TECHNICAL FORUM

Efficiency of Prosthetic Cable and Housing

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ABSTRACT

Research was conducted on the efficiency of cable and housing systems for body-powered, upper-limb prostheses. The tension required to actuate prosthetic components was found to grow exponentially with the product of the friction coefficient between the cable and housing and the total angle through which the cable bent. Values of the friction coefficients of various cable and housing material combinations were tabulated. The efficiency of the system can be calculated by knowing the cable and housing material and estimating the total angle of bend between the harness and prehensor. A sample calculation is provided.

Introduction

Body-powered, upper-limb prostheses are actuated by relative body motion that generates tension in a cable. The cable is routed from a shoulder harness through a helically coiled housing to a prosthetic component such as a prehensor or elbow. However, friction between the prosthetic cable and its housing reduces the amount of force available to the prosthetic component. To compensate, amputees must generate more tension in their harnesses, which can result in discomfort and, eventually, musculoskeletal disorders. Inefficiencies in cable and housing systems, therefore, must be well understood by prosthetists.

Some researchers have investigated means of reducing the coefficient of friction in cable and housing systems (1,2). LeBlanc (3) measured the efficiencies of two types of cable in three types of cable housings (3). He showed that efficiency depends upon the angle of wrap and the types of cable and housing used. However, to the authors' knowledge, no research adequately *models* the effect of the friction coefficient and other variables on frictional losses in upper-limb prostheses. This paper proposes and experimentally verifies such a model. Variables investigated include the type of cable and cable housing used, the angle through which the cable bends, the radius of the bend and the amount of tension in the cable.

Methodology

When an amputee actuates a body-powered prehensor or elbow, he or she generates tension in a prosthetic cable. Wherever the route of the cable bends, the cable is forced against the wall of the housing, and frictional forces arise. According to Coulomb's classic model,

$$F_f = \mu N$$

where F_f is the frictional force, N is the normal force between two bodies and μ is the friction coefficient.

The value of the friction coefficient varies according to the surface condition and material composition of the cable and housing; it also varies according to whether the two surfaces are stationary (static friction) or sliding (kinetic friction). To actuate a prosthesis, the cable must slide within the housing. Therefore, only kinetic friction is considered in this paper. It should be noted, however, that the coefficient of static friction is typically higher than the coefficient of kinetic friction. Therefore, *initiation* of cable motion may require higher forces than subsequent actuation of a prosthetic component.

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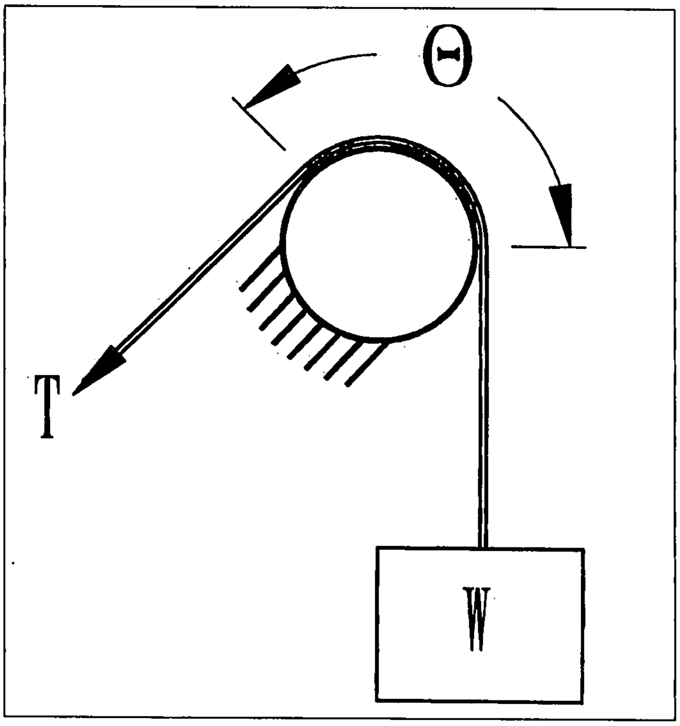

Figure 1. **A weight lifted by a cable and routed over a stationary object.**

The interaction between a prosthetic cable and its housing at a bend is similar to a rope routed over a stationary cylinder (not a pulley). If a weight is lifted by a rope that wraps a given angle around a stationary cylinder (see *Figure 1*), the amount of tension required to lift the weight is given by

$$T = We^{\mu\Theta}$$

where T is the tension needed to lift the weight at a constant velocity, W is the weight of the object being lifted, μ is the coefficient of kinetic friction between the rope and mandrel, and Θ is the wrap angle measured in radians (4).

The authors propose this equation accurately models the behavior of the cable and housing system in body-powered, upper-limb prostheses.

Test Methodology

Figure 2 depicts the apparatus used to measure the efficiency of various cable and housing configurations. Prosthetic cable was routed through cable housing over a stationary cylindrical mandrel. To simulate the tension required to actuate a prosthesis, a weight was suspended from one end of the cable. A winch was used to create an input tension, lifting the weight at a constant speed. A load cell in series with the cable between the winch and the mandrel measured the input cable tension. This apparatus was used in a series of experiments exploring the behavior of prosthetic cable and housing systems. The effects of different variables were measured by changing one while keeping others constant.

