AN APPROACH TO POWERED GRASP

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Summary

The concept of synergetic prehension in the electromechanical design of a grasping mechanism is introduced along with the myoelectric control principle of myo-pulse modulation. Preliminary clinical results with these concepts are discussed and analyzed.

Introduction

In the near future powered grasping mechanisms should quietly find acceptance in the prosthetic field alongside their body-powered predecessors. Hopefully, the two types of mechanisms will be complementary and expand the range of fitting possibilities available to prosthetic practitioners.

These grasping mechanisms are required on practically all upper-limb prostheses and this commonality suggests that their design should be given considerable emphasis in prosthetics. This importance also applies, perhaps to a lesser degree, with respect to upper-limb orthotic components and with manipulators.

The grasping mechanism is important of itself but the controller which interfaces the human to the mechanism may be of equal importance. This paper therefore presents not only an electromechanical approach to the design of a powered hook or hand mechanism but looks into the design of a myoelectric controller as well.

Synergetic Prehension

Bottomley /1/ and McLaurin /3/, among others, have pointed out that in most cases real work is not required during grasping. When most objects are grasped a force is exerted with very little excursion while excursion of the grasping fingers usually occurs in space and requires very little force. Consequently, the work involved in both of these conditions is minimal. This means that, theoretically at least, it should be possible to construct a powered grasping mechanism which would meet the functional requirements of speed and pinch force while requiring very little energy to operate.

One obvious way to accomplish this is through changing the gear reduction ratio at the appropriate time. Therefore, for free excursion of the grasping finger a small gear reduction ratio might achieve an adequate finger excursion rate but insufficient grasping force. If the gear reduction ratio could be greatly increased at the appropriate moment when force without excursion is needed, it should be possible to achieve adequate grasping performance with the same small drive motor. Indeed, this principle was apparently employed many years ago in the Vaduz hand. The modern Otto Bock electric hand mechanism employs this principle very effectively today. Bottomley /1/ has even suggested a continuous gear reduction change as perhaps being more desirable than the simple two-stage reduction. With proper continuous reduction the electric motor drive could be made to always operate at maximum output power or at maximum efficiency. Gear shifting thus appears very attractive in the design of grasping mechanisms. It is, of course, a concept widely used in other powered machinery and vehicles of conveyance.

The two-step gear reduction scheme is of interest here. Figure 1 shows the speed torque relationship for two permanent magnet motors and three gear reducers. No-load speed ω_o and stall torque T_o may be achieved by a single reducer and motor having the characteristic shown by line "A" or by using a smaller motor

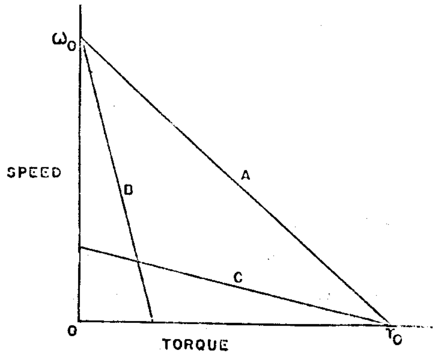

Fig. 1. Line A is the speed torque relationship for permanent magnet DC motor and gear reducer having no-load speed ω_o and stall torque T_o. B illustrates the relationship using a smaller motor and gear reducer which has a no-load speed of ω_o. In C the same smaller motor is used with a gear reducer which produces a stall torque of T_o.

and two gear reducers which give characteristics shown by lines "B" and "C".

An alternative to the gear-shifting approach is one which I have chosen to call synergetic activation or more specifically synergetic prehension, if the mechanism is used in prehension. Synergetic prehension is prehension which is produced by the combined effect of two or more actuators working together. In its simplest form for a prosthetis gripping device it consists of a motor and gear reducer which drive one finger to produce rapid excursion at low force and another motor and gear reducer which drive the opposing finger to produce high force with small excursion. Therefore, the two motors work in synergy much as muscles of the human body frequently do. This synergetic approach is illustrated in principle by Figure 2.

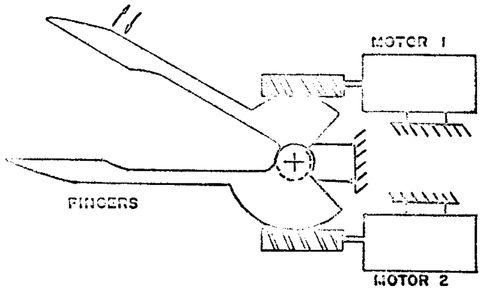

Fig. 2. Principle of synergetic prehension. Motor 1 drives one finger rapidly with low force capability. This drawing does not represent an actual design and is used only as a means for explaning the principle involved.

