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Adjustable Robotic Tendon using a 'Jack Spring'™

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Abstract— **An adjustable Robotic Tendon is a spring based linear actuator in which the properties of a spring are crucial to its successful use in a gait assistance device. Like its human analog, the adjustable Robotic Tendon uses its inherent elastic nature to both reduce peak power and energy requirements for its motor. In the ideal example, peak power required of the motor for ankle gait is reduced from 250W to just 81W. In addition, ideal energy requirements are reduced from nearly 36 Joules to just 25 Joules per step. Using this approach, an initial prototype is expected to provide 100% of the power and energy neccessary for ankle gait in a compact 0.84kg package. This weight is 8 times less than that predicted for an equivalent direct drive approach.**

I. Introduction

In the United States one in five persons live with some form of disability and 61% of these suffer from either a sensory or physical disability[1]. As a person ages, so increases their chances for becoming disabled. Within our growing elderly population, 20 to 50% are afffected by abnormal gait, i.e. walking impairment[2]. Abnormal gait in the elderly does not have a specific cause, however many age-related factors can affect normal locomotion. Some examples include; 1) muscle weakness, 2) slow reaction times, and 3) impaired tactile sensation from the feet.

The ability to balance is the first requirement for successful gait. The factors that affect gait also affect a person's ability to balance upright. Impaired sensory information, long processing times and weak actuation all lead eventually to an unstable balance control system. For the complex tasks of balance and gait, significant deficiency in any of these factors pushes the limits of postural stability to 'marginal' at best. The result of these factors is an increase in duration of double-limb support during gait, which leads to a decrease in walking speed. This decrease is approximately 20% less than the speed of a typical young adult[3]. Interesting to note is that this decrease in speed is not due to a reduction in cadence (i.e. frequency of gait), but is attributed to a decrease in stride length, or reach. The term 'cautious gait', coined by Nutt et. al.[4], describes this phenomenon as the response to a "real or percieved disequilibrium". Cautious gait is the result of apprehension to falling.

Many disabled individuals could benefit from some form of robotic intervention. A robotic device could provide strength where there is weakness, respond to stimuli quickly rather than slowly, and a wearable robot could sense problems early, rather than after it is too late. A robotic device in assistance to the disabled elderly can provide a solution to problems and ailments of getting old.

II. Background

The most effective form of robotic intervention would be a wearable system that could provide the strength and performance augmentation to a person in need. However, use of the term 'wearable' implies that such a robot be portable, lightweight and most importantly safe. In order for such a device to be accessible for home use, the additional implications are that the wearable robot be economical and easy to operate. In contrast, a factory floor robot is none of these things, so simple adaptation of existing technology is not possible. In order to handle the needs of the disabled population, actuated wearable robots that are portable, lightweight, safe, economical and simple to operate are required[5].

The prevalence of powered assistance devices for the weak and elderly can be seen almost every day. Powered-seated scooters are increasingly popular and are available from a variety of commercial sources. Often these scooters even require additional modifications to one's home and automobile to accommodate their use. The popularity of the seated scooter is testament to the need for powered assistance; however, the use of these devices are in direct conflict to the belief that long term health is maintained by the inclusion of "the types of activities that provide an adequate load-bearing stimulus"[6]. Powered assistance is required, but should come in a form that promotes and supports standing/walking activities. To maintain general health and wellbeing load-bearing walking is essential.

Well known projects in the area of assisted locomotion are the BLEEX (Berkely Lower Extremity Exoskeleton)[7] robot and the HAL-3 (Hybrid Assistive Leg)[8] robot. Both devices are rigidly attached to the wearer and are directly driven, i.e. no compliant interface. The BLEEX robot uses hybrid hydraulic actuators to drive the system, whereas the HAL-3 robot uses DC motors and gearboxes to provide power for movement to the user. The goals of the individual projects are different, but conceptually they each provide the same solution, to provide directly, both positive and negative forces to the user to achieve a desired movement pattern. For example in gait, sometimes the robot needs to push the user (positive) and sometimes for support the robot needs to resist the user (negative) and in either case the robot is putting power into the system.

