac{\dot{F}}{K} \end{aligned} \tag{13}$$

The motor angular velocity is given by:

$$\omega = \dot{\theta} = 2\pi \cdot \dot{n}$$
$$\dot{\theta} = \frac{2\pi \cdot \dot{r}}{l} = \frac{2\pi}{l}(\dot{x} - \frac{\dot{F}}{K}) \quad (14)$$

The input power is determined by multiplying the input torque and angular velocity. In this case, the input power does not equal the output power. To be consistent with the standard gait literature, the power curves will be inverted and a negative sign is added.

$$\tau\dot{\theta} = -F \cdot \dot{r} = -F \cdot (\dot{x} - \frac{\dot{F}}{K}) \quad (15)$$

The term $\frac{F \cdot \dot{F}}{K}$ can increase or decrease the required input power. In the specific case for analyzing ankle gait, the maximum peak motor power and motor angular velocity are both reduced. The spring stores braking energy releasing it when needed. Because of the ability of the spring to store energy, the total input energy is kept to a minimum. This term corresponds to the storage of "translational potential energy."

It is interesting to note that the input speed shown in equation (14) is not only a function of the lead, *l*, but also the changing force. The slope of the external force or the slope of the load curve can speed up or slow down the required motor speed. In this sense, the spring acts as a "load variable transmission." In our work [17], we have been studying a dynamic stiffness defined by:

$$K = \frac{\dot{F}}{\dot{x}} \quad (16)$$

3. GAIT

Gait is the term used to describe the locomotion of legged animals. Gait is a recurring pattern of leg and foot movements, rotations, and torques. Due to its repetitive nature, the discussion of gait is done in terms of percentages of a gait cycle. A gait cycle is defined for a single leg and begins with the initial contact of the foot with the ground or 'heel strike', the conclusion of a cycle occurs as the same foot makes a second 'heel strike'. The end of one gait cycle is of course the beginning of another. The input motions are typically determined using a motion capture system and the torques are derived using an inverse dynamics calculation. The ankle gait data is digitized from Whittle [15].

The ankle position is shown in Figure 3. Initially after heel strike, the ankle plantarflexes or moves downward. After the foot is flat on the ground, the shank then rolls over the ankle, i.e. dorsiflexing. During this period, the spring in the robotic tendon stores energy. At 40% of the gait cycle, the foot rapidly plantarflexes , which propels the person forward. During powered push-off or powered plantarflexion the moments and angular speeds are high. In this phase of gait, the spring releases its energy aiding in push-off. At 60% of the gait cycle, the toe comes off of the ground and the ankle rapidly dorsiflexes to insure that the toe does not touch or skid on the ground during the next phase of gait. From 60% to 100% of the gait cycle, the foot is in the air during the swing phase. During this phase of gait the ankle moments are low.

The ankle moment is shown in Figure 4. The ankle moment data was scaled for an 80kg person. At 40% of the gait cycle, the moment is at its peak just as the angular velocity begins to increase rapidly. The combination of high forces and high velocities means that large powers are experienced in this region of the gait cycle, see Figure 5.

Figure 5 shows both positive and negative powers developed during a typical gait cycle. Utilizing a robot to aid in gait, sometimes the robot needs to aid the user (positive power) and sometimes for support the robot needs to resist the user (negative power) and in either case the robot is putting energy into the system. A tuned, spring-based system allows for a well timed energy storage when resisting the user and energy release when assisting the user.

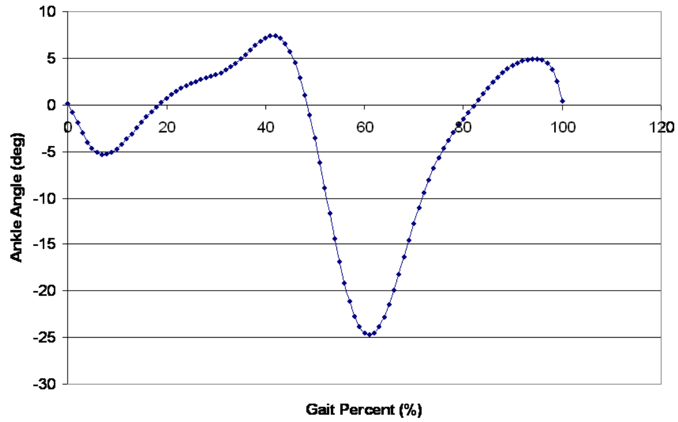

Figure 3. The ankle position in degrees as a percent of the gait cycle.

