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Design of a bioinspired cable driven actuator with clutched elastic elements for the ankle

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Abstract— **Bioinspiration can be used to improve the efficiency of these assistive biomechatronic devices. In this paper, a cable driven actuator for the human ankle was designed using a bioinspired approach. The torque reduction was achieved by means of force amplifying elements such as cables with pulley, and, to reduce the power requirements for the motor, the actuator mimics a muscle using a clutched parallel elastic element. The simulations to validate the model were performed using real gait data and the results prove the viability of the device to be used in anthropomorphic legs and exoskeletons. Although the losses due to friction were not considered, the simulations showed a reduction of 60% in the force peak and 40% in the power peak.**

I. INTRODUCTION

In the field of prosthetics, there are passive and active devices. An active prosthetic device uses an external energy source to move the joints and assist the user in walking [1]. The commercial Power Knee® prosthesis, Össur, is a lower limb device powered by a strain wave gearing that moves the knee for a position required and allows amputees to perform activities[2]. A semi-active prosthesis is a device in which the passive mechanisms bearing the load can be changed actively, e.g. switching between different springs [3].

However, there are still some limitations that all these technologies have in common: the low ratio between the power and the volume of the motor. The actuators available on the market with enough power to move human joints are large and heavy, increasing the final weight of their portable devices [4]. A possible solution is to seek inspiration in biological actuator systems, in this case, the muscles. This approach has led to substantial improvements in the system's weight and energy use [5].

The use of springs with actuators have two main configurations: Series Elastic Actuators (SEAs) and Parallel Elastic Actuators (PEAs) [6], [7]. The spring used in actuators of lower limb devices stores energy during the stance phase of the gait and releases at the beginning of the swing phase [8], complying with the muscles behavior. These dynamics reduces the power requirement to walk [7], [3]. One study collected gait data from subjects in walking tests and applied optimization using PEA and SEA configurations. The results showed that SEA can provide about an 80% reduction in ankle motor power requirements and PEA provides a reduction of approximately 60% but only PEA does a significant reduction in motor torque requirements [9]. It is also possible to use a clutch to engage and disengage the spring so that the dynamics do not interfere with the others gait phases [10]. While decreasing the power and torque demand can lead to a lighter and smaller motor, there is still a problem with the cantilevered mass of the actuator. This problem is worsened in the more distal joints. To overcome this issue, a solution is to shift the motor to a place that minimizes interference in the human center of mass. For example, the actuators for the lower limbs could be placed close to the body center of mass, around the lumbar region. In this way, it is possible to use a backpack and a cable-driven system to transmit the power to the joints[11].

In this article, first an analysis of bioinspiration for the ankle muscles is presented, followed by the requirements for a biomechanical device using PEA, clutch and cable-driven. Then, is explained the mechanical design of the proposed biomimetic solution. The results section shows the simulation of the device with further discussion and conclusions.

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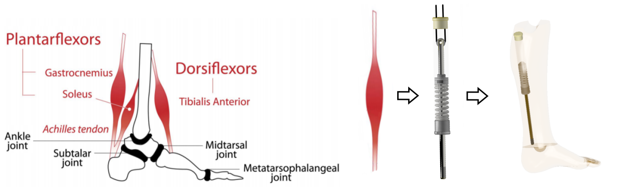
II. METHODOLOGY

A. Bioinspiration

The human ankle-foot complex can execute movements in the anatomical planes: sagittal, transverse and coronal. However, the progression of the gait occurs mainly in the sagittal plane. To simplify its translation into mechanical devices, the anatomy presented in Fig. 1a is commonly used[12].

Human joints are best simulated if their mechanical design includes passive components, such as springs and also a clutch mechanism to disengage the springs to prevent disturbances in walking dynamics when energy stored in the spring is not needed. Thus, the ankle muscles shown in Fig. 1a reach their best results if simulated with elastic actuators (SEA and PEA) combined with clutches.

In this work, the plantarflexor muscle, Fig. 1a, was designed using a combination of a cable transmission with pulley, PEA and clutch. The bioinspired device consists of an axis inside a tube, that makes the link between the knee and the foot, this is presented in Fig. 1b, with the objective of producing a future shank prosthesis. There is a spring, with a diameter smaller than the tube and larger than the shaft to avoid friction losses, that simulates the muscle-tendon behavior and a clutch to engage the elastic element to the axis when necessary. In the upper part of the axis, the power transmission is made by a bowden cable with a pulley to amplify the torque.



