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THE LADD ACTUATOR AS A PROSTHETIC MUSCLE

Jacobsen, S.C., Jerard, R.B., Knutti, D., and Carruth, J.

I. INTRODUCTION

There are numerous methods by which a prosthetic limb may be actuated. Electrically powered limbs typically utilize a motor together with a reduction mechanism such as gear train, harmonic drive, ball screw or belt and pulley system. These devices may be competitively rated according to criterion such as weight, cost, noise, efficiency, life, dynamic performance, etc. The LADD actuator offers a favorable alternative when evaluated under the above criteria (2)(3).

The LADD actuator is a contractile mechanism which can be used in antagonist pairs in a manner similar to natural muscles. Figure 1 illustrates that the principle of operation is similar to a rope ladder which shortens when twisted. In contrast to the rope ladder, the LADD consists of numerous flexible links (fibers) deployed around the circumference of the series of hoops. The LADD actuator can be used to convert rotary to linear motion or linear to rotary motion. Fibers are attached to the hoops such that strength, fatigue life, and efficiency are maximized.

Figure 1 - The fundamental element of the actuator is the single LADD cell which consists of two rings joined by many flexible links. When the rings incur relative rotation the cell shortens. The cells may be joined together in a chain to provide larger contraction deflections.

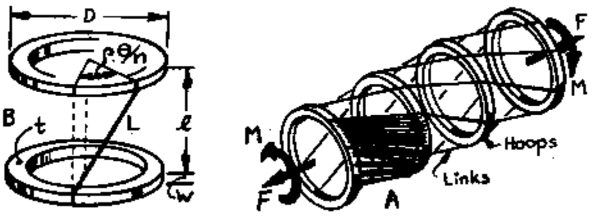

Figure 2 - Performance of the LADD actuator is described mathematically in terms of the parameters shown in the diagram.

II. APPLICATIONS

The LADD is an excellent prosthetic and orthotic actuator for the following reasons:

1. Minimal acoustic noise generation
2. High strength
3. Low weight
4. Inexpensive to manufacture
5. High efficiency
6. Lubrication is not required
7. The LADD exhibits very favorable dynamic performance

To date the LADD actuator has been utilized in two devices. In the "Utah Arm" elbow flexion is actuated by LADD's. In another configuration, the LADD has been used to actuate prehension in an orthotic hand splint.

1. The Utah Arm

Figure 3 shows a view of the "Utah Arm" which is a prosthesis for above-elbow amputees. In this application the LADD's are configured as antagonist pairs much like the biceps and triceps muscles. The LADD's are positioned axially within the forearm shell. At the wrist end of the forearm the LADD's are driven by a DC servomotor. At the elbow end, the antagonist LADD's terminate over a nonlinear pulley. The nonlinear pulley serves to maintain tension within the LADD actuators and achieves a position dependent reduction ratio between the servomotor and the elbow. The LADD's are very quiet and permit very free motion of the forearm when not under power. The LADD's also contribute to the very low weight of the "Utah Arm." The "Utah Arm" weighs approximately 2.5 pounds and has fully powered elbow flexion, wrist rotation, and terminal device closure. All batteries and electronics are contained within the arm itself (1)(4).

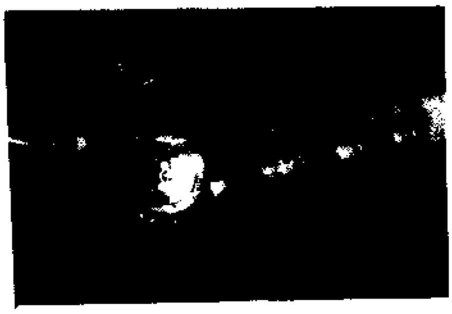

Figure 3 - The "Utah Arm" utilizes antagonist concentric LADD actuators for elbow flexion.

2. Orthotic Device

Figure 4 shows the LADD actuator configured on a hand orthotic splint. The function of the LADD actuator is to cause closure of the hand. Again, the LADD actuator is driven by a small DC motor through an overriding clutch which limits the maximum torque which can be generated by the system. The device is almost totally noiseless, requires no lubrication, and is very light in weight. The device shown in the figure was used primarily to evaluate performance. Later models will be redesigned so that the LADD actuators are totally enclosed.

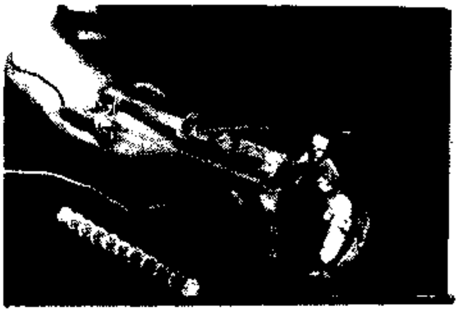

Figure 4 - The LADD can be used to control hand closure in an orthotic splint.

