Nylon vs. Control Cable Fricton

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Sliding friction, with its consequent loss of efficiency and resultant wear of components, has long been a serious problem for prosthetic teams in their attempts to restore a measure of function to amputees. This has been especially true in the field of upper extremity prosthetics, where the complex functional requirements impose a heavy burden on limited physical resources. Upper extremity control cables have given trouble in various ways for many years. A search through patents related to the science of upper extremity prosthetics revealed many early attempts to cope with the relatively long sliding motions required for elbow flexion and terminal device operation. For instance, Thomas Uren[1] discloses an ingenious arrangement of catgut and rollers for easy flexion of the elbow of an AE arm. A somewhat different arrangement of leather thong and rollers is used in an Irish arm of uncertain but venerable vintage in the museum of the Engineering Artificial Limbs project. This arm was a gift by Chester C. Haddan, of Denver, Colo., and bears the inscription "P. K. Arm L'td., Belfast, No. 2;" it is believed that the wrist and elbow mechanisms were patented during the nineteenth century. Additional examples may be found in Marks[2]; all serve to give the background of the problem.

The early work cited seems to have been largely based on empiricism. It seems that the first analytical approach to the problem might have been made by the Northrop Artificial Arm and Leg Research and Development project as reported by Motis[3]. Here we read on page 92, ". . . Much of the general use and acceptance of an arm by an amputee is dependent upon the efficiency and reliability of the control system power transmission. The majority of the early systems of power transmission used leather thongs or gut cords operating through leather or metal guides and reaction points to transmit the power. Generally, devices using this means of power transmission had a very short service life and a great amount of re-adjustment was necessary to compensate for the stretching or deformation of the flexible transmission system. Friction losses were very high and reduced the efficiency of the over-all control so much that the amputee lost power which should have been available to operate the hand or hook. Average efficiency approximated 25%, measured around a fully flexed elbow in the case of an above-elbow arm which meant that 10 pounds of pull applied at the shoulder harness resulted in a 2½ pound load to open or close the hand or hook. This did not prevent the amputee from operating his device, but meant merely that he lost so much power that the arm accomplished no more for him than could be done by a unilateral who depended solely upon his good arm to do his work."

This Northrop study resulted in the application of flexible steel cable of the aircraft type to prosthetic controls. Further study developed the flexible steel housing to give reaction points and fairing around bends in the cable path. Although no specific data are given by Motis, a minimum satisfactory efficiency of 50% is specified in the section on tests of

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AE arms in the Manual[4]. From this figure and the figure given by Motis it appears that a relative gain of 100% in control system efficiency was made by use of steel cable. Further gains were realized in elimination of stretch and increase of transmission life.

With resumption of basic research into upper extremity prosthetic problems at the close of the School for Upper Extremity Prosthetics in February, 1955, one of the subjects looked into was that of the short above-elbow prosthesis. It appeared that the 50% efficiency figure would need to be increased if amputees using these prostheses were to be given useful control forces. Previous attempts to use nylon cable and nylon-coated steel cable had not been satisfactory because of cable stretch and excessive wear; however, experience by the author with nylon bushings in small mechanisms indicated that the right grade of nylon or teflon in the form of a tubular lining for a steel housing might give satisfactory service in the present application. It was hoped that the steel housing would support a rather thin tube and retain the advantages of the steel housing with additional advantages due to the resiliency and good frictional characteristics of the nylon. This hope was largely realized by results.

The Mechanical Theory

Before discussing these results it is necessary to give the mechanical theory on which they are based. The principal factor is belt friction, commonly used in power transmission belts and pulleys, winches, capstans, and related applications in machinery. For these applications it is desirable that friction be as large as possible to minimize slipping. In an ideal mechanism belt friction depends on the coefficient of friction, u, and the angle of wrap-around o, as commonly expressed in texts of Engineering Mechanics by the following equation:

$$Fo = Fi\,e^{uo} \qquad (1)$$

where, Fo is the force being acted against, Fi is the force acting, e is the base of the system of natural logarithms, and the exponents are the terms already described.

The force acted against in most machine applications would be a load due to such a factor as work being done in a machine tool or tide pull on a ship; from the nature of the exponential relationship given in eq. (1) it is apparent that both u and o should be made large for those applications.

