External Power in Upper-Extremity Prosthetics and Orthotics

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After some twenty years of research and experimental fittings external power is being applied to upper-extremity prosthetics and orthotics in fairly large numbers, particularly in Russia and other parts of Europe. It is now becoming increasingly evident that in many applications powered devices have distinct advantages over conventional appliances, and it is the purpose of this brief paper to outline the characteristics of externally powered systems in the hope that it may help indicate where they may be used to advantage.

There are two fundamental differences in prosthetics and orthotics. Firstly, an orthotic device demands greater structural sophistication because it must lift and move the weight of the existing arm with all the joints and mechanisms external to the arm. The problem is somewhat eased in most cases since the device can be secured directly to a chair so that the weight is not critical. This is particularly significant with respect to the power supply. The second important difference is that in most prosthetic applications it is sufficient for the device to perform gross motions only since the fine positioning can be achieved by the remaining part of the body. For example, in the case of the bilateral shoulder-disarticulation amputee, the actual motions of writing are performed by the trunk to which the prosthesis is attached. Usually in an orthotic device the patient does not have this residual body motion and hence the fine positioning as well as the gross motions must be within the capacity of the orthosis. This suggests a highly responsive mechanical device and very difficult control problems.

Although there are many possibilities with respect to storage and conversion of energy the only practical solutions used to date, either experimentally or in service, are electrical systems and pneumatic systems. It is interesting to compare the characteristics of these two systems from a standpoint of energy storage, motors and controls. The commercial availability of nickle cadmium cells have made possible a reliable economical method for storing electricity. A pound of these cells can store 22,000 ft. lbs. of energy, enough to lift 1,000 lbs. to 22 feet. Unfortunately this isn't all available for use since the batteries should not be fully drained and since the motors and drive mechanisms usually have efficiencies of 50% or less. Thus if we use the batteries to one-third capacity we still have 15,000 ft. lbs. left, if the motor is only 50% efficient this is further reduced to 7,500 ft. lbs. and if the drive mechanism is only 50% efficient we are left with 3,700 ft. lbs. This is, however, a sizeable amount of energy to be carrying around in a pound pack. The cells can be recharged about 1,000 times and a service of a year or more is common. Other cells such as silver zinc have aproximately five times the energy storage per lb. but are not available in suitable sizes.

Other sources of electricity such as fuel cells although old in concept are still largely experimental and one cannot expect anything suitable for the prosthetic and orthotic field for many years to come. However, when better batteries are produced it is a very simple matter to connect them to any existing electrical system providing the voltage is suitable. Most systems used today require 12 volts. This was agreed to on two concurrent Panel Meetings of the Subcommittee on Design and Development of CPRD.* It is admittedly a compromise but does allow use of many types of commercial components.

In a typical pneumatic system carbon dioxide is stored in the liquid state in a high pressure cylinder which must meet rigid government specifications. The actual gas pressure available depends upon the temperature and is approximately 850 psi. at 70 degrees fahrenheit. According to Kiessling† at this temperature the theoretical energy available in a gram of carbon dioxide is 370 in. lbs. which is equivalent to 12,000 ft. lbs. per lb. However, since the container may weigh several times as much as the liquid contained therein and since energy is lost when the operating temperature is reduced to a safe level of 50 to 80 psi. the actual available energy is in the order of 2,000 ft. lbs. per lb. This is considerably less than the energy that can be stored in a 1 lb. battery pack and the re-charging process is much less convenient. Batteries can be recharged overnight with a small charger plugged into a household circuit. Carbon dioxide bottles can be re-filled from a larger container stored in the house or at most soda fountains or bars. Since there is considerable hazard in over-filling, some countries, such as Great Britain and Sweden, insist that bottles be refilled at a central station.

Other gases have been suggested, notably freon, which is used in aerosol cans. Freon contains less energy per lb. than carbon dioxide but since the pressure is low it can be stored safely in light weight containers. It is also more expensive than CO^2. From a standpoint of energy storage, batteries offer very definite advantages over CO^2 in terms of weight saving, convenience of recharging and safety.

One of the principle reasons for using compressed gas is the simplicity, light weight and high power of the motors or actuators. Although many of the original systems based on the Heidelberg pattern used a simple bellows, most systems use pistons for converting the gas into useful motion. The bellows are light in weight and can be easily fabricated using a rubber bladder contained in a fabric sack, but this is not durable, particularly in an industrial atmosphere, and can be used to exert a force in one direction only. Pistons can act in both directions and, with pressure on both ends of the piston, act as a lock. The McKibbon muscle (or braided pneumatic actuator) has received a lot of popularity because of its inherent simplicity but like the bellows is relatively vulnerable to corrosive atmosphere (smog) and acts only in one direction. Also because the volume of the muscle must be filled before any work can take place there is considerable wastage of gas. Variations on the piston have been utilized such as the

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* Committee on Prosthetic Research and Development, National Research Council, National Academy of Sciences, Washington, D. C.