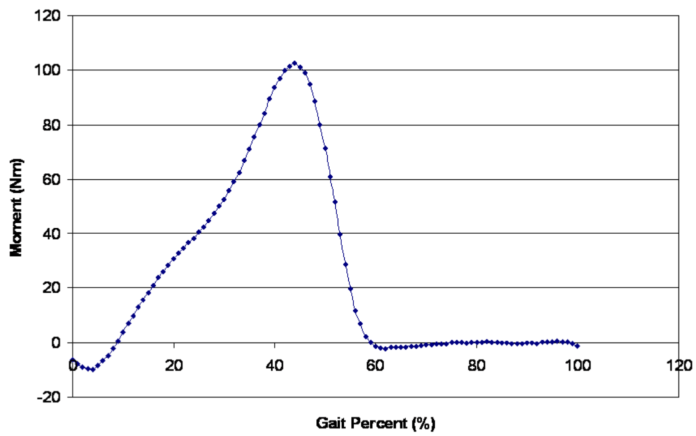

Figure 4. Ankle moment as a percentage of the gait cycle.

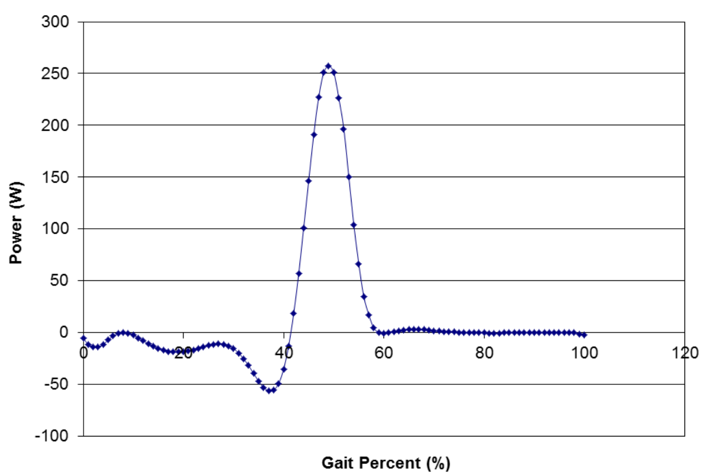

Figure 5. Ankle power as a percentage of the gait cycle, assumes a 0.8 Hz gait frequency.

4. SIMULATIONS

In this section, three scenarios of spring placement were modeled; 1) our typical robotic tendon configuration, with multiple spring stiffness choices, 2) a robotic tendon including a parallel spring and 3) a robotic tendon including a spring in series with the ankle joint.

4.1 Simulation of the Robotic Tendon model using gait data

In the ideal case (i.e. no friction) for one walking condition (Model 1 in Table 1), if one was to assume that energy can be stored and released properly, the peak motor power is 257.6 W and the energy required for each step is 19.4 J. In this ideal case, all of the braking energy is stored and used in push-off. We assumed an 80kg subject and the gait cycle duration is 1.25 seconds. The area underneath the power curve in Figure 5 is integrated to determine 19.4 J.

Table 1. Different springs are modeled to determine the required peak motor power and energy

Model	Spring Stiffness	Peak Motor Power	Input Motor Energy	Optimization Criteria
1		257.6 W	19.4 J	Ideal Case
2	infinite	257.6 W	38.8 J	Lead Screw Model with no additional spring
3	53,224 N/m	96.6 W	21.2 J	Robotic Tendon spring is optimized to reduce the peak power of the motor
4	43,658 N/m	106.9 W	22.1 J	Robotic Tendon spring is optimized to reduce the peak power of the motor to zero at push-off
5	51,627 N/m	97.9 W	21.2 J	Robotic Tendon spring is optimized to reduce the required input energy of the motor

A mechanical system based on the lead screw model is not adequate because peak power and energy required are both very high (Model 2 in Table 1). If a lead/ball screw system assuming 100% efficiency is used, the peak motor power equals 257.6 W and the energy equals 38.8 J. The energy is much larger because a motor must resist the load as the shank rolls over the ankle and must provide the push-off energy to propel the person forward. In this simulation, the absolute value of the input power was integrated to determine the 38.8 J.

Using a tuned spring in the simulation of the robotic tendon model (Model 3 in Table 1), the peak power and energy are both reduced. The peak input power is reduced to 96.6 W and the integration of the absolute value of the input power equals 21.2 J. This is a remarkable reduction in peak power and a large energy savings. In the model, the spring is optimized to reduce peak power. The spring stiffness is 53,224 N/m and a lever arm at the ankle is assumed to be 0.07 m. In Figure 6, the peak motor power is reduced and the spring supplies much of the push-off power.

The input power is drastically reduced because the motor velocity is reduced with the addition of the spring. In Figure 7, the velocity of the motor is shown for two cases. If there is a tuned spring, the velocity of the motor is low during 40-60% of the gait cycle. During the swing phase because the derivative of the force is close to zero, the velocity of the motor matches the lead screw model. If a spring is eliminated, the velocity of the motor must match the velocity of the gait cycle.

In Figure 8, the input position, r, and the output position, x, are determined from the gait data (equation 13). The deflection of the spring in the robotic tendon is determined by the desired force, F and the spring stiffness K (equation 9).

The robotic tendon actuator has been used to power our SPARKy prosthetic ankle [4, 5, 10, 18]. In Figure 9, the actual motor power and output power at the spring were determined as the user walked on a treadmill.