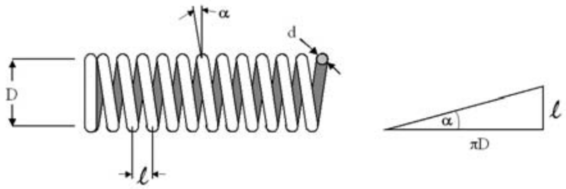

Fig. 1. Helical Spring Geometry

In other work, a robotic powered knee, RoboKnee[9], and an active ankle foot orthosis, AAFO[10], have been developed to assist with an individual's gait. Each of these devices feature the linear Series Elastic Actuator[11] as the means of robotic control. The linear series elastic actuator features a helical spring in series with a ball screw mechanism, similar to the actuator developed by Sugar and Kumar[12] for grasping tasks.

In other literature, van den Bogert describes a theoretical, passive mechanism that reduces peak power for human gait by more than 70%[13]. The passive device uses a series of elastic cords and pulleys around multiple anatomical joints to accomplish reduced power requirements. As written, the specific implementation described would not likely be practical, but the point of including springs in the design of wearable robotic systems is beneficial.

In order to meet the demanding requirements stated above, a wearable robotic device must include lightweight, energy conservative, power reducing springs to be both portable and inherently safe.

III. 'JACK SPRING'™CONCEPT

A 'Jack Spring'™is a new mechanical element which is based upon the concept of *structure controlled stiffness*[5]. A basic Jack Spring™mechanism can be described as a helical or coil spring that can adjust its number of active coils. The use of such a mechanism is comparable to a linear screw, the exception is that for a Jack Spring™its lead is variable based upon an imposed axial force.

To further understand this concept consider the geometry of a helical spring, see figure 1. The key features to a helical spring are coil diameter, **D**, wire diameter, **d**, and lead, l. Also important to a spring is the number of coils, n_a. Along with material properties, number of active coils, n_a, coil diameter, **D**, and wire diameter, **d**, drive the stiffness of a spring. This relationship given in a text by Shigley and Mischke[14] is shown in equation 1.

$$K = \frac{G \cdot d^4}{8 \cdot D^3 \cdot n_a} \quad (1)$$

In the preceding equation the value **G** represents a material property called shear modulus. Each of the parameters of equation 1 influence the stiffness of a coiled spring. In particular, an increase in wire diameter, **d**, will increase stiffness. Whereas, either an increase in coil diameter, **D**, or number of active coils, n_a, will decrease spring stiffness. So, to create a *structure controlled stiffness* device, based upon the properties of a coil spring, any of these parameters could potentially be adjusted. The simplest parameter to change and thus adjust stiffness is the number of active coils, n_a. A conceptual diagram of utilizing this approach can be seen in figure 2.

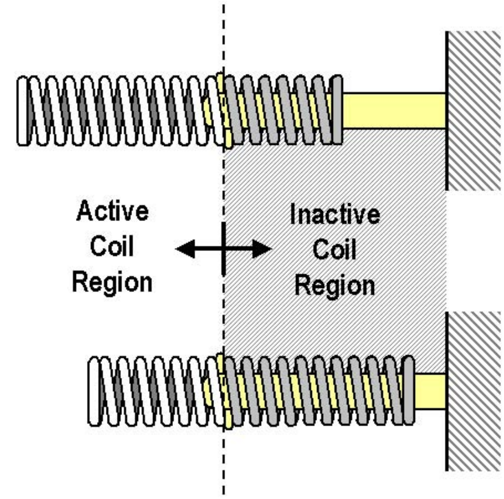

Fig. 2. Jack Spring™Concept: As the number of active coils is decreased, the stiffness of the remaining spring is increased

The diagram above shows the basic concept of a Jack Spring™. Through a rotation of either the spring or the shaft/nut, coils can be added to or subtracted from the number of active coils, thus changing the effective stiffness of the structure. In this example, both displacement and stiffness are coupled. A similar approach to this has been found in a thesis by Herder[15]. However, in Herder's work, the method was intended for the manual adjustment of spring stiffness in a gravity compensation mechanism. In contrast, more useful to the *structure control* approach, this parameter can be adjusted dynamically in closed loop feedback.