(a) Principal joints and muscles of the ankle–foot complex [12] (b) Concept design of bioinspired muscles

Fig. 1: Bioinspiration for muscle device

B. Model Specifications

The requirements of the actuator could be defined in such a way that they behave with similar characteristics to the leg muscles. The torque required, in the ankle joint, for walking is about 1.5 N.m/kg [13]. Another requirement is the length of the actuator, Zatsiorsky [14] and De Leva [15] determined the length of body segments with respect to the height of the subject. For the shank segment, which represents from the knee joint center to the lateral malleolus in the foot, for a subject with height equal to 1.74 m, the length is 434 mm [15]. Weight is an important requirement for the proper functioning of the biomechanical system, as it can interfere with the dynamics of walking. [14] and [15] have also determined the mass of body segments, which in the case of the shank is 3.25 kg for a subject of 75.0 kg body mass, using this data it was defined that the actuator must remain its weight below 500 g.

C. Mechanical Design

The biomechanical model was designed using the bioinspiration principles mentioned before with the specifications above and the software Autodesk Inventor Professional 2020® (Autodesk Inc., San Rafael, California). The actuator will be connected to the shank by an U shaped part. Each side of the U part will be connected to the top of the actuator's tube with screws and threads into the lid. The "base" of the U shape will be connected to the shank.

1) Bowden cables: The motors available on the market, which guarantee 1.5 N.m per kg torque, will not fit the weight or space available on the ankle actuator. To solve this, the Power Pack, a backpack with electric motors, ball screws and bowden cables was used. The bowden cables, which consists of an inner cable inside a flexible sheath, is used to transmit the power. Its flexibility allows the motors to be relocated freely, however, the transmission efficiency is related to the friction between the inner cable and the sheath.

2) Pulleys: The required ankle torque can be obtained with a force of 1875 N, this force was calculated using the torque in the literature of 1.5 N.m/kg, for a subject of 75.0 kg and a moment arm length of 0.06 m [11]. However, using the principles of the pulley it's possible to reduce this force required in the bowden cable, because when a force is transmitted by a mobile pulley, it is amplified by 2. Thus, the force T, provided by the Power Pack to reach 1.5 N.m per kg will be 937.5 N.

The mechanical design proposed for this solution is presented in the Fig. 2a. The pulley is mounted on a ball bearing. In the bearing inner race is mounted a pin, which is fixed in a transverse bore in the end of the main axis. This design allows the force of the motor to be amplified by 2.

3) Parallel Elastic Element: Although the pulleys reduce the torque, they also reduce the speed of the axis by two, keeping the same power required from the motors. Analyzing the behavior of the ankle during the stance phase, we see that energy is absorbed and, most importantly, it is absorbed almost linearly compared to the variation of the angle. This makes the ankle behave like a linear spring [9].

As discussed before, a parallel arrangement was chosen, because of the significant torque reduction in the motor torque. The free body diagram of the actuator acting on the foot is shown in Fig. 3a. The moment arm is represented by the length L. The force F_{ank} is required to balance the joint moment M and the foot is rotated with the angle θ. The horizontal distance projection of the actuator is represented by d and the vertical distance is h, calculated as follows:

$$d = L\cos(\theta) \quad and \quad h = L\sin(\theta) \tag{1}$$

The force required F_{ank} is, therefore, calculated with the moment equilibrium. However, as mentioned before, the required force can be reduced using the principles of the pulley and using the spring behavior of the muscle. The Fig. 3b shows a free body diagram of the actuator: the force on the bowden cable is represented by T. The force F_{spr} represents the spring force and it contributes to the reduction of T. The spring force F_{spr} is calculated using an elastic force model, with the elastic constant k and the deformation Δh.

