THE LIFT LOCK: A DEVICE TO INCREASE THE LIFTING ABILITY OF DUAL-CONTROL PROSTHESES[a]

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INTRODUCTION

In spite of recent developments in powered prosthetic components, y far the majority of above-elbow prostheses in use today are cable perated through relative body motion. Of the various configurations, he dual-control system is probably the type of control system most requently fitted, at least in the United States. It has one major draw-ack, however; its live-lift capacity is severely limited because the pri-nary control cable tends to open the terminal device as well as flex the lbow. As a result, most unilateral amputees use their prostheses simply s a holding tool, rather than as an active lifting device, except for light bjects.

Several methods have been tried to circumvent this limitation of ual-control prostheses. The lift lock described in this paper has evolved s an apparently successful device which improves lifting capability ithout sacrificing the ease of operation inherent in dual control.

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DUAL CONTROL

A typical dual-control prosthesis has two control cables (Fig. 1, Pursley, 1955). The primary control cable attaches to the Figure-8 harness passes through a Bowden cable housing fixed to the rigid socket by the proximal retainer, then through a "lift tab" pivoting on the forearm, and finally attaches to a spring-loaded terminal device (either a hook, as shown, or a hand). A secondary control cable, on the front of the socket operates an alternating elbow lock in response to a combination of humeral extension, scapular abduction, and shoulder elevation. The primary cable, operated by humeral flexion and/or biscapular abduction, then produces either terminal device opening or elbow flexion depending on the state of the elbow lock (Table 1).

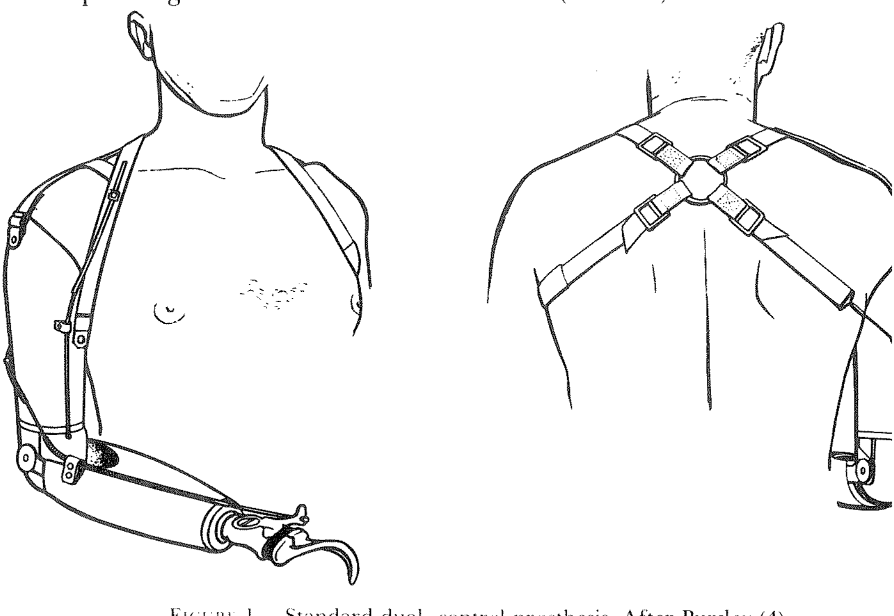

FIGURE 1.—Standard dual-control prosthesis. After Pursley (4).

TABLE 1.—*Dual-Control Operation*

Primary Control		Secondary Control		Prosthesis Operation
Humeral flexion and/or biscapular abduction	→	Elbow locked	→	Open terminal device
	→	Elbow unlocked	→	Flex elbow

The amount of cable tension required to hold a given angle of elbow lexion with the elbow unlocked may be determined with the help of igure 2. This is given by Equation (1), assuming lossless transmission of orce.

$$F_1 = \frac{Wl}{d} \tag{1}$$

vhere

F_1 = cable tension

W = total effective load at the terminal device

l = moment arm of weight

d = moment arm of cable force

The total load, W, can be represented as the sum of the weight of the orearm and the load being lifted:

$$W = W_{arm} + W_{load} \tag{2}$$

vhere

W_{arm} = equivalent weight of the forearm and terminal device effective at the terminal device