A. *Jack Spring™Actuator*

As an actuator concept, the Jack Spring™offers a combination of compliance and energy storage to it's actuation tasks. For a wearable robot, these are desirable attributes. In addition, since this device acts like a lead screw system, a very lightweight gearbox is built-in. Also, with measurement of the number of active coils, n_a, and end effector displacement, force sensing is easily obtained. To understand the basic behavior of Jack Spring™actuator, consider a basic diagram of the system, figure 3.

In the diagram, the end effector position is described by **x** and the free length of the active portion of the spring is described by **a**. The term Δ**x**, represents the spring deflection, **F** is the applied force and τ describes resulting torque or required motor torque. In addition, the referenced environmental position, $\mathbf{x}_e$, for convenience is offset from the actuator datum by the variable **u**. Treating the Jack Spring™system in terms of a lead screw, we can conclude that required motor torque is represented by equation 2 for

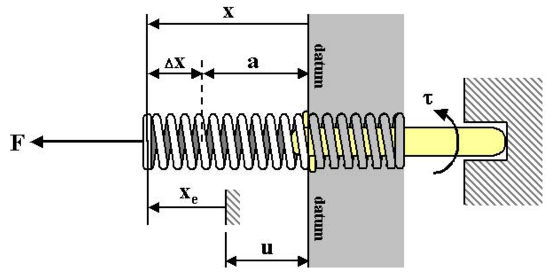

Fig. 3. Jack Spring™Actuator: Force from interaction with the environment causes spring deflection, Δx. A rotation from the shaft adds or subtracts the number of active coils in the system, n_a, and thus coupling stiffness and displacement

an ideal system[14].

$$\tau = F \cdot \frac{D}{2} \cdot \tan(\alpha) \tag{2}$$

Where from figure 1, l can be derived to equal,

$$l = \pi \cdot D \cdot \tan(\alpha) \tag{3}$$

However, for the Jack Spring™the lead, l, or lead angle, α, is variable depending on force. Therefore deflection of the spring must be considered. For the Jack Spring™system, two quantities are measured; end effector displacement, **x** and number of active coils, n_a. The lead for this variable pitch screw is simply, end effector position, **x**, divided by the number of active coils, n_a.

$$l = \frac{x}{n_a} \tag{4}$$

and at $x = a$, $l_o = \frac{a}{n_a}$.

Starting from the basic equation of force for a spring, it can be shown that for a Jack Spring™the force on the system is broken down into a per coil basis. If the geometry of a spring is considered constant then the per coil stiffness of a spring can be shown as a constant, β, see equation 5.

$$K = \frac{\beta}{n_a} \tag{5}$$

and from figure 3 we know the following relationship between x, a and Δx to be.

$$\Delta x = x - a \tag{6}$$

where $a = n_a \cdot l_o$; thus substituting these results into the equation of a spring, i.e. $F = K \cdot \Delta x$, yields.

$$F = \beta \cdot \left(\frac{x}{n_a} - l_o \right) \tag{7}$$

or finally,

$$F = \beta \cdot (l - l_o) \tag{8}$$

The force on the actuator is determined by multiplying the spring constant, β, by the difference of measured lead, l, to free lead length, l_o. Using this relationship, an equation describing torque in terms of lead can be determined.

$$\tau = \frac{\beta}{2 \cdot \pi} \cdot \left(l^2 - l_o \cdot l \right) \tag{9}$$

Knowledge of the original free lead length, l_o, measured lead, $l = \frac{x}{n_a}$ and spring constant, β, is all that is necessary to determine both force, **F**, and required motor torque, τ.

For a Jack Spring™system, rather than consider a spring's overall stiffness or free length, the single coil stiffness and free lead length become the important factors. Again, knowing the number of active coils, n_a, and the environment's actual position, x, a measure of lead, l, is easily determined.