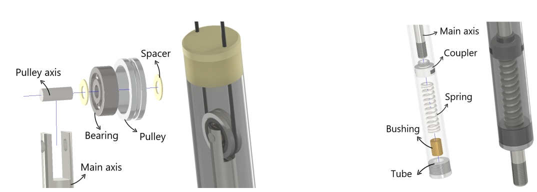
$$F_{ank} = \frac{M}{L\cos(\theta)} \quad and \quad F_{spr} = kL(\sin(\theta) - \sin(\theta_0)) \tag{2}$$

Thus, the force required on the bowden cable provided by the motor, T, can be calculated with the equation.

$$T = \frac{F_{ank} - F_{spr}}{2} = \frac{M}{2L\cos(\theta)} - \frac{kL(\sin(\theta) - \sin(\theta_0))}{2} \tag{3}$$

The parallel elastic element was designed as presented in the Fig. 2b. The main axis can freely slide in the bushing concentric with the elastic element. The spring is supported on the lower end by the tube and on the upper end by the coupler, the spring acts parallel to the axis.

4) Clutch: With the energy being absorbed by the spring, one problem arises: what will happen if the gait is stopped during the stance phase? In this case, the energy stored in the



(a) Ankle actuator pulley (b) Ankle actuator spring

Fig. 2: Design of the main axis pulley (a) and the spring (b)

(a) Actuator and the foot (b) Actuator

Fig. 3: Free body diagrams

spring will be transferred to the joint and the leg will recoil. For this reason, it is important to be able to disengage the spring anytime during the gait cycle, creating the necessity of a clutch to couple the spring and the main axis of the actuator. Moreover the ability to disengage the spring will help during the dorsiflexion movement. The clutch device proposed to engage and disengage the spring it will have teeth that engage grooves on the main axis, the Fig. 4a shows the design. The step motor the gear and from this movement the pin of clutch jaw slides trough the gear slot. When the pin reaches the slot extremity closer to the clutch's center the fit occurs between the clutch jaw and the main shaft coupling those two components. The Power Pack provides an external actuation from electric motors through bowden cables to the ankle actuator, effectively moving the ankle Fig. 4b.

D. Stress Analysis

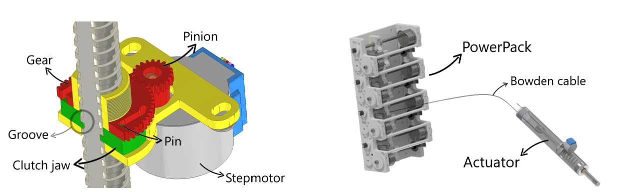
The Autodesk Inventor Professional 2020® (Autodesk Inc. San Rafael, CA, USA) was used to perform stress analysis of the critical elements of the actuator. All the load values were obtained from the simulations with the physical model.

The pulley, its axis and the main axis bore, which accommodates the pulley's axis underwent through Finite Element Analysis. To do so, a parabolic load, with 1875 N of magnitude, was applied over each component.

The material chosen for the main axis and the pulley axis was the AISI 8630, with 550 MPa yield strength, because these two components will be under the biggest stress during the operation of the actuator. The pulley will be just under the compression of the cable, which the Aluminum 6061, with 276 MPa yield strength, could withstand easily.

E. Simulations

For the simulation of the physical model shown in Fig. 3b MATLAB®(Mathworks, Inc. Nattick, MA, USA) was used. The input was the force needed to actuate the ankle (F_{ank}) and the output were the force (T) and the power (P) that the Power Pack have to apply on the main axis of the actuator.



(a) Ankle actuator clutch. (b) PowerPack with the actuator.

Fig. 4: Design of the ankle clutch(a) and the final system(b)

To obtain F_{ank}, the data of 13 gait trials of a subject with 64 kg of mass and 1.66 m of height were used. The data contained motion, as well as ground reaction forces. Using these forces the internal joint torques were computed using inverse dynamics [16], [17].

To determine the heel strikes, the ground forces were analyzed to see when the foot was making contact with the ground. Then the torque, angular velocity and angle data between two consecutive heel strikes of the same foot was extracted and normalized to 100 points. After this first analysis, the data of the right ankle of the subject appeared to be incomplete. In this case, only the left ankle data was used in the simulations.

Analyzing the ankle joint size from [11], the actuator can be fixed at 60 mm from the ankle joint, so, let's assume $L =$ 60 mm. The spring constant (k) was calculated dividing each value of F_{ank} displacement at the same instant. The Power Pack cannot apply a negative force to the axis of the actuator. Therefore, to avoid this situation, the value of k must be the minimum value obtained during the gait which is $k = 86750$.