The first prototype of a prehension mechanism using the synergetic approach which has been tested by a patient is shown in Figure 3 and 4. The hook has detachable fingers (Sierra) and it is comparable in size to the APRL hook which has been frequently used by amputees in America. The maximum opening and closing speed of the "fast finger" in the prototype model is 4.5 rad/s and the pinch force is approximately 60N. Initial experience indicates that a greater pinch force on the order of 100 N may be desirable. The 4.5 rad/s maximum velocity was appreciated by the test patient. However, this velocity required proportional control by the patient to use it effectively. The maximum opening at the finger type is 120 mm.

The effective speed-torque relationship with synergetic prehension is shown in Figure 5. This characteristic assumes that the motor on the high-speed side stalls and becomes ineffective as a torque producer through the back-locking mechanism on its side. Therefore it is advantageous to turn this motor off as soon as it stalls in order to conserve energy.

Fig. 3. Above-elbow patient using prototype hook having synergetic prehension. Control is by myoelectric signals from the biceps and triceps.

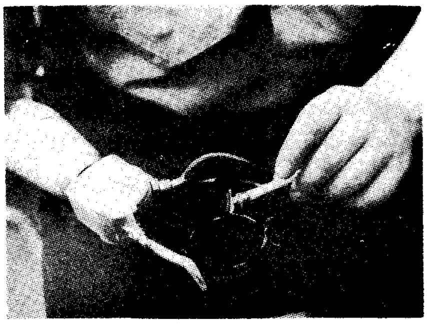

Fig. 4. Another view of patient using the prototype hook. This is to illustrate the wide angle of opening.

The slaw finger basically finctions as the stationary finger does on a body-powered hook, since its velocity is quite small with respect to the fast finger. Thus it can be used as a guide for positioning the hook prior to grasp. This stationary position of one finger has been thought to be of some advantage to the patient although simultaneous motion of both fingers has worked well on patients also.

The slow finger must be biased so that after repeated operations of the hook fingers it is still in or near its most extended position. Otherwise, the maximum angle of opening between the fingers may become too small. In other words, it is desirable for the fast finger to be able at all to make nearly its maximal opening excursion. This, of course, requires the force-producing finger to always remain near its fully extended position.

The fast finger should realise immediately upon command to open the fingers even when the pinch force is maximal. We have used an efficient spur-gear drive with a back-locking mechanism on the "fast" side and a lead-screw drive on the "slow" side. Back drive is not possible through the lead screw because of its small pitch angle. Many different combinations are, of course, possible, but some form of anti-backdrive characteristic is required on both sides with the overall system having the immediate-release characteristic.

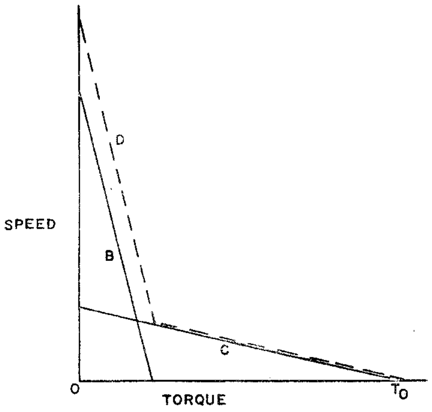

Fig. 5. Dashed line D shows the effective speed torque relationship when the two drive systems having characteristics B and C are used togetther.

The mechanism described has the advantage of not needing a gear-shifting mechanism. It has the disadvantage of requiring an extra motor and extra gear reducer. Whether its advantage compensate for the disadvantages will be told in due time. Its feasibility has been demonstrated.

Myo-Pulse Modulation

For the human operator to effectively control angular velocities which range from zero up to 4.5 rad/s in a prehension mechanism, it is necessary to have good proportional control. On-off control is practically useless for accurate positioning of the fingers when these relatively high angular velocities are employed.

Myoelectric control of prehension has been shown to be a clinically usable approach in prosthetics at several prosthetic centers, and it has seemed desirable to attempt to use the myoelectric signal to control the grasping mechanism already discussed. However, the proportional myoelectric controllers which have been available to our laboratory have been less than adequate for this application. So it has seemed important to investigate other myoelectrical control approaches.

Isidori and Nicolo /2/ introduced the idea of using the avarage of the time in which an amplified myoelectric signal was above a certain threshold level as an electrical signal-processing scheme. Their results indicated this processing approach to be advantageous and our experience of using this principle in patient fittings has been positive. Not only is the processing method rather good, but the scheme is extremely simple to realize electronically. Symbolically the function to be averaged, $\gamma(t)$, may be written as in the following equation:

$$\gamma(t) = \frac{V}{2}\left\{1 + \mathrm{Sgn}\ (|e(t)|-\delta)\right\}, \quad \delta > 0,$$

where: $|e(t)|$ is the absolute magnutide of the amplified myoelectric signal

δ is the threshold value

V is the power supply voltage.