† Edward A. Kiessling, American Institute of Prosthetic Research. (The Application of External Power in Prosthetics and Orthotics. Publication 874, Washington).

helical arrangement by Kiessling. In this device an oval piston moving in an oval cylinder causes rotation of the helix (something like a twist drill) mounted longitudinally through the piston. This rotation is coupled directly to an elbow joint or wrist unit. The motion provided by pneumatic devices is generally smooth and quiet and any associated sponginess is not detrimental to gross motions such as used in prosthetics. However, if a load is suddenly released while being lifted there is a corresponding jump in the lifting motion such as when a spring is released. One of the big advantages in using compressed gas is that it will do work much faster than most electrical systems. If you are lifting a weight with a piston the rate of lifting is limited only by the speed in which the gas can be conducted to the piston. Therefore, a gas system can not only be designed to lift a fairly heavy load but to lift it rapidly. In engineering this is termed horsepower. Electrical devices on the other hand have relatively low horsepower, so that even though they can be geared to lift similar loads, they will lift them much more slowly.

The usual method for converting electrical energy for useful work is the electric motor, although solenoids and other mechanisms have been proposed. The solenoid is useful only for a short stroke with a low force and hence has applications only for operating locks or brakes, and must be arranged so that they are used instantaneously only, to avoid unnecessary battery drain.

There are many types of electrical motors but the most common type and generally most effective type for use in this area is the permanent magnet D.C. motor. These are used in toys, household appliances such as shavers and tooth brushes, as well as in the aircraft and missile industry. Surprisingly enough there is very little difference in performance between a good toy motor and an expensive military type unit. However, the latter offers advantages in durability and convenience since usually they can be obtained complete with gear boxes with almost any ratio. A typical motor will weigh about 2 ounces and develop 1/400 horsepower at well over 10,000 r.p.m. The actual torque or turning effect of the motor is usually very small, about 2 to 7 inch ounces, thus before the motor can be used purposefully suitable gearing or other means of increasing the mechanism advantage must be employed.

Hydraulics have often been proposed as a means for converting the rotating motion of a motor to a useful purpose. Hydraulic systems are attractive because the pressure can be high without undue safety risks and therefore pistons can be quite small. The possibilities afforded by hydraulic transmission systems in prosthetics and orthotics are being investigated by General Electric.

Gears are heavy and noisy and, because of their flywheel effect, introduce a lag when starting or stopping the system. A common alternative is a screw mechanism wherein the motor rotates a shaft which is threaded, causng a nut to move up and down the shaft. This system is simple, quiet and rugged but wastes a lot of power through friction even though materials such as teflon and impregnated nylon are used for the nut. Ball bearing screws have a high efficiency, so high in fact that they will not hold against external forces. A promising alternative is produced by Roh'lix Corporation where the "nut" contains slightly canted roller bearings rotating on a plain shaft. This allows high efficiency and a fine pitch.

A further disadvantage of the electric motor system should be noted. If the load is increased until the motor stalls the current continues to flow, causing waste of electricity and possible damage of the motor. This can be overcome with suitably mounted cut-out switches, but this increases the complexity of the mechanism.

The actual lifting power of these small electric motors should also be noted. Horsepower is defined as the lifting of 550 lbs. a height of one foot in one second. Therefore, 1/400 horsepower motor will lift 550/400 lbs. (approximately 1.4) through one foot in one second. However, since the drive system is usually less than 50% efficient the actual lifting capacity would be somewhere around 0.7 foot lb. per second. It could be geared of course to lift ten times this much but it would take ten times as long to raise it through one foot. This must be recognized as a very definite limitation to small electric motors. Gas powered actuators offer very definite advantages over electric devices in size, weight, quietness and power.

CONTROLS

There are two aspects of controls—the mechanism by which the power is turned on and off and the means whereby the body can be harnessed for this function. The means of turning the actuator on and off in electrical devices is either a switch or rheostat. In most practical applications to date a switch is used. These are cheap, simple and reliable. In gas devices valves are used. These can be either on-off or variable. There is very little to choose between the two systems although valves tend to be noisy.

Electric wiring may be a little easier to employ as a transmission device than the flexible tubing that is used in pneumatics but it is interesting to note that the breakage of wires, particularly at the terminals, is one of the most frequent problems encountered in electrical devices in routine use.