III. KINEMATICS AND STATICS OF THE LADD ACTUATOR

The following characteristics of the LADD actuator will be discussed.

1. Angular rotation versus linear contraction.
2. Applied torque versus contraction force.
3. Applied force and torque versus link load and hoop stress.
4. Actuator compliance which results from elasticity of the links.
5. Stability versus cell aspect ratio.

1. Angular Rotation of the Actuator Versus Linear Contraction

Figure 1 illustrates the simple geometry of the device. Equation 1 describes the deflection versus input rotation for a LADD with zero length hoops assumed.

$$C = 1 - \frac{\ell}{L}, \quad \frac{\ell}{L} = \sqrt{1 - \left(\frac{1}{\mu}\right)^2 \sin^2\left(\frac{\theta}{2n}\right)} \qquad (1)$$

C is the percent contraction and μ is the cell aspect ratio (L/D). n is the number of cells in the chain and θ is the total rotational input. For the case with unity cell aspect ratio, Equation 1 simplifies as shown below:

$$C = 1 - \cos\left(\frac{\theta}{2n}\right) \qquad (2)$$

2. Applied Torque Versus Contraction Force

The overall force (F) vs. torque (M) relationship is defined by Equation 3.

$$\frac{FD}{m} = \frac{4\mu\ell}{L \sin\left(\frac{\theta}{n}\right)} \qquad (3)$$

3. Applied Force and Torque Versus Link Load and Hoop Stress

The tensile load (P) carried by the links is shown by Equation 4.

$$\frac{Pm}{F} = \frac{L}{\ell} \qquad (4)$$

m is the number of links around the hoop.

Equation 5 shows the compresive hoop stress (s) carried by a thin walled hoop with links evenly and densely attached (5).

$$\frac{swt}{F} = \frac{L}{2\ell\mu} \sin^2 \left(\frac{\theta}{2n}\right) \qquad (5)$$

4. Actuator Compliance Versus Link Elasticity

In practice the elasticity of the fiber links causes the entire LADD to exhibit elastic behavior. Due to the geometry of the LADD actuator, the compliance is dependent upon the particular position of the LADD. Consideration of the compliance is important to many applications since it effects positional accuracy and dynamic performance. The following equation gives the effective linearized compliance of a single LADD cell. The complete nonlinear expression is considerably more complicated and will not be given here.

$$\text{Compliance} = \frac{\delta}{F} = \frac{L}{mAE} \left(\frac{L}{\ell}\right)^2$$

δ is the deflection of the LADD under load F. "A" is the cross-sectional area of the links and "E" is the modulus of elasticity of the link material. Note that for zero input rotation compliance of the LADD is just that of the links. As the cell contracts, the compliance increases.

5. Stability Versus Cell Aspect Ratio

As a LADD is twisted it contracts. For aspect ratios greater than one, it is possible for cell to become unstable when a certain input rotation is achieved--that is as θ increases, the torque ceases to increase and in fact begins to decrease. If the length of the links is larger than the diameter of the hoops in the LADD, then an instability will occur if the input rotation exceeds a certain amount. For that reason, most LADD's used to date have had a cell aspect ratio smaller than unity.

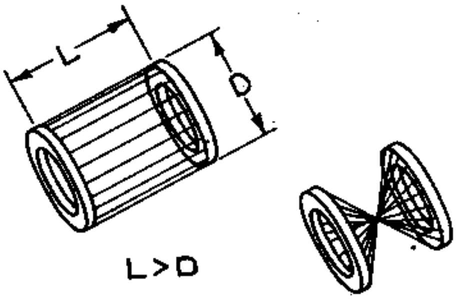

Figure 5 - If the cell aspect ratio is greater than one, a LADD cell may exhibit unstable contraction characteristics.

IV. PERFORMANCE OF THE LADD ACTUATOR

A number of tests have been conducted to establish the ultimate strength characteristics of the LADD actuator and its potential fatigue life. In conjunction with these tests, a variety of materials and manufacturing techniques have been investigated. As expected, materials and manufacturing techniques are critical importance to high performance of the LADD actuators.

1. Ultimate Strength

A nine-sixteenth inch outer diameter LADD actuator fabricated of Kevlar® can support in excess of 850 pounds with zero input rotation. If the LADD is contracted approximately 20 percent, its ultimate strength will be approximately 450 pounds. A typical test LADD for this situation is eight inches long, produces an excursion of about two inches, and weighs less than six grams.