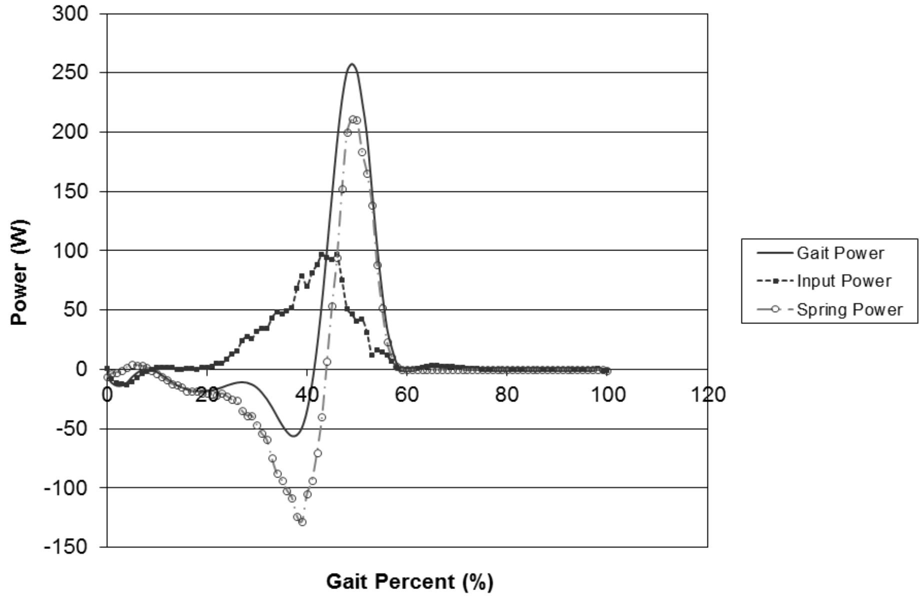

Figure 6. The spring power and the input power add together to match the output gait power.

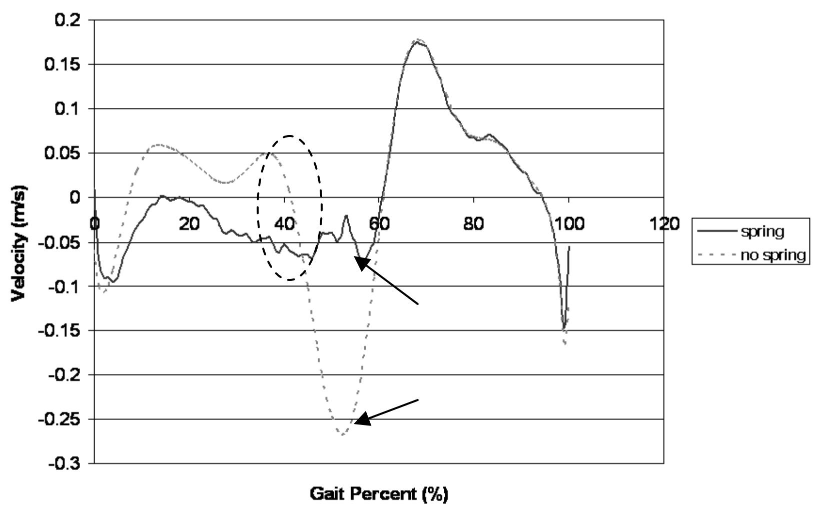

Figure 7. In the lead screw model without a spring, the velocity of the motor is determined by the ankle motion. In the robotic tendon model, the velocity of the motor is lowered during the push off phase of gait (40-60% of the cycle). More importantly, the motor does not change directions under high loads, see dashed oval.

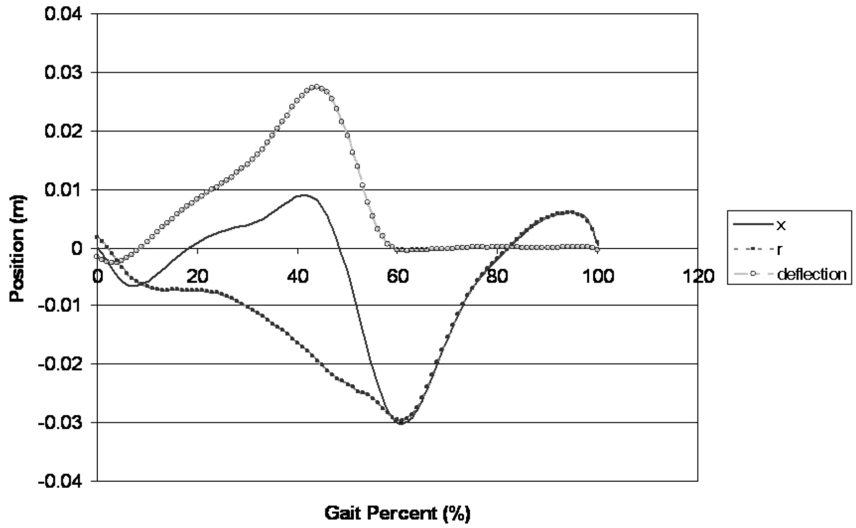

Figure 8. The output position, *x*, is determined by the gait data. The input position of the robotic tendon is determined by the position *x*, the desired force, *F*, and the spring stiffness *K*. The deflection of the spring in the robotic tendon is determined by the desired force, *F* and the spring stiffness *K*.

