SOME ARGUMENTS IN FAVOUR OF DIRECT ELECTRIC DRIVE FOR AN ARTIFICIAL ELBOW

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Experience with patients using artificial arms powered by compressed carbon dioxide indicates that reasonable requirements for a powered elbow are: 1) a starting torque of about 80 pound inches; 2) an energy store of 4,800 foot pounds (100 per cent efficient conversion) carried on the body; and 3) an energy store of maximum weight of 3 pounds.

The figure of 4,800 foot pounds is arrived at by calculating the work done at full load by the present Hendon carbon dioxide motors and assuming a store of 150 grammes of carbon dioxide which is judged to be adequate as a day’s supply for an adult.

The present motors use complete admission: that is, they work at a constant pressure, with very little expansion of the carbon dioxide in the working cylinder. The working pressure is pre-set to between 70 and 100 pounds per square inch. This means that the number of elbow movements is dependent only on the swept volume of the working cylinder and the mass of carbon dioxide carried in the store. With the Hendon motors assuming a store of 150 grammes of carbon dioxide, a working pressure of 70 pounds per square inch and a working temperature of 40 degrees Fahrenheit, about 280 full elbow movements (flexion or extension) through 150 degrees are possible. This performance can be improved by having the downward pulling or extensor cylinder of smaller cross-sectional area and by increasing the working pressure. For example, if the diameter of the extensor cylinder is reduced to half (to about 0·6 inch), the number of full movements is increased to about 440 because of the smaller volume swept during extension.

An increase in the working pressure allows a smaller flexor cylinder diameter, giving a smaller swept volume, but the density of the carbon dioxide in the cylinder increases, so that the advantage is not significant; it allows a smaller, lighter motor but the energy utilisation is not much improved. Some motors with small extensors have been made at Hendon and work quite satisfactorily, but control of the position of the forearm is more difficult because the two cylinders, having different working areas, require different pressures for equilibrium.

An ideal motor, expanding 150 grammes of stored carbon dioxide isothermally from 840 pounds per square inch to fifteen pounds per square inch at 70 degrees Fahrenheit, would produce about 10,500 foot pounds. If this figure is taken as the maximum possible work available, the present motors (with flexor and extensor components of equal size) are about 42 per cent efficient if they are used at full load. The motors with unequal cylinders are about 72 per cent efficient.

It is very unlikely that any other gas-powered motor—such as a small turbine—would have an efficiency which even approached 40 per cent, and it would probably be much more noisy. It must be concluded that the Hendon carbon dioxide systems are as good as they can be. In theory the system might be improved for an arm having two or more motors by cascading the motors: this would improve the energy utilisation but the increased complexity would probably rule it out. If longer use is required between bottle changes it is much easier to fit larger bottles.

This last statement may seem naïve, but it is nevertheless worth making. The Hendon systems will soon use two bottles, each containing 75 grammes of gas, with one reducing valve and a change-over valve, weighing about 1·1 pounds (500 grammes). A child might object to a heavier store, but an adult should be able to carry 3 pounds (1,362 grammes), properly supported on the body, without undue inconvenience.
If other types of gas motor are discounted the only safe alternative methods of powering an arm are systems based on: 1) a direct current electric motor driving a pump which fills a reservoir; or 2) a direct current motor driving each joint through gearing. It is not possible at this stage to give precise performance figures based on tests, but some theoretical predictions may be made about the performance of these systems.

A small pump such as might be required is unlikely to have an efficiency greater than 50 per cent and it might well be less. A colleague, Mr D. Kalyanvala, is having a very small gear pump made from Delrin and should soon begin performance testing. Assuming that the efficiency can be 40 per cent, a direct current servo motor of the size likely to be necessary (size 18) has a maximum efficiency of 60 per cent—say 50 per cent in use at varying loads. It may be assumed that the efficiency of the joint actuators is very nearly 100 per cent. The overall efficiency of a hydraulic system, therefore, might be 20 per cent.

This may seem low by comparison with the gas system, but the energy storage capacity of batteries must be included in the calculation. Four silver-zinc accumulators weighing 1.