W_{load} = weight of load being lifted

In the dual-control system, the primary cable is usually connected to a oluntary opening terminal device, such as the hook shown in Figure 3. ssuming a lossless transmission, this tension (F_2) opposes the pinch orce generated by the elastic bands on the hook, reducing the gripping orce (F_3) as shown in Equation (3).

$$F_3 = F_{pinch} - \left(\frac{a}{b}\right) F_2 \tag{3}$$

vhere

F_3 = resultant gripping force

F_{pinch} = gripping force at the hook fingers due to elastic bands

$F_2 = F_1$ = cable tension

a,b = moment arms (Fig. 3)

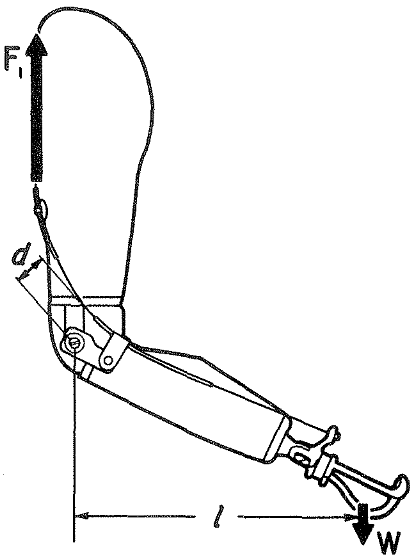

FIGURE 2.—Force relationships in a dual-control prosthesis. From Carlson (1).

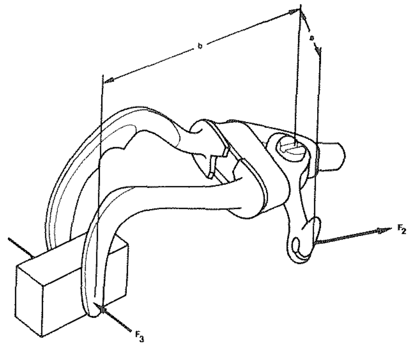

FIGURE 3.—Force relationships in a prosthetic hook.

Taking the worst orientation with respect to gravity (hook fingers vertical), the maximum load that the gripping force will hold is:

$$\left(W_{load}\right)_{max.} = 2\mu_1 F_3 \tag{4}$$

where μ_1 = coefficient of friction between hook fingers and object being lifted.

Combining these equations yields the maximum load that can be lifted with a dual-control system:

$$\left(W_{load}\right)_{max.} = \frac{2\mu_1[F_{pinch} - C\ W_{arm}]}{[1 + 2\mu_1 C]} \tag{5}$$

where

$$C = \frac{al}{bd} \text{ (geometric parameter)}$$

If, however, the primary cable is fastened directly to the forearm during elbow flexion (i.e., $F_2 = 0$), then the maximum load would be:

$$\left(W_{load}\right)_{max.} = 2\mu_1 F_{pinch} \tag{6}$$

The actual maximum load depends on the material being lifted, the number of elastic bands, and the particular configuration, but is instructive to compare the dual-control system with an ideal system in a typical situation. Taking a pinch force of 8 lb. (35.5 N) and representative values for the other parameters,[c] Equations (5) and (6) yield curves of maximum load lifted as a function of coefficient of friction, μ_1, as shown in Figure 4. These curves clearly demonstrate the limitation of the dual-control system and suggest that a mechanism which would disconnect the primary control cable from the terminal device during elbow flexion would significantly improve the lifting performance of the prosthesis.

PREVIOUS SOLUTIONS

The live-lift limitation of dual control has been recognized since the inception of this control principle, and there have been several attempts to rectify the problem.

Alternative Harness Patterns

Many harness patterns have been tried for above-elbow amputees, some of which do not utilize the same cable for elbow flexion and terminal device operation and therefore do not suffer from the problem under discussion. For example, the triple-control system (Pursley, 1955) had three cables: one for the elbow lock, one for elbow flexion, and one for terminal device operation. It was, however, more complex to fit and to operate and did not gain the wide acceptance in the U.S.A. accorded the dual-control principle.

Another control system which isolated the terminal device from elbow operation was the Navy Fitch arm (Northwestern Technological Institute, 1947). This system utilized humeral flexion to flex the elbow and biscapular abduction to open the terminal device independently. It did not, however, have an elbow lock, which is perhaps one reason it, too, did not achieve wide acceptance.