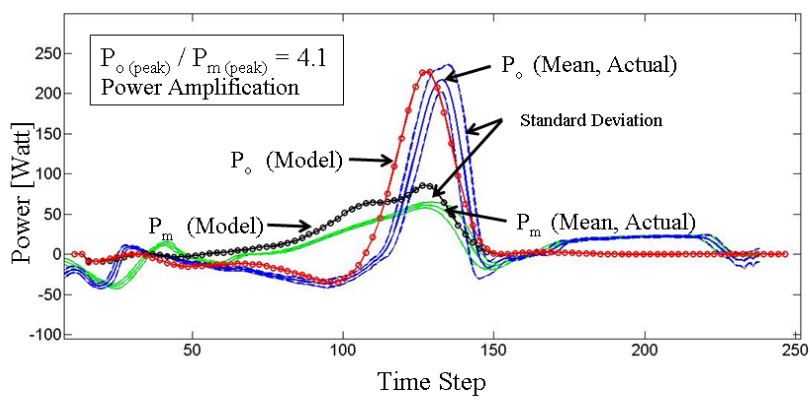

Figure 9. A robotic tendon actuator was used to power a prosthetic ankle. A powered push-off was achieved at 225 W with a 55 W peak motor power [4]. Pm (model) is the simulated power required by the motor. Pm (actual) is the mechanical power at the motor in the SPARKy ankle. Po (Model) is the output power required from published gait data. Po (actual) is the output power at the spring in the SPARKy ankle.

In a second example (Model 4 in Table 1), using the robotic tendon model, a spring can be optimized to reduce the push-off power at 49% of the gait cycle to zero, Figure 10. In this example choosing a spring stiffness of 43,658 N/m, the peak power increases to 106.9 W and the energy increases to 22.1 J. In this case, the spring is doing the work during push-off.

In a third example (Model 5 in Table 1), stiffness can be chosen to minimize energy. In this example choosing a stiffness of 51,627 N/m, the peak power is 97.9 W and the energy needed per step is reduced to 21.2 J. The energy in this case is just slightly lower than in Model 3 in Table 1.

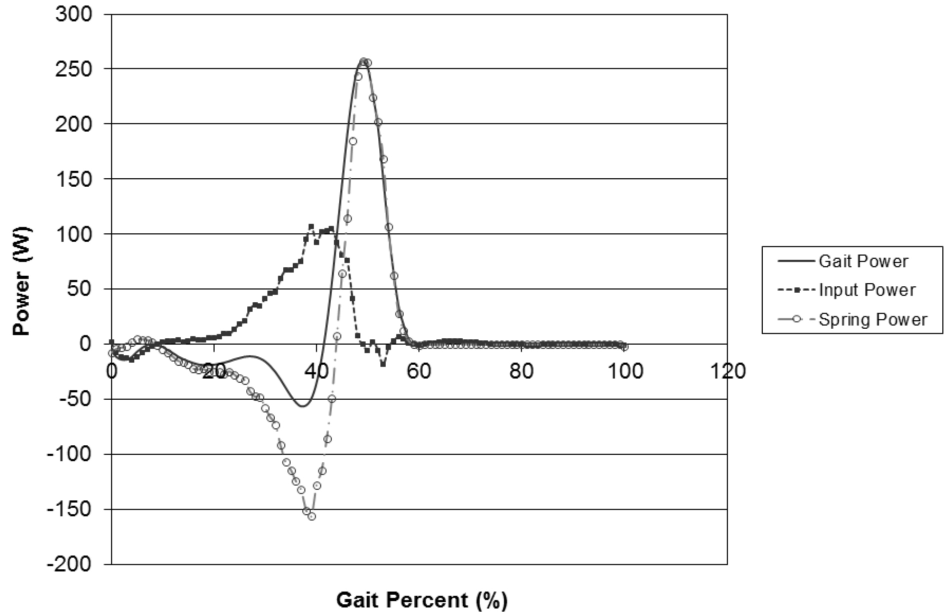

Figure 10. The robotic tendon model can be optimized so that the input power at 49% of the gait cycle is zero. In this example, energy is stored early in the spring so that it provides the push off power.

4.2 Simulation of the Robotic Tendon model with an additional parallel spring

A passive spring can be added in parallel to the robotic tendon to add an additional load path, Figure 11. The additional spring will lower the forces needed at the robotic tendon. In this model, the parallel spring can only be pushed and cannot be pulled. Thus, this spring will aid in reducing the forces during dorsiflexion at the peak loads from 35 to 48% of the gait cycle.

$$F_{external} = F_{gait} - K_{parallel} x \tag{17}$$

An additional parallel spring can be added to the model (Model 1 in Table 2). The maximum force is reduced from 1462 N to 1351 N. This will reduce the peak loads on the actuator. On the other hand, the peak power increases to 137.6 W and the energy increases to 22.0J, Figure 12. In this model, the robotic tendon stiffness is 51,627 N/m and the parallel spring stiffness is 14000 N/m. The problem is that the actuator must work against the parallel spring in the swing phase, Figures 13 and 14.