Prosthetic applications, in contrast with most other machine applications, require that the ratio between Fo and Fi be as nearly unity as possible. From eq. (1) it appears that this could only be achieved by making either u or o be equal to zero. Since the angle of wrap-around is fixed by the realities of prosthetic practice, the coefficient of friction is the only variable left open for investigation. If o be arbitrarily fixed at two radians, (115°), u be selected as 0.35, (a reasonable value for semi-lubricated steel surfaces), and eq. (1) be solved for efficiency the following equations result:

$$E = \frac{F_i}{F_o} = \frac{1}{e^{\mu\theta}} = \frac{1}{e^{(2)(0.35)}} = 0.502 \qquad (2)$$

$$E(\%) = 50.2\% \qquad (3)$$

In these solutions, Fi has been considered due to terminal device or lift loading, while Fo has been considered as the necessary muscle force. If, now, the value of u be reduced to 0.10, (a conservative value for nylon or teflon against dry steel), eq. (2) becomes

$$E = \frac{1}{e^{(2)(0.10)}} = 0.826 \qquad (4)$$

$$E(\%) = 82.6\% \qquad (5)$$

By comparison between eqs. (3) and (5) it can be seen that a relatively small reduction in the value of u yields a relatively large increase of efficiency.

Computations of the previous section were based on simplified theory which ignored compliance of the nylon tubing due to surface loading, as well as deformation of the tubing due to flexure. As a check on the validity of the procedure a test was run in two parts: the first part consisted of efficiency measurement on a typical AE prosthesis transmission with steel cable housing, while in the second part the same cable and housing were used, with a commercially available nylon tubing added between cable and housing. Both cable and housing were degreased with carbon tetrachloride for the second part. At 115° flexion the efficiences were 54% and 86% for steel housing and nylon lining, respectively, with a six pound load at the hook thumb. These figures indicate that addition of the nylon liner gives a relative increase of efficiency of 59% as shown by the following:

$$I = \frac{86-54}{54}(100) = 59\% \qquad (6)$$

This result agrees closely with theory; details of the method of application, size of tubing used, and source of tubing are given in the Manual of Upper Extremity Prosthetics, second edition.[5]

Results of amputee trials of this system have been generally favorable, with the exception of a very few bilaterial amputees who give cables extra hard use. The nylon liner has not given trouble itself, but the small (3/64) diameter cable has been broken a few times. Currently available housing does not leave room for a liner around the larger cable, although a suitable nylon tubing is available. Possibly one of the cable manufacturers will develop a heavy duty system.

Fortunately for the majority of amputees, the hard users comprise a small minority; for instance, of over 100 amputees fitted, six or seven have accounted for 9/10 of the broken cables. On the credit side of the ledger is the experience of the remaining 100, who are being benefitted by increased efficiency and decreased wear. From the standpoint of wear, cable replacements for all amputees in the group have been reduced from an average of more than one per month to less than one in ten months. An additional benefit comes from the smoother action possible when the steel housing is nylon-lined; BE amputees using biceps cineplasty are especially enthusiastic concerning the finer grading of prehension they can achieve with both voluntary-opening and voluntary-closing terminal devices.

From the foregoing it seems apparent that all UE amputees can benefit from universal application of this simple procedure. Additionally, it would appear that this is another opportunity for the Prosthetics Profession to gain by increased amputee acceptance of UE prostheses, thereby filling more of the many empty coat sleeves, as well as giving improved user satisfaction through improved reliability and increased life of cable power transmissions.

REFERENCES

[1] United States Patent Office Letters Patents nos. 46,158, 46,159 and 48,000; January and May, 1865

[2] Marks, A. A., *Manual of Artificial Limbs*, New York, (1931)

[3] Motis, Gilbert M., *Final Report on Artificial Arm and Leg Research and Development, Northrop Aircraft* ,(1951)

[4] *Manual of Upper Extremity Prosthetics, Department of Engineering, University of California at Los Angeles*, (1952)

[5] *Manual of Upper Extremity Prosthetics, Second Edition*, Department of Engineering, University of California at Los Angeles, (in press)