It would seem that the dual-control system is the product of 25 years of natural evolution; in spite of its limitations, it apparently has enough good qualities to make it acceptable both to patients and prosthetists. Therefore, further refinements of body-powered prostheses will probably incorporate the dual-control system.

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[c] $a = 1.6$ in., $b = 3.75$ in., $l = 13.5$ in., $d = 1.92$ in., $W_{arm} = 0.75$ lb.

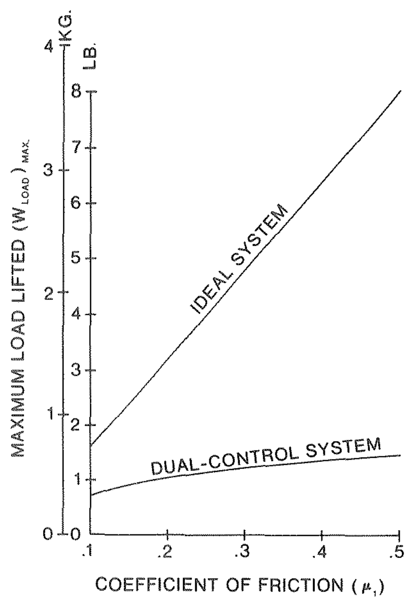

FIGURE 4.—Maximum load lifted as a function of coefficient of friction between the hook fingers and object.

Northrop Concept

One scheme was tried at Northrop Aircraft, Inc. (Motis, 1951), to improve the live lift of a dual-control prosthesis. This is illustrated in Figure 5. The primary control cable passed through a device in which a knurled cam wedged the cable during elbow flexion; when the elbow was locked the cam was automatically disengaged by a mechanism in the elbow. Therefore, during elbow flexion the cable tension was taken by the cable lock, preventing it from relaxing the hook's grasp.

The concept was sound but the device was never successfully applied, as far as is known. Undoubtedly, a main problem is the deleterious effect of the knurled cam on the cable. The cable used in prostheses consists of many fine stainless steel strands twisted together and then swaged to form a smooth cable. Squeezing the cable directly tends to separate the strands and to shorten the cable life drastically. It is probable that wedging the cable with a knurled cam would damage the cable excessively in a very short time.

The Northrop group also developed an elbow, the Norplex Model I, which completely separated the lift and hook operations when driven by the same control cable (Motis, 1951). However, the unit had several disadvantages in operation, was bulky, and was expensive to make. It was used only experimentally.

Capstan Principle

The lift lock was originally conceived as a pulley mounted on the forearm which could be locked or free to rotate. The locking mechanism would be coupled to the elbow lock in a complementary fashion; that is, when the elbow is unlocked the pulley is locked (elbow flexion), and when the elbow is locked the pulley rotates freely (terminal device operation). The primary control cable wraps around the pulley, as shown in Figure 6, so that when the pulley is locked it functions as a capstan. In that case, the ratio of the cable tensions above and below the pulley is given by:

$$\frac{F_1}{F_2} = e^{\mu_2\theta} \tag{7}$$

where

F_1 = cable tension above capstan

F_2 = cable tension below capstan

μ_2 = coefficient of friction between cable and capstan

θ = angle of wrap (rad)

For one wrap, Equation (7) predicts F_2 to be about ¼ F_1, reducing the tendency of the hook to open. Combining Equations (1), (2), (3), (4), and (7) yields the maximum load that can theoretically be lifted with the capstan locked (compare with Equation (5)):

$$(W_{load})_{max.} = \frac{2\mu_1\left(F_{pinch} - \frac{C\,W_{arm}}{e^{\mu_2\theta}}\right)}{1 + \frac{2C\mu_1}{e^{\mu_2\theta}}} \tag{8}$$

For the same conditions calculated earlier,[d] Equation (8) yields a curve that lies approximately midway between the two curves presented in Figure 4. Thus, the maximum load is about half of the theoretical maximum but still represents a threefold improvement. Another advantage of this system over conventional dual control is that the cable is

[d]In addition to the parameters used earlier, an experimentally determined coefficient of friction (μ_2 = .22) was assumed with one wrap of cable (θ = 2π).

always tangent to the pulley; therefore, the sharpest bend in the cable is the radius of the pulley. This has the effect of improving cable life and performance since sharper bends, such as can occur at the lift tab in extreme elbow flexion, decrease cable life (Spets, 1970) and increase cable drag.