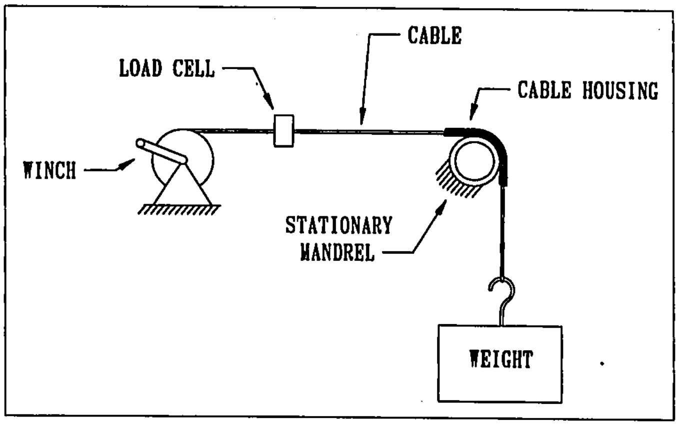

Figure 2. **The cable efficiency test apparatus.**

First, different combinations of cable materials and housings were tested to evaluate and compare their coefficients of friction. Steel[a], Spectron 12[b], nylon and Dacron cables were tested in combination with helically coiled steel housing with and without Teflon lining[c]. All tests were performed with a 23.7-lb weight, a mandrel diameter of 1.91 inches and a wrap angle of 100 degrees.

The wrap angle was varied from 0 to 180 degrees in 30-degree increments to evaluate its effect on efficiency. Steel cable in unlined housing was used to lift a 23.7-lb load in each test. The effect of bend radius on the frictional losses was investigated by repeating the tests with mandrels of varying diameters (0.85, 1.32, 1.91 and 2.39 inches).

Finally, the effect of the load amount on the performance of cable and housing systems was investigated. The weight at the end of the cable was varied from 15 to 65 lbs in 10-lb increments. Steel cable in unlined housing was wrapped 100 degrees around a 1.91-inch mandrel for each test.

Results and Discussion

Table 1 lists the coefficients of friction for various cable materials and housings. The data show that switching from steel cable in unlined housing to steel cable in Teflon-lined housing reduces the coefficient of friction by nearly 40 percent. If higher efficiency is desired or required, switching from a steel cable to a low-friction polymer cable, such as Spectron 12, reduces the coefficient by an additional 40 percent. How such a reduction in the friction coefficient affects the prosthesis' performance depends on the cable routing.

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[a] 1/16-inch C-100 cable, Hosmer Dorrance Corp., 561 Division St., Campbell, CA 95008.

[b] Spectron 12 is the trade name of cable and rope products manufactured by Samson Ocean Systems Inc., Ferndale, Wash.

[c] Catalog #50455 (unlined) and #50456 (used with Teflon liner #50482), Hosmer Dorrance Corp., 561 Division St., Campbell, CA 95008.

		CABLE			
		steel	Spectron 12	nylon	Dacron
HOUSING	no lining	0.150	0.120	0.102	0.165
	Teflon lining	0.092	0.055	0.052	0.124

Table 1. **Coefficients of friction for various cable materials and cable housings.**