Table 2. A robotic tendon and an additional parallel spring are modeled to determine the required peak motor power and energy

Model	Spring Stiffness	Peak Motor Power	Input Motor Energy	Optimization Criteria
1	51,627 N/m and 14,000 N/m	137.6 W	22.0 J	A parallel spring is added to reduce the peak forces on the robotic tendon
2	51,627 N/m and 3,991 N/m	106.8 W	21.4 J	A parallel spring is added to reduce the peak forces on the robotic tendon by a small amount.
3	51,627 N/m and 3,991 N/m	106.8 W	21.2 J	A parallel spring is added to reduce the peak forces on the robotic tendon. The parallel spring is only functional during the stance phase of gait.

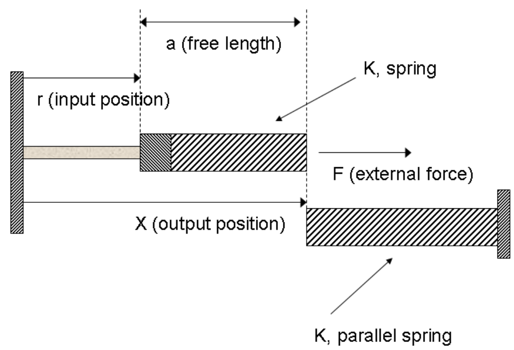

Figure 11. A parallel spring is added to reduce the loads during dorsiflexion (when the ankle position is greater than zero). The spring can only be compressed and cannot be pulled.

In a second example (Model 2 in Table 2), the robotic tendon stiffness is 51,627 N/m and the parallel spring stiffness is 3991 N/m. In this example the energy is reduced to 21.4 J and the peak power is reduced to 106.8 W. With the energy savings, there is a cost. The maximum force is only reduced from 1462 N to 1431 N.

In a third example (Model 3 in Table 2), a passive parallel spring is added only during the stance phase of gait. It could be imagined that a latch is activated when the foot is on the ground. In this example, the stiffness parameters are the same as in Model 2 in Table 2. The peak power remains at 106.8 W but the energy is reduced to 21.2 J.

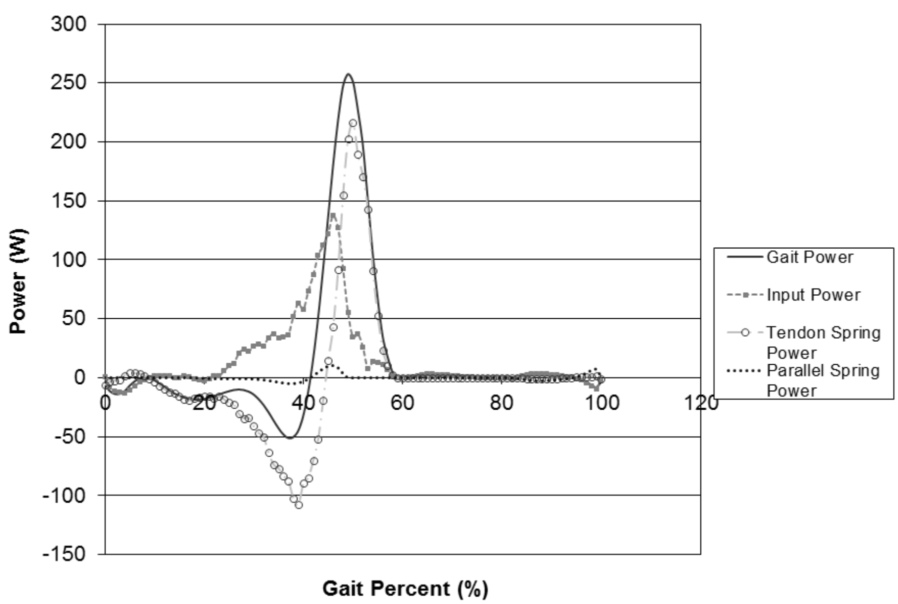

Figure 12. With the addition of a parallel spring the peak motor power does increase to 137.6 W.