For a wearable robot, the Jack Spring™actuator is an ideal system. The Jack Spring™actuator embodies all of the criteria for a good wearable robot actuator. Using the spring as a gearbox creates a system that is very **lightweight**. A spring has very little hysteresis, so it is **efficient** and is able to **store energy**. A spring is **powerful**, only the inertia of the system limits the rate at which energy can be released and a spring by its very nature is **compliant**; therefore, some measure of **safety** is always available to the system.

IV. Adjustable Robotic Tendon

Use of the term Robotic Tendon implies an analogy to human physiology. Mentioned earlier, the simple inclusion of a spring to a linear actuator can provide energy and power savings to the design of a wearable robotic device. The premise of the following development is that the human muscular system uses the advantages inherent in its elastic nature. Those advantages result in a minimization of both work and peak power. In terms of an electric motor, minimizing peak power implies the reduction of requirements for motor size and thus weight. Minimizing work implies a reduction of stored energy supply necessary to fulfill the demands of gait. For a portable robotic system, these are both very important considerations.

To illustrate a typical pattern of gait, consider the kinematics and kinetics of a normal ankle[16], figure 4. Notice that the ankle moment (torque) data is normalized by body weight, kg. In this figure, peak ankle moment occurs at roughly 45% of the gait cycle and at a value of -1.25Nm/kg or for a 80kg person, -100Nm. The negative sign represents the physiological direction for which the moment occurs, in this case peak moment is acting to move the foot in a toes down direction.

In our previous work, a Robotic Tendon based upon the concept of *equilibrium controlled stiffness*[5] was used to provide ankle gait assistance [17]. The results of this earlier work show an increasing optimal stiffness, K, for increases in body mass. This early work also indicated that not only does body mass influence the spring stiffness needed, but so does the dynamic task, i.e walking, running, climbing stairs. Thus, to handle a variety of masses or tasks, a more robust system is required. More specifically, an Adjustable Robotic Tendon is desired.

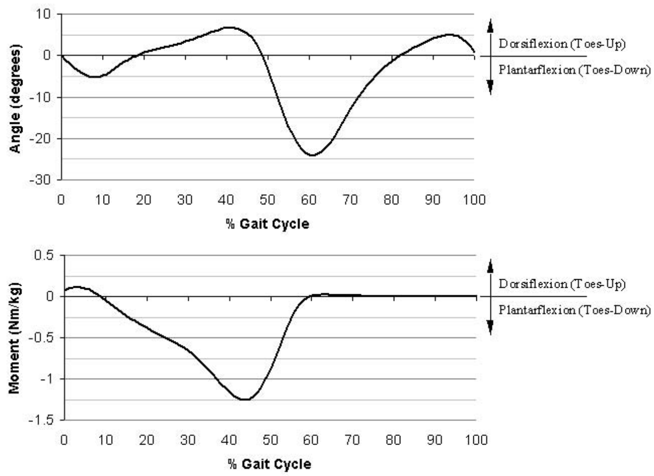

Fig. 4. Normal Ankle Gait: Kinematics and Kinetics

A. *Jack Spring™ for Ankle Gait Assistance*

Creation of an Adjustable Robotic Tendon can be done using the concept of the Jack Spring™. However, the coupled nature of the Jack Spring™'s stiffness and displacement requires a more detailed investigation of how it can be used to assist ankle gait. From figure 3 we know the basic variables of a Jack Spring™actuator. In particular, the environmental forces, **F**, and displacements, $\mathbf{x}_e$, are determined from normal ankle gait. Like our previous work on the Robotic Tendon concept, the key to designing a lightweight yet powerful actuator for human gait lies in understanding how to minimize required input power.

Input power to a spring actuator system can be different from its resulting output power. The reason is that a spring can store energy over a significant period of time, but can still release that energy very quickly. Thus high output power is possible using input from a low power motor.