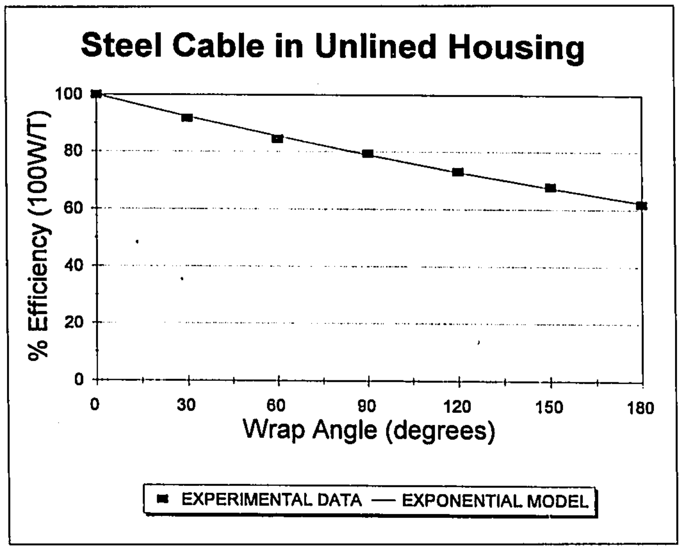

Figure 3. **Efficiency of steel cable in unlined housing.**

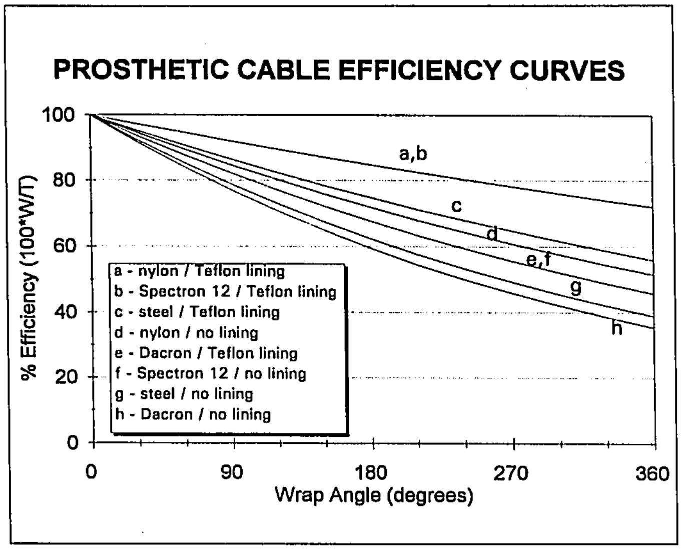

Figure 4. **Efficiency of various combinations of prosthetic cable materials and housings.**

Cable efficiency is defined as the ratio of tension at the prehensor or elbow compared to tension developed at the harness (*W/T*). The efficiency of steel cable in unlined steel housing is plotted against the wrap angle in *Figure 3.* Close agreement between the data and theory (r^2=0.998) suggests that the exponential equation above is an accurate model of the behavior.

Using the friction coefficients of *Table 1* and the exponential equation, the efficiencies of various cable and housing combinations were calculated and plotted (see *Figure 4*). The figure shows the difference between the materials is more pronounced at greater wrap angles. With a 30-degree wrap angle, the lowest friction combination (Spectron or nylon cable in Teflon-lined housing) was only 5 percent more efficient than a high-friction combination (steel cable in unlined housing). With a 180-degree wrap angle, the low-friction system is 23 percent more efficient than the high-friction system. This finding is significant because as cable routing becomes more sinuous, low-friction cable and housing becomes more important.

This experiment also found that cable efficiency is not significantly affected by either bend radius or magnitude of the cable tension. The smallest bend radius tested was 0.425 inches. It is likely that smaller bend radii could adversely affect efficiency, especially if stiff steel cable is used. Also, for Spectron 12 cable, the coefficient of friction drops as pressure is elevated between the cable and mating surface. Under high tension, therefore, the actual efficiency of Spectron 12 is somewhat higher than predicted using data presented here. This phenomenon also causes knots in Spectron 12 to pull free unless special precautions are taken (2).

Sample Calculation

To illustrate how this information can be used in a clinical setting, the following sample calculation is provided. Imagine that a unilateral, transradial amputee is considering adding a Teflon liner to his or her housing. In the body position representing a worst-case scenario, the cable bends 30 degrees at the shoulder and 160 degrees at the elbow. The total wrap is 190 degrees (the sum of the bend angles). If 1/16-inch steel cable and unlined steel housing are used, the efficiency of the system (from curve "g" in *Figure 5*) is 61 percent.

If a Hosmer/Dorrance 88X hook with three standard prosthetic bands is used, approximately 12 lbs will be required to fully open the prehensor. The tension required at the harness is determined by dividing the tension at the prehensor by the efficiency. In this case, about 20 lbs of tension is required at the harness.

With the addition of a Teflon liner, the efficiency of the cable and housing system is increased to 74 percent (from curve "c" in *Figure 5*). The corresponding force required at the harness is about 16 lbs. In this case, the addition of a Teflon liner will reduce the load on the harness by 4 lbs (or about 20 percent) each time the hook is opened.

Conclusion

A simple formula derived from Coulomb's classic theory of friction proves to be an adequate model of the inefficiencies of prosthetic cable and housing systems. Experiments have shown frictional losses primarily depend upon the material composition of the cable and housing and the total angle through which the cable bends. Given the exponential formula and the values of the coefficient of friction in *Table 1*, the performance of upper-limb prostheses can be estimated. ☐

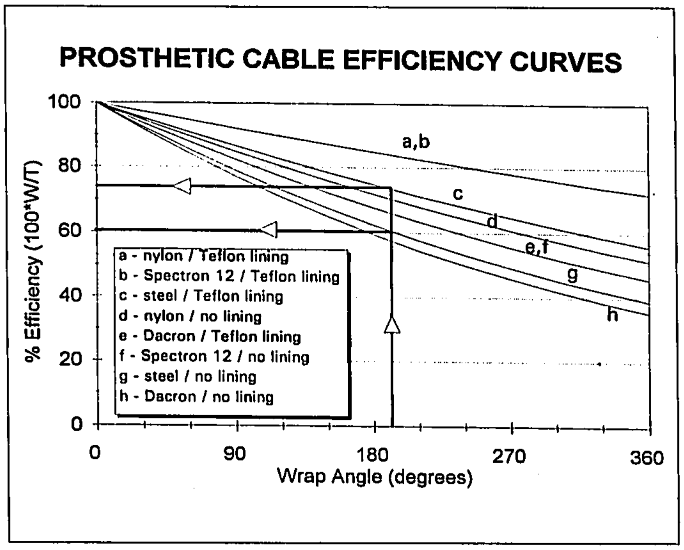

Figure 5. **Use of the efficiency curves in a sample calculation.**

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