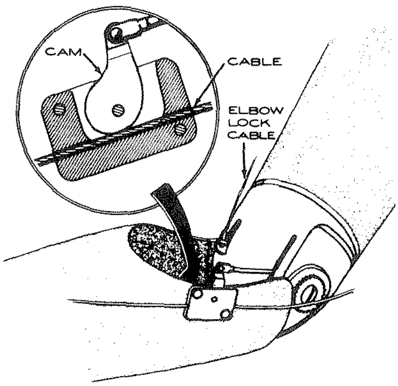

FIGURE 5.—Northrop cam lock. From Motis (2).

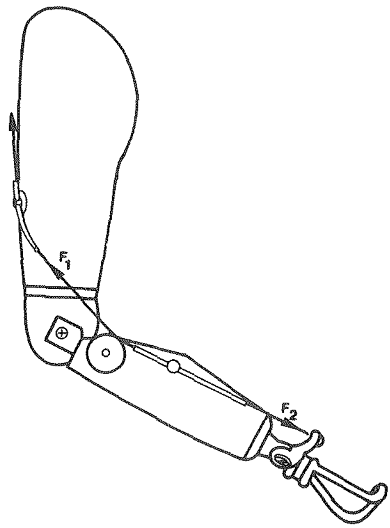

FIGURE 6.—Lift-lock capstan principle.

The first version of the lift lock was constructed in accordance with this concept. However, amputee evaluation showed it to be unsuccessful for two reasons. The primary reason was the Equation (7) is only valid when the cable is wrapped tightly on the capstan. Prosthesis cable is

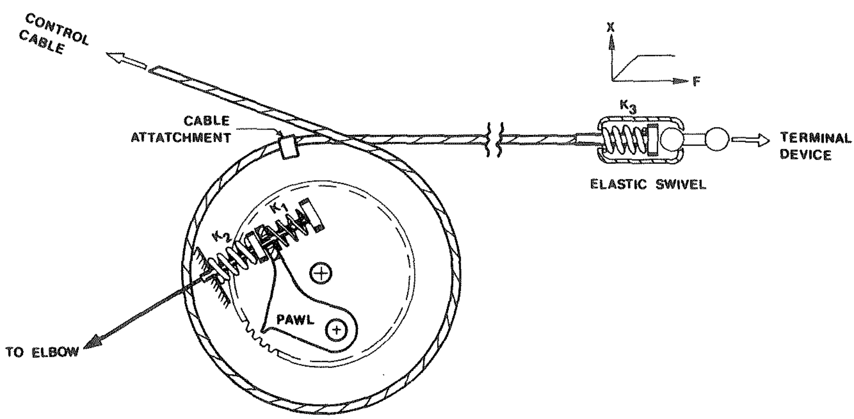

FIGURE 7.—Lift–lock schematic.

relatively stiff, however, and tends to straighten out in the absence of tension. Even though the pulley was enclosed, the cable would expand away from the pulley circumference prior to elbow flexion. When the amputee began to flex the arm to lift a heavy object, the terminal device would open slightly (about 1mm., or 0.04 in.) before the tension differential predicted by Equation (7) would develop, and the object would be dropped.

A secondary reason was the limitation of the maximum live lift of half of its theoretical value. It was felt that this compromise was unnecessary; therefore, methods were explored to lock the cable rigidly to the forearm so that the cable tension at the terminal device (F_2) would always be zero during elbow flexion.

Final Design

A schematic drawing of the final design (Fig. 7) shows the essential elements of the lift lock mechanism. The primary control cable is wrapped around a 1-in. diameter (2.54 cm.), freely-rotating pulley. A small U-shaped piece, silver soldered to the cable, engages a notch in the pulley, providing a positive mechanical connection.

A small cable connected to the locking bar of the Hosmer[e] E-400 elbow causes a pawl to engage an internal gear recessed into the pulley to lock the pulley when the elbow is unlocked. When engaged, the pawl is self-locking due to its pivot location. A return spring (K_2) disengages the pawl upon locking the elbow for terminal device operation.