For a Jack Spring™system, each revolution from the shaft of a motor is equivalent to the addition or subtraction of a single active spring coil. This relationship between motor and the Jack Spring™is the foundation for determining how much power is delivered to this robotic spring mechanism. From figure 3, the following relationship for coupled stiffness and displacement, equation 10, and finally motor power, equation 11, can be determined.

$$K = \frac{F + \beta l_o}{x_e + u} \tag{10}$$

and,

$$P_m = \left| \underbrace{F \cdot \dot{x}_e}_{\text{gait power}} - \underbrace{\frac{F \cdot \dot{F}}{K}}_{\text{Jack Spring™power}} \right| \tag{11}$$

Notice the inclusion of an absolute value for equation 11. The reason for this is, that regardless of a motor's power contribution to the system (positive or negative), power used by the motor is always positive. This equation is similar to that derived for our original Robotic Tendon work[17], the major difference, however, is that in the earlier work, stiffness, **K**, is constant. Thus the result of this derivation is that the Jack Spring™model is the general solution to the specific case of the *equilibrium controlled stiffness* Robotic Tendon, where K≡constant. In addition, if K is treated as infinite, then the Jack Spring™model can describe a basic ideal lead screw system as well.

Nevertheless, for the current implementation we are interested in exploring the general nature of a Jack Spring™actuator and its coupled stiffness and displacement behavior in gait. From equation 10, it is shown that the parameters that influence stiffness, **K**, are gait forces, **F** and displacements, $\mathbf{x}_e$ as well as parameters, βl_o and **u**. The parameter βl_o simultaneously captures both single coil stiffness and undeflected lead in a coil spring, and thus becomes an intrinsic spring property. A physical spring can have a variety of **D**, **d** and $\mathbf{l}_o$ combinations, but if the βl_o of each are equivalent, then they are considered interchangeable within the Jack Spring™model.

Intuitively, it is easy to understand why βl_o is significant to the power performance of an Adjustable Robotic Tendon. Less intuitive however, is why a variable like offset, **u**, has any significance at all. The explicit definition of the offset variable, **u**, has an implicit influence on the beginning or initial stiffness of the system. The system's initial stiffness is an assumed quantity and ultimately influences the power requirements of the motor. To appropriately design the Jack Spring™actuator and minimize input power requirements from the drive motor, an optimization considering both intrinsic spring properties and initial system stiffness is required.

B. *Jack Spring™Optimization*

The intrinsic character of any coil spring can be broken down into a single coil basis, hence the parameter βl_o. For a Jack Spring™, individual coils are continuously being added or subtracted to the active portion of the mechanism and so the intrinsic properties of a single coil are important. Also mentioned previously, the selection of the offset variable, **u**, implicitly assumes an initial stiffness, $\mathbf{K}'$, for the Jack Spring™system. The relationship between initial stiffness and offset can be seen in equation 12.

$$u = \frac{1}{K'} \cdot [F(t=0) + \beta l_o] - x_e(t=0) \tag{12}$$

Using the above relationship and equation 11, an optimization routine was created to seek the lowest peak power over an ankle gait cycle. The routine incrementally changed offset variable **u** and intrinsic spring property βl_o while computing power throughout a gait cycle.

The results of this evaluation yielded the conclusion that for a single ankle gait design point (i.e. assumed body mass), values of βl_o and **u** can only asymptotically approach the results of the previous Robotic Tendon work. For a single design point, the optimized fixed stiffness of an *equilibrium controlled stiffness* actuator creates the lowest possible peak power situation for a motor. Thus values of βl_o and **u** must

Body Mass (kg)	Offset **u** (m)	$\mathbf{K}'$ initial(N/m)	Motor peak(W)	Output peak(W)
60	0.117	10,733	60.5	185.3
80	0.096	12,963	81.5	247.1
100	0.083	14,795	102.9	308.8
120	0.074	16,278	124.8	370.6
140	0.069	17,505	147.0	432.4