By far the most significant aspect of controls is related to body application and there are two major classifications. First, bio-mechanical, in which an actual mechanical motion of the body is used to operate a switch or valve, and second, bio-electrical, where the electrical phenomena of the body is used through a suitable relay system to trigger valves or switches. Bio-mechanical control is usually the easiest to apply and the simplest to understand and is quite satisfactory for many practical applications.

One example of bio-mechanical control may be illustrated by a patient with a shoulder disarticulation, where the shoulder cap of the prosthesis is fitted loosely, allowing freedom of motion of the shoulder tip inside the cap. Valves or switches are arranged within the cap so that upward motion of the shoulder tip controls joint motion in one direction and downward motion of the shoulder tip controls the motion in the opposite direction. Similarly forward and backward motion of the shoulder tip can control motion about another joint. The use of the joy stick principle in this application allows simultaneous motion of the two joints.

Bio-mechanical controls also can originate from standard prosthetic harness systems, chin operated switches, finger switches for phocomelic fingers, chest and abdominal straps, in fact almost anywhere that convenient voluntary control is available. In quadriplegics the selection may be somewhat limited, but shoulder elevation and head control are obvious choices. The head control can utilize switches mounted in the back of a suitable headrest or by a light beam within an eyeglass frame directed to a photo sensitive keyboard as in the Case Orthotic Research Arm. Such things as ear-wiggling and eyebrow raising have also been shown to be useful but perhaps the most versatile is the tongue. In one system used at Rancho Los Amigos, the tongue operates seven switches in both directions.

The use of bio-electrical control systems introduces a great many possibilities and at least as many problems. The method usually used is myo-electrical (the electrical signal from a muscle). When a muscle is tensed an electrical signal is given off and this signal can be picked up with a surface electrode or inserted needle and amplified to a useful level in a similar way that a radio can pick up and amplify a signal. The signal is further processed so that when it reaches a pre-determined level it operates a relay controlling the flow of current to the actuator. This system is interesting because it makes possible the use of muscles which do not bulge enough to operate switches or valves. There are also indications that several independent signals can be generated from one muscle group with proper training.

The most prominent example of myo-electric control is the Russian hand. This has been fitted to more than 1,500 below-elbow amputees with the electrodes placed on the flexors and extensors of the forearm controlling the opening and closing of the hand. Experimental control units have been developed in Great Britain, Canada, Italy, Yugoslavia and Japan. Bottomley* indicated the feasibility of the control principle some 16 years ago and since then he and other researchers have demonstrated proportional control from a myo-electric signal.

The Philco Corporation is investigating a system whereby the prosthesis responds not to a single muscle signal but to a specific pattern of activity of six muscles. The control can be designed to respond to the "natural" activity of the individual thus minimizing training.

One of the interesting possible applications of myo-electrics in orthotics is the use of a signal from a muscle under voluntary control to produce a stimulating signal in a paralyzed muscle so that it may be usefully employed. This is in effect an external nervous system and is currently being investigated at Highland View Hospital, Cleveland, Ohio.

There are fundamental principles that apply to both myo-electrical and bio-mechanical controls. First of all, the muscles so used should be under control at all times (i.e., they work when you want them to and they don't work when you don't want them to). Second, the use of the muscles should not inhibit other activities. Third, if more than one muscle is used, and this is nearly always the case, then the muscles should be able to operate independently or together as required. Fourth, the muscle should be able to produce a variable signal so that the force or speed of the resulting motion is correspondingly varied. Fifth, the time required to train a muscle for a specific task should be minimal. Also it should be possible to do mental arithmetic or carry on an intelligent conversation while performing a task, without excessive concentration.

One important aspect in controls is feedback. This refers to the means of determining the results of the control motion. The most common cue is visual and often peripheral vision is satisfactory. Audio cues are also significant and this is why some noise is desirable. There are other methods that can be used as a substitute for the proprioceptive sense of the human body. The position servo system suggested by Simpson* is one example. In this instance the arm swings about the shoulder joint and the terminal device moves to and from the body controlled by a joy stick. Pushing the stick away from the body will cause the terminal device to move away, and moving it to the side will cause the arm to move to the side. The resulting motion is in turn coupled to the control stick so that the position of the arm can be determined by the position of the control stick.

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Force reflecting servos have been applied in hands and hooks. An early example is the Vaduz hand where grasping is initiated by pressure on a small bladder, suitably located within a below-elbow socket. When the hand closes and grips an object the gripping force is transmitted back to the bladder indicating the strength of the grip by a corresponding back pressure. Marquardt† has demonstrated a control valve which similarly reacts to the actual gas pressure supplied to the actuator. Although feedback can be extremely complex, in practical applications there are a few considerations which may help to simplify the problem. In prosthetics the position of the arm can usually be determined by contact of the stump in the socket. The above-elbow amputee can tell when his arm is abducted because of the socket pressures. Also, if the elbow unit has a constant rate of speed, the amputee can tell by subconsciously timing the motions what angular change is occurring. AMBRL‡ has demonstrated a simple (from the standpoint of the amputee) method of controlling the grip of a terminal device. A Peizo electric crystal in the thumb generates a signal when an object starts to slip in a manner similar to the signal generated from a needle of a record player. This signal causes an increase in the grip of the hand until the slipping stops or maximum pinch is reached. This device not only eliminates the feedback problem but is a clever means of obtaining proportional control automatically.