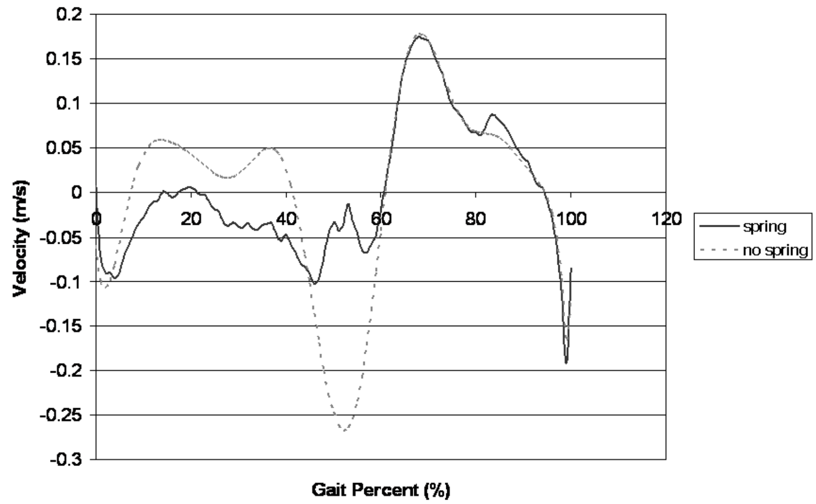

Figure 13. The motor velocity with the two springs is reduced during the stance phase but the velocity slightly increases during the swing phase because the motor must push against the parallel spring.

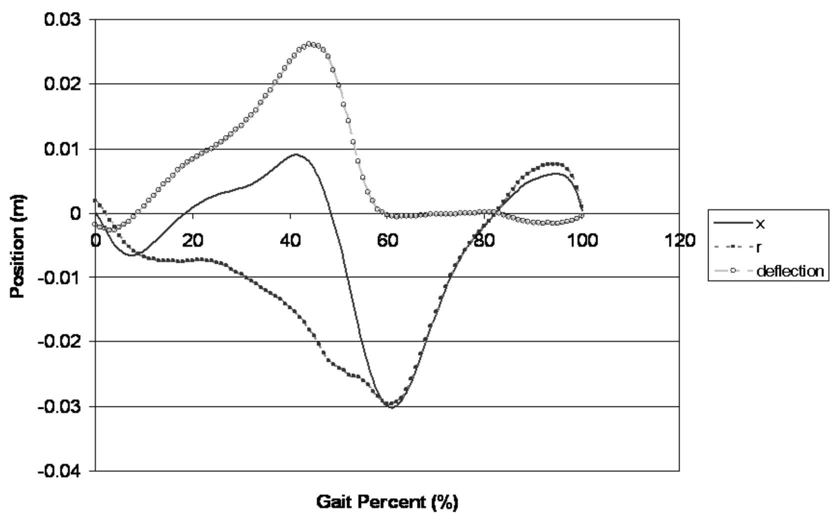

Figure 14. Additional parallel spring model. The motor position, *r*, and the deflection of the robotic tendon spring are shown. During the later part of the swing phase, 80-100%, the robotic tendon must push against the parallel spring.

4.3 Simulation of the Robotic Tendon model with an additional series spring

A passive spring can be added in series to the robotic tendon to reduce the overall stiffness, Figure 15. The additional spring will lower the stiffness of the entire system when the foot is on the ground. In this model, a spring is added to the forefoot of the shoe to act in series with the system from 8 to 41% of the gait cycle. Thus, this spring will aid in reducing the needed motion of the actuator from 8 to 41% of the gait cycle. The movement of the robotic tendon motor is reduced because the series spring will stretch or deform under load.

$$x = x_{gait} - \frac{F_{gait}}{K_{series}} \tag{18}$$

In this example, the robotic tendon stiffness is 51,627 N/m and a series spring is added underneath the ball of the foot with a stiffness value of 877,760 N/m (Model 1 in Table 3). The peak power is 97.9 W and the energy is reduced to 20.1

J, Figure 16. Using a series spring, there was a reduction of 1.1 J as compared to the other cases. One joule might not seem significant but over 3000 to 5000 steps per day, it will add up. The velocity and position of the robotic tendon motor are shown in Figures 17 and 18.

Table 3. A robotic tendon and an additional series spring are modeled to determine the required peak motor power and energy

Model	Spring Stiffness	Peak Motor Power	Input Motor Energy	Optimization Criteria
1	51,627 N/m and 877,760 N/m	97.9 W	20.1 J	A series spring is added to the robotic tendon to reduce the required input energy of the motor.

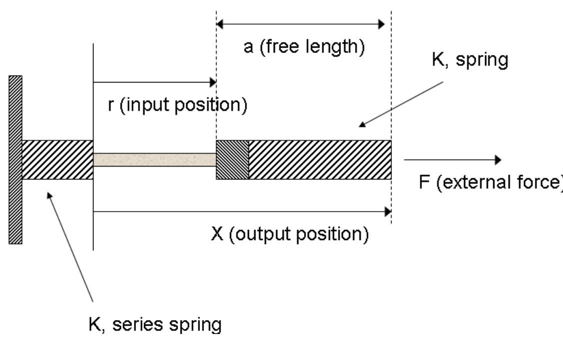

Figure 15 A series spring is added to reduce the stiffness when the forefoot is on the ground. The spring only acts when the foot is on the ground. For example, a spring mounted under the ball of the foot can be thought of as a series spring reducing the stiffness of the Achilles tendon.