Thus $\gamma(t)$ takes on the value V if the sign of $|e(t)|-\delta$ is positive and takes on the value zero if the sign is negative. Figure 6 shows in detail the relationship between $\gamma(t)$ and the amplified myoelectric signal, $e(t)$.

It has been conventional to smooth this signal ($\gamma(t)$) with an RC filter to generate the control signal. However, it was conjectured that the electrical smoothing could be circumvented entirely and that $\gamma(t)$ could be used to directly drive the output mechanism. Smoothing was to be accomplished in the mechanics of the mecahnism. Therefore, one way to solve the electrical smoothing problem seemed to be to do away with electrical smoothing altogether. The feasibility of this was discussed early on with Taylor /4/.

Clinical and laboratory trails indicate that using $\gamma(t)$ as a direct electrical drive is indeed a very suitable method of achieving near-proportional control. Subjective tests indicate a rather substantial improvement in the control of closing and opening speeds as compared with methods using conventional

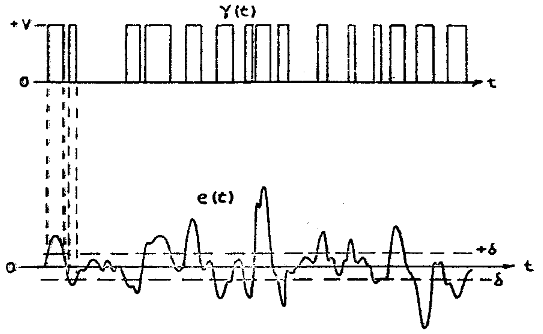

Fig. 6. The lower record represents a typical band-pass amplifier myoelectric signal, e(t). When |e(t)| exceeds δ the function γ(t) takes on the value V as illustrated in the upper record.

types of electrical smoothing. With feedback the prehension forces may be controlled within 2.25 N over a range from zero to 60 N.

Advantages of the myo-pulse modulation approach are:

1) Simple electronic implementation.
2) No electrical time-constant delay and consequently faster response.
3) Control signal already in pulse-modulation form.
4) Wide dynamic range of muscle control.

One method of simple implementation is shown in Figure 7. Many other variations are possible. The instant electrical output voltage to the motor in response to a myoelectric signal is illustrated in Figure 8. Thus, the dynamic response of the system is almost totally dependent upon the dynamic properties of the mechanical output device since electrical delays are essentially eliminated.

The control signal is of pulse form by its nature. Of course, the pulse width varies continuously but the average pulse width increases as the level of myoelectric signal increases. The pulse drive allows for efficient operations of the power transistors which power the motor even though the frequencies which predominate in the pulse drive are not high enough to minimaze total energy consumption.

The controller has a wide dynamic range. It is capable of driving the output mechanism with signal ranging from single motor unit activity all the way up to a maximal muscle contraction. This wide dynamic range is not altogether advantageous since it requires a moderately good myoelectric signal to be most effective. The pulse output is also never on 100 percent of the time no matter how strong the contraction. Nevertheless, these disadvantages seem to be outweighed by the advantages.

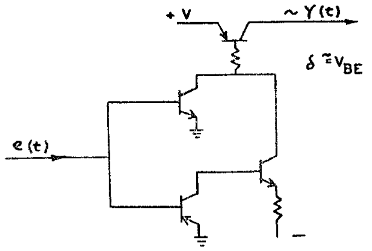

Fig. 7. One relatively simple electronic method for approximating $\gamma(t)$, given e(t). δ is determined by the base-to-emitter voltage V_{BE} of the two transistor at the input.

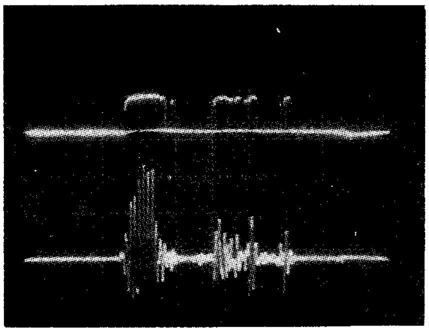

Fig. 8. The lower oscillographic trace is of an amplifier myoelectric signal. Vertical: 2V/cm; horizontal: 50 ms/cm. The upper trace shows the output voltage of the transistor driver. Vertical: 10V/cm; horizontal: 50 ms/cm.

Conclusion

The powered mecahnism presented is still in the prototype stage. Consequently, clinical feedback from this device is not yet forthcoming. The controller is presently in use by the Veterans Administration in the United States in many myoelectric hand prostheses for below-elbow amputees. Patients report being able to successfully eat potato chips with a hand powered by this controller. They like the excellent fine control and the preliminary conclusion is that myo-pulse modulation is a very effective control method. It is felt that when it is used in conjunction with the synergetic prehension that a very satisfactory approach to grasping will have been established.

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