Proportional control and feedback become very important when it is desired to operate two or more joints simultaneously. Using only visual feedback, simultaneous control of 2 joints has been successfully demonstrated, but the simultaneous control of three joints is extremely difficult. The problem in orthotics can be more acute since the orthotic device may be chair-mounted so that no proprioceptive sense is possible. Position servos would seem to be extremely valuable in this case especially when arranged in the polar co-ordinate system as illustrated by the Simpson* arm.

A complex control system can be avoided if the functional requirements of the appliances are accurately determined and the joints suitably arranged and coupled either mechanically or otherwise programmed to perform the task with the single control input. There are variations in the way in which a control input can be applied either to a single actuator or a complex system. The control can simply initiate motion of the device, which proceeds at a pre-determined rate until the control is released. The control may also be used in the same way but in a proportional manner so that increased pressure causes increased speed or displacement. Another alternative is to initiate motion and then utilize the control to steer the device similar to driving an automobile.

A quick review of applications both experimental and in service illustrates a wide variety of hardware. The Case Orthotic Research Arm has control motion about five joints, which can be suitably programmed by a tape recorder for many specific tasks. The joints can also be co-ordinated to respond to continuous inputs in the three co-ordinate directions. A more modestly powered electric orthosis developed at Rancho Los Amigos has similar mechanical function but the control is by tongue operated lever

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* Dr. David C. Simpson, Dept. of Medical Physics, Edinburgh, Scotland. (Aug. 1965—British Vol. Journal of Bone and Joint Surgery.)

switches. A powered orthosis developed by Engen* at Baylor University is essentially a ball bearing feeder type arm rest, powered to provide elevation of the arm. This is a much simpler device, but does require residual function in the upper-extremities.

In prosthetics the most common devices in widespread use, are the Heidelberg type pneumatic arms consisting of elbow joints and locks, wrist rotators and locks, humeral rotators and prehensile hands or hooks. Originally these appliances were controlled with sequential valves, wherein one pull type control could operate the various actuators in sequence. This required considerable concentration to get the right one, and negated the possibility of combined motions. They are now usually fitted with a variety of controls placed where the operation is easiest, utilizing phocomelic fingers, chin switches, toe switches, shoulder elevation, scapular abduction, etc.

The Beograd hand illustrates some of the most advanced thinking in prosthetic devices. This electrically powered hand can grasp using the thumb in a pinching fashion, or with the thumb rotated outwards such as might be used in grasping a ball. The selection is automatically controlled by pressure sensitive pads in the fingers and palms.

In prosthetic use, it is seldom that one requires pure elbow flexion or pure wrist rotation in moving a terminal device from A. to B. There is therefore a trend to provide joint motions which are more closely related to the actual needs of the individual. The feeder arms developed by Northwestern and AIPR are an example of the latter, wherein the wrist and elbow are linked to keep a spoon level when lifting from plate to mouth.

It is apparent that there is no shortage of ideas and possibilities in the application of external power to orthotics and prosthetics. What is required is the realization of the actual needs of the patient which can be fulfilled with such devices and then to make available simple well designed hardware to fit these needs. It is apparent in severely handicapped cases, bilateral amelias, quadriplegics, etc. that the only practical solution is external power. This, of course, is not going to answer all their needs but can answer some. If an arm, for example, can be designed to provide feeding, writing, typing, book handling and toilet care with associated clothing manipulation then a great deal has been accomplished. These tasks are well within existing technical capacity, but there is perhaps need for greater comprehension of the way in which the man and the machine can best be combined for the needed tasks. This can be worked out in an experimental situation where engineer, prosthetist, therapist, doctor and patient can work together to establish the criteria in an informal manner. Once this criteria is established (and some already is) the real need is for a well designed product that is simple, light, and economical. This is somewhat similar to designing an electric shaver or carving knife. They are acceptable only if the product is reliable and attractive. The actual fitting, servicing and training are in no way more complicated than with harness powered devices and unlike the harness powered units there is greater possibility for future improvements in terms of power, speed and ease of operation. One of the biggest difficulties of course is that the sales volume is very small compared to household appliances, but proper orientation of the many competent people involved nationally in this programme could yield very real results in the near future.

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