Rather than actuating the pawl directly, the cable from the elbow acts through a light spring ($K_1 << K_2$). This insures that the cable is relatively free even if the pawl should fall on top of a tooth. In the event that the pawl tooth is not precisely lined up with a tooth space, the pulley must rotate until the tooth engages. In the worst case, the pulley will rotate approximately 5 deg. before locking, pulling the cable at most 0.04 in. (1.1 mm.). To prevent this displacement from reaching the terminal device, an "elastic swivel" is used in place of the conventional swivel terminal assembly. A spring (k_3) allows the cable to displace 0.1 in. (2.5 mm.), enough to allow the pawl to engage without opening the terminal device. This movement is small enough not be felt by the amputee when operating the terminal device.

As far as the amputee is concerned, the lift lock functions essentially automatically. The only alteration to his established control pattern is that after lifting an object and locking the elbow, he must relax the

[e] Hosmer/Dorrance Corporation, P. O. Box 37, Campbell, California 95008.

primary control cable prior to opening the terminal device. This unloads the pawl so that the return spring can disengage it, allowing the pulley to rotate freely.

RESULTS OF PATIENT FITTING

One lift-lock mechanism has been fitted to an above-elbow amputee. This 29-year-old male amputee had used a dual-control above-elbow prosthesis for 8 years and was an excellent user of this prosthesis. He generally likes the result provided by the lift lock although he states that it will take time to become accustomed to having increased live-lift capability. He does notice that the cable must be relaxed slightly more than usual after locking the elbow in order to permit the pawl to release. He felt that he would adjust to this with daily use. Otherwise the operation of the arm was no different from his earlier, conventional prosthesis.

Figure 8 shows a lateral view of the lift-lock mechanism as it appears during actual use by an above-elbow amputee who has the limb extended. Figure 9 is a similar view with the limb flexed. Figure 10 shows a frontal view of the arm and mechanism. The mechanism does protrude laterally and this may tend to wear out sleeves which cover it. It may be covered with leather to lessen this problem.

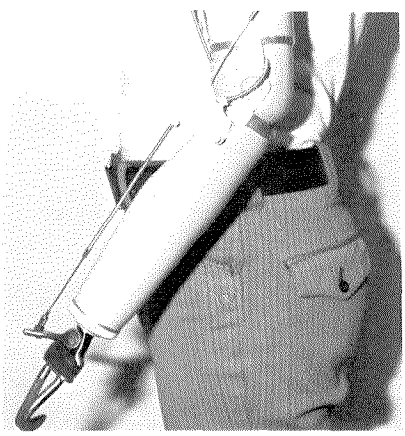

FIGURE 8.—Lateral view of the lift lock on a prosthesis—elbow extended.

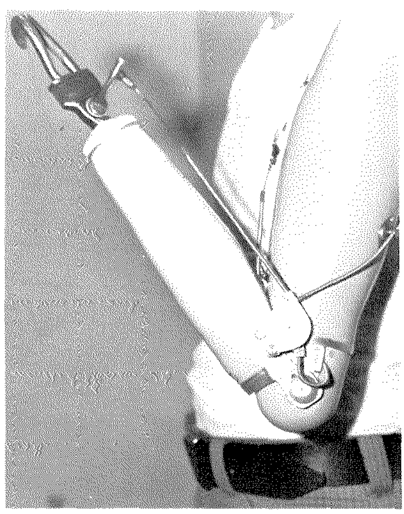

FIGURE 9.—Lateral view of the lift lock on a prosthesis—elbow flexed.

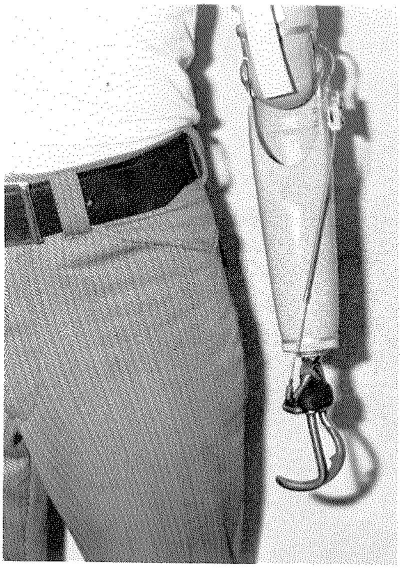

FIGURE 10.—Frontal view of the lift lock.

SUMMARY

Preliminary results obtained from limited use by one amputee along with previous laboratory trials on other amputees indicate that the lift-lock principle can improve the operation of above-elbow prostheses which are body powered. A wider evaluation will be necessary to determine its full worth.

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