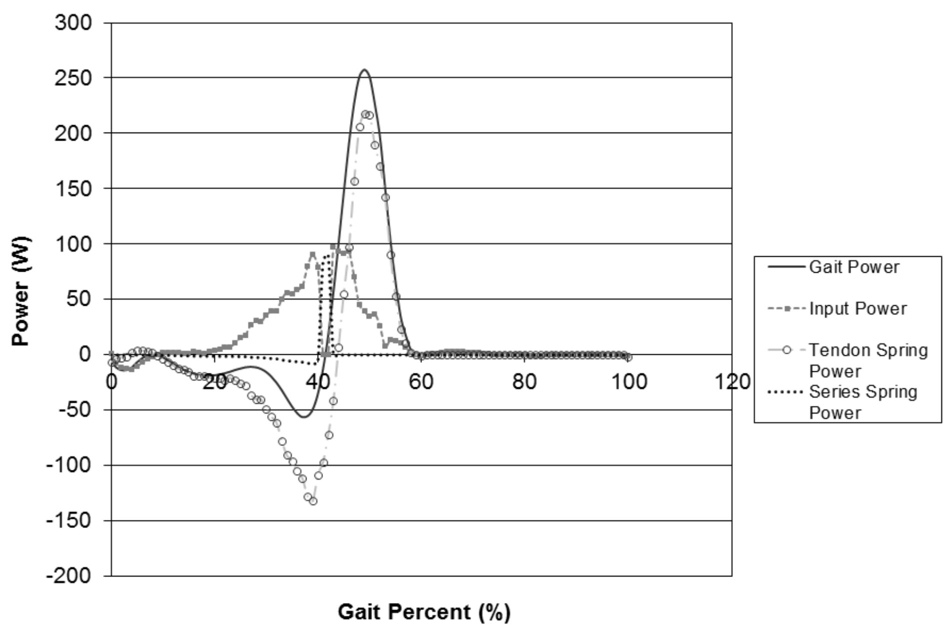

Figure 16. The input power is reduced significantly at the start of push off, 40% of the gait. At this point, the series spring releases its energy and the overall stiffness increases from 48,759 to 51,627.

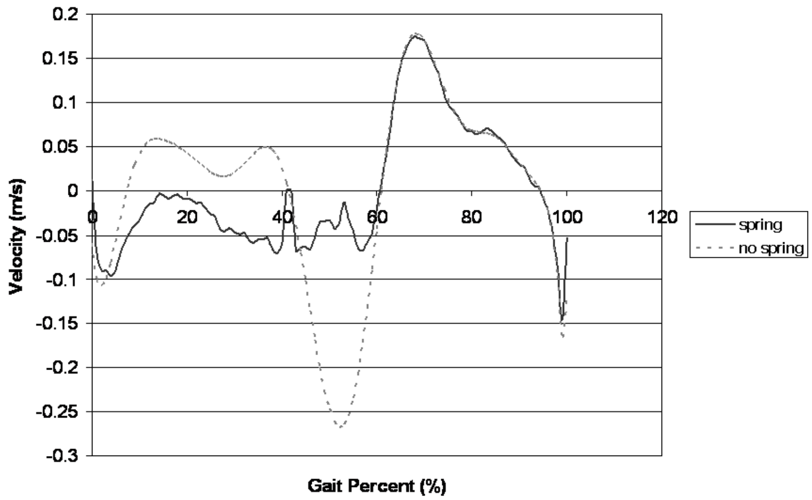

Figure 17. The velocity of the motor using a series spring and a robotic tendon is reduced at 40% of the gait cycle.

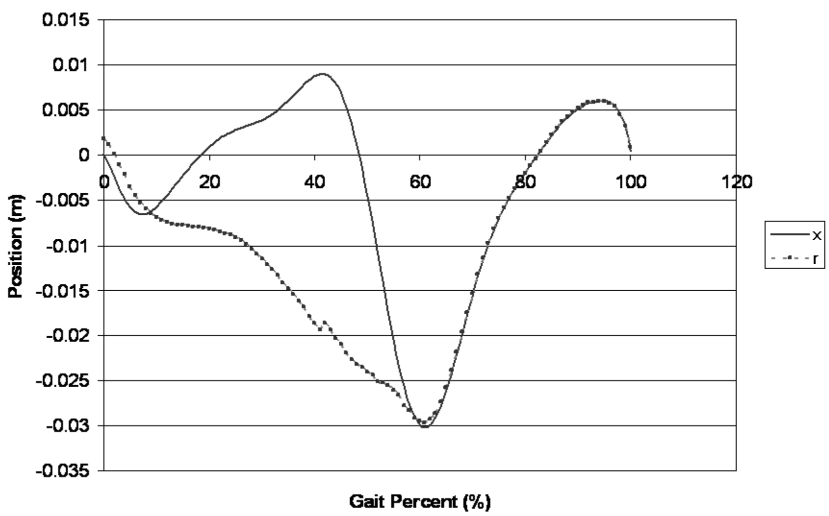

Figure 18. The motor position, *r*, is shown with a discontinuity when the system increases stiffness at 40% of the gait cycle.