2. Fatigue Performance

Fatigue tests have also been conducted on LADD's with a variety of materials and fabrication techniques. For example, a nine-sixteenth inch outer diameter LADD with an undeflected length of eight inches has performed in excess of 6,000,000 cycles. The particular tests involve cyclically pulling a 50 pound load through a two inch excursion at a rate of three cycles per second.

In various tests, LADD's exhibit both plastic and fatigue type failures. Failures occur in the hoops, in the links, and at the points where the hoops attach to the links depending on the particular loading situation.

V. CONFIGURATIONS FOR THE LADD ACTUATOR

As with other mechanical devices, LADD's can be utilized in a variety of compound configurations. The simplest configurations of LADD involve its actuation against a load which causes its own return (against a spring). Figure 6 illustrates that configuration.

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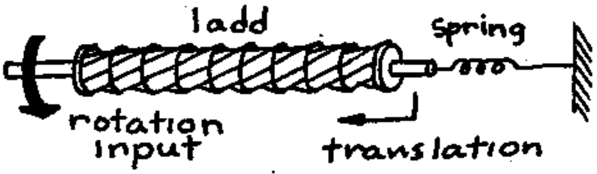

Figure 6 - LADD pulls against spring to convert rotary input to a linear displacement.

LADD's can also be used as antagonist pairs for double acting actuation. Figure 7 illustrates that configuration schematically. Note that the antagonist LADD's are driven in unison from one end and at the other end terminate about a nonlinear pulley. This configuration permits the design of various position dependent reduction ratios. The nonlinear pulley configuration is used for elbow flexion of the "Utah Arm." Figure 3 shows a photograph of two concentric LADD's acting over a nonlinear pulley.

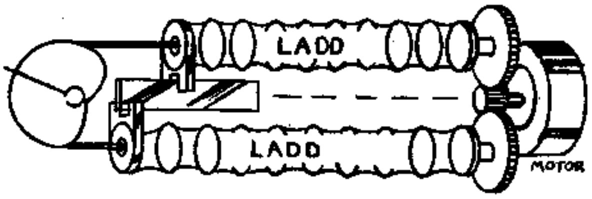

Figure 7 - LADD's operate as antagonist pairs over nonlinear pulley.

LADD's can also be used in a variety of other compound configurations. Figure 8 shows the LADD's in the concentric and cascaded configuration. These configurations have the advantage that they increase the strength while decreasing the length of the actuator assembly.

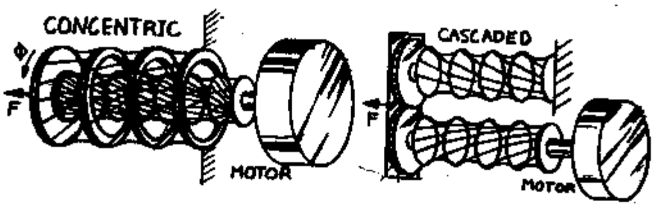

Figure 8 - The LADD actuator may be used in various compound configurations such as the concentric and cascaded form.

VI. CONCLUSIONS

The stringent requirements for actuation of various prosthetic limbs have caused many devices to meet with various degrees of failure. The LADD overcomes some of the previous difficulties because of its very desirable performance characteristics. The LADD is lightweight, strong, quiet, inexpensive, greaseless, and efficient. The simplicity of the LADD actuator makes it an ideal candidate for prosthetic and many other applications.

VII. ACKNOWLEDGMENTS

The efforts described in this paper have been accomplished at the University of Utah in collaboration with the Liberty Mutual Research Center at Hopkinton, Massachusetts. The project has been supported in part by the National Science Foundation and Mr. Maurice Warshaw of Salt Lake City, Utah. Thanks is also extended to Dr. Willem Kolff who is the Director of the Division of Artificial Organs at the University of Utah.

VIII. REFERENCES

(1) Jacobsen, S.C., Jerard, R.B., and Knutti, D., "Preliminary Report on the Utah Arm," Conference on Engineering Devices in Rehabilitation, Boston, Massachusetts, May 1974.

(2) Carruth, J.C., "Operations Characteristics of the LADD Actuator," M.S. Thesis, University of Utah, May 1975.

(3) Jacobsen, S.C., and Jerard, R.B., "Torsion of Rope-Connected Hoops Leads to Light Weight Prosthetic Actuator," 26th ACEMB, September 1973.

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(5) Albano, E.D., and Seide, P., "Bifurcation of Rings Under Concentrated Centrally Directed Loads," Journal of Applied Mechanics, Vol. 40, No. 2, Trans. ASME, Vol. 95, Series E, June 1973, p. 553.

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