TABLE I
EXAMPLE JACK SPRING™OPTIMIZATION: WHERE βl_o = 1300N

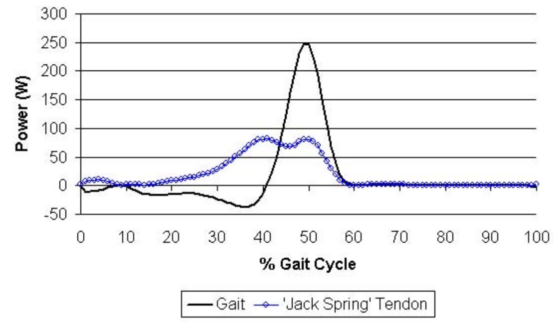

Fig. 5. Ankle Gait Power Results: Output Power (thick solid line) and Input Power (thin line with circles)

approach infinity to reach the same result. However, using reasonable sizes for both βl_o and **u** can still yield results very near to that of the original Robotic Tendon optimization (within 2% of power reduction results).

So now the question becomes, "What does this mean?" The answer is that simultaneous optimization of both βl_o and **u** is not possible. Simply put, either βl_o or **u** must be assumed so that the remaining term can then be optimized. As an example, if a spring with βl_o = 1300N (i.e. K=18,000N/m & a=0.072m) is used, then values of offset **u** can be determined for various assumptions of body weight. Table I describes the results of this example.

For clarity, K' represents the initial stiffness of the Jack Spring™system and is implicitly determined by the offset variable, **u**. The results for the offset optimization show, that a small 5cm change in the variable **u**, can result in an optimized performance over an 80kg range of body mass. This means that the same Jack Spring™actuator can be easily adjusted to be re-optimized for large changes in gait load (i.e. body mass). Either the same actuator can be used to support a variety of people or it can be re-tuned to support the same person with added weight on his back. Of special mention, is that by a simple adjustment of offset, optimized input power requirements remain about 1/3 of those produced as output by the Jack Spring™actuator.

C. Comparison

In order to understand the significance of reducing required power by 1/3, a comparison of the adjustable Robotic Tendon or Jack Spring™actuator to that of an equivalent direct drive system shall be described. However, in order to compare each, some assumption about the human operator and device must be made. For this analysis, consider a 80kg person, who has a walking rate of 0.8Hz. Also consider that the lever arm necessary to convert the rotational ankle joint characteristics to linear movements is 12cm. With these assumptions peak power for human gait is nearly 250W. Although the peak power requirement for gait is high, it is only at this magnitude for the instant at which 'push off' is initiated. For the remainder of the gait cycle the power requirements are much more modest.

A peak power requirement of 250W for human gait is not easily accomplished given the constraints for a desirable wearable robot design. In the case of a direct drive solution, a motor of significant size and weight is necessary to provide the full 250W required. As an example, the Maxon motor RE75 (Maxon Precision Motors, Inc., San Diego, CA) is rated for 250W continuous power (rated peak power, 393W) and weighs 2.8kg not including a gearbox. Adding an appropriate gearbox to match ankle torque requirements increases the weight by 3.8kg. The combined 6.6kg is not a small amount of weight to add to a person's ankle. Due to the frequency and duration of typical gait and manufacturer recommendations, continuous power was used to size this, HAL-3[8] like, example system.

In contrast, the above described Jack Spring™actuator can provide the same 250W of power necessary for gait, but can use a DC motor sized for less than 90W power, see figure 5. The Maxon RE35 is a 90W rated (continuous) motor, which weighs only 0.34kg. This motor is 8 times less weight then the afore mentioned Maxon RE75 motor. Since the Jack Spring™mechanism is its own gearbox, a standard gear assembly is not required. Using weight estimations based upon an original prototype as a guide, the anticipated weight for the Jack Spring™actuator is approximately 0.84kg, 8 times less than the direct drive solution. An eight fold savings in weight is a significant achievement for a wearable robot design.

To see how stiffness must change through a gait cycle and provide the appropriate angles/moments necessary for normal gait see figure 6. Based upon described set of assumptions, initial stiffness is shown to be 12,963N/m and then reaches its maximum value of 28,296N/m at 60% of the gait cycle. After reaching that peak, the stiffness is quickly dropped back down to the level of initial stiffness as the device prepares for the next cycle.