We have been actively studying actuators that can change stiffness and developed a Jack Spring actuator [19]. In this actuator, the spring is used as a lead screw and the motor adds and subtracts coils of the spring. As more coils are added, the stiffness is reduced and vice versa. Changing stiffness is not always beneficial because the input velocity is altered when K varies. If one were to build a robotic tendon actuator that can change stiffness as well as change the input position of the spring, the input velocity will be different than equation (13). In this new case, a third term is added.

$$\dot{r} = \dot{x} - \frac{\dot{F}}{K} + \frac{F\dot{K}}{K^2} \tag{19}$$

The input power becomes:

$$F\dot{r} = F\dot{x} - \frac{F\dot{F}}{K} + \frac{F^2\dot{K}}{K^2} \tag{20}$$

5. PROTOTYPE ANKLE

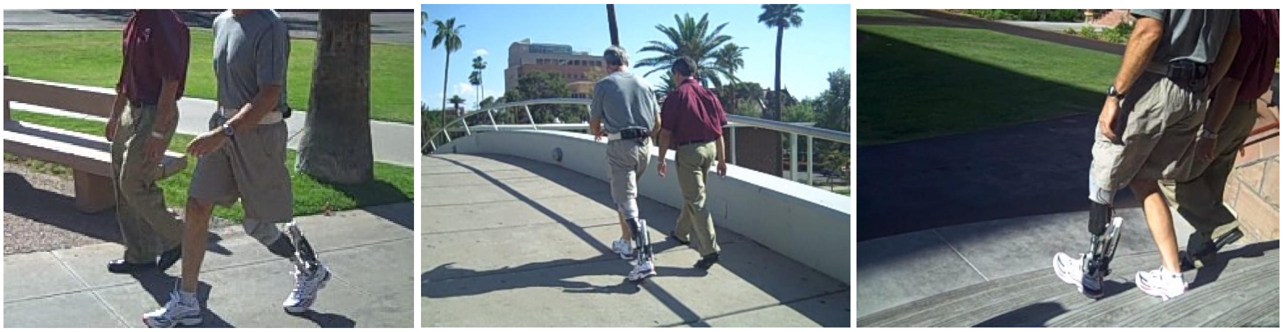

Figure 19. Using a robotic tendon actuator, a user is able to walk over ground, walk up and down inclines, and ascend and descend stairs.

Our research has been able to show the following characteristics. The user has full range of sagittal ankle motion comparable to able-bodied gait (23 degrees of plantarflexion and 7 degrees of dorsiflexion.) They have 100% of the required power for gait delivered at the correct time and magnitude. The peak output power is 3-4 times larger than the peak motor power allowing a reduction in motor size and weight [4, 5]. The design provides the user the flexibility to easily remove and install the Robotic Tendon to allow SPARKy to be used as a "powered and computer controlled" prosthesis or a "standard" keel and pylon prosthesis.

In our second year, a roller screw transmission was purchased that is very robust and lightweight. The system is completely portable allowing the user to walk over ground, Figure 19 [4, 5, 20, 21].

SPARKy's biggest advantage lies in the fact that we are storing energy in a spring uniquely chosen for an individual. If one chooses the correct stiffness, the spring can be adjusted by the motor to allow for a 3 to 4 times power amplification. Because we have a large power amplification, we can use a small motor allowing a user to walk. Currently, we are only using 55 Watts of a 150 Watt motor so that we can easily power large individuals and can power fast walking.

We are focused on developing the most durable, versatile, and powerful walk/run prosthetic ankle that meets the goals of a highly functional Military amputee. Because of our power amplification, we can easily walk very fast and have confidence in building a jogging device [18].

6. CONCLUSIONS

Significant advances have been achieved towards creating a computer-controlled, powered transtibial prosthesis that can actively support a user in their normal environment and conditions. Low power, high energy consumption, and sophisticated control methodology are key challenges towards realizing a smart, powered prosthesis. The SPARKy project was able to develop a prosthesis that can supply high peak power to the user at push-off in a light weight and energy efficient device.

The analyses and test data show that the motor power can be amplified to provide the user 100% of the required power. We showed a power amplification of the output power compared to the input power of 3 to 4 times. This power amplification allows the downsizing of the actuator to a portable level. For example, a small 150 W motor in combination with a transmission and spring provides 200 W to 400 W during testing. This size and weight of the system is to a level that is comfortably portable to the user while powerful enough to support an 80 kg subject up to his maximum walking speed of 1.8 m/s (4 mph). We show that adding a passive spring in parallel to the robotic tendon reduces peak loads but both the power and energy increase. Adding a passive spring in series to the robotic tendon reduces the energy requirements.

The SPARKy project developed a very lightweight prosthesis that is used in over ground walking. Our new control methodology and embedded microprocessor control allows the device to move from the laboratory to the unstructured and highly dynamic environments that include stairs, inclines/declines, and over ground walking.

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