III. RESULTS

A. Stress Analysis

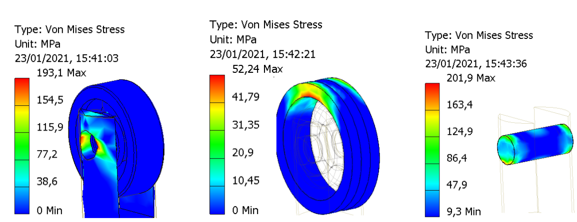
The stress analysis of each critical element was performed and the safety factor was calculated to endorse the solution.

The results of the simulations for the loads described in methodology section can be seen in Figs. 5a, 5b and 5c. The Von Mises stress values were evaluated and the safety factor obtained were 2.8 for the main axis, 5.3 for the pulley and 2.7 for the pulley shaft. With the loads was possible to select the SKF 635 deep groove ball bearing with $\leq 6mm$ width, 5mm inner hole diameter.

B. Simulations

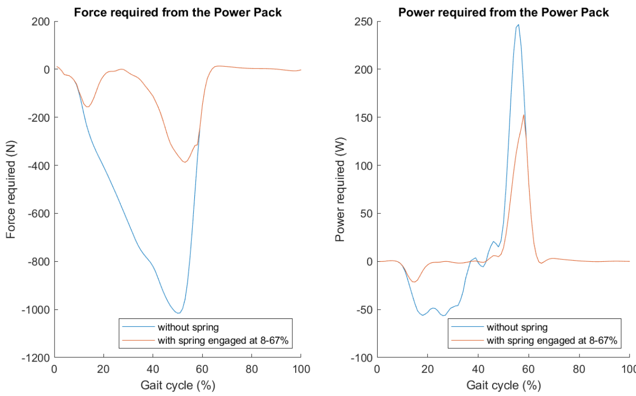
The first simulation was made considering the spring disengaged during the entire gait cycle. Thus, the results shown in the blue series of the Fig. 6a for T and in Fig. 6b for P. Between zero and 43% of the gait cycle, the Power Pack must absorb energy most of the time. At 56% of the gait cycle there is a peak of power, around 246.6 W.

If the spring is engaged since the beginning of the gait, some of the energy would be lost, caused by the decrease in the angle of the joint. Therefore, the best option is to engage the spring when the angle of the joint is the lowest. This occurs between 7 and 8% of the gait cycle.



(a) Main axis. (b) Pulley. (c) Pulley axis.

Fig. 5: Stress Analysis



(a) Force

(b) Power

Fig. 6: Requirements from the Power Pack with spring engaged and disengaged

The disengagement will occur just after the toe-off, since there is no significant force applied to the joint after this moment. The result of the controlled engagement of the spring can be seen in the orange series of Figs. 6a and 6b. The maximum force required from the Power Pack in this scenario is $387.5N$. The maximum power required is $152.8W$. In terms of size, the device length in neutral position is 310 mm, within the limits described in the requirements. The total mass calculated by Inventor® is 465 g, again within the limits proposed.

IV. DISCUSSION

In this work we presented the design and simulation of a novel cable-based actuator intended for robotic legs. Its main feature is the use of a spring that simulates the behavior presented by the plantar flexors of the ankle during the stance phase of the gait. The main goal with this is to reduce the force peak and the power consumed from the motors to actuate the ankle.

The reduction in the power peak is 40% and the force peak in 60% approximately, compared to a direct actuation via cable-pulley. But the peak power required is still much higher than the one provided by one motor of the Power Pack ($70W$). In this case, two or more motors will be necessary. The peaks shown in the orange series of the Figs. 6a and 6b are due to the difference between the force required to actuate the ankle (F_{ank}) and the force provided by the spring (F_{spr}). F_{ank} is dependent of the secant of the angle of the joint and F_{spr} is dependent of the sine of the joint angle. This implicates F_{ank} and F_{spr} will never be equal if we keep the spring constant (k) or the distance between the application of the force and the center of the joint (L) constant.

The are two aspects which were not considered during the simulations: the losses due to friction inside the actuator and the power losses during the coupling/uncoupling of the spring. These aspects may be better understood after the construction and tests of a prototype of the actuator.

The results of the simulations are promising. The reductions reached indicates the device works as intended and it is also viable for construction and testing, the tests will be important to evaluate the friction losses and the coupler losses. An aspect that needs further investigation is the spring force behavior. It may require the use of a combination of springs or a additional device to change the distance of the actuation (L). The main objective of these changes is to reduce even more the force and power peaks.

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