During the loading phase of gait (approximately 10% to 40% of a gait cycle) the stiffness of the Jack Spring™actuator gradually increases and the spring deflection continues to grow until the peak ankle moment is reached. At this point, 'push off' (roughly 40% to 60% of a gait cycle) begins and the actuator stiffens further, which drives actuator output power to its peak levels, 250W.

Lastly, the energy requirements for ankle gait have been computed to be approximately 19J, this was determined by integrating the power curve shown for gait in figure

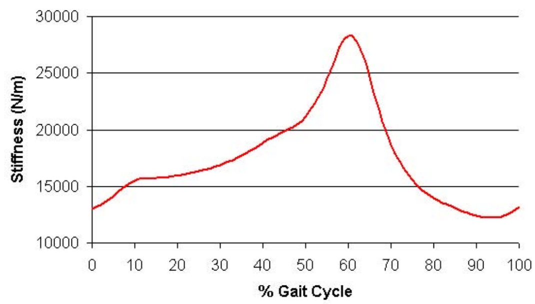

Fig. 6. Jack Spring™Stiffness Profile Through a Gait Cycle

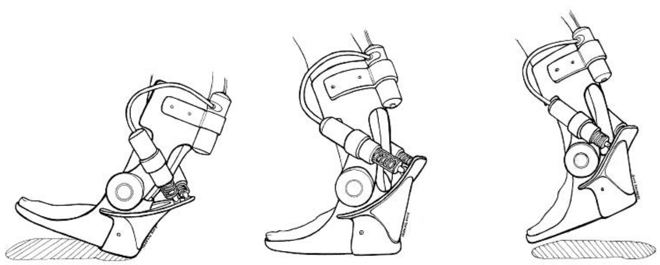

Fig. 7. Adjustable Robotic Tendon Robot Concept: Sequence shows from left to right; Heel Strike, Mid Stance and Toe Off

5. Discussed earlier, a direct drive solution would have to consider its power to be the absolute value of the gait power curve just described and so its computed energy requirements would be 36J. This is nearly twice that shown for normal ankle gait. Whereas, computing energy required for the Jack Spring™Robotic Tendon reveals that its energy requirements are just 25J for each step.

In comparison with a direct drive approach, the Jack Spring™Robotic Tendon shows that significant savings in weight, power and energy can be achieved, which all result from this novel implementation of a coil spring. To illustrate how a Jack Spring™Robotic Tendon may be implemented in an ankle gait robot, figure 7 shows a conceptual configuration. Besides the adjustable Robotic Tendon actuator, the conceptual design shows three key features; 1) Actuator manipulates a rigid orthosis, 2) Motor attaches to the device via a flexible drive shaft, and 3) the Jack Spring™mechanism is attached at an angle to the orthosis. As a result of these features, this design configuration should still be lightweight, worn comfortably and will be easy to don and doff.

V. Conclusions

To develop wearable robotic systems for human force and performance augmentation, devices that are portable, lightweight, safe, economical and simple to operate are required. Stated previously these demands can be difficult to achieve using traditional direct drive approaches. Again, in our simple example for ankle gait a DC motor/gearbox combination would require a minimum of 250W of peak power and consume nearly 36 Joules of energy for each step. With the addition of 6.6 kg per ankle joint, this proposed direct drive scenario is neither lightweight nor portable for very long periods of time.

It has been shown that with simple adjustments to initial stiffness a Jack Spring™based actuator can be re-tuned to maintain power optimizations to 1/3 of direct drive needs at a weight 8 times less than that for a direct drive solution. Although only shown for increases in load or body mass, similar minimal adjustments are expected to re-tune for other dynamic tasks. The Jack Spring™based, adjustable Robotic Tendon offers a powerful, robust, energy efficient and safe solution to the task of human gait assistance.

VI. Acknowledgment

The Jack Spring™mechanism is currently protected by a United States provisional patent with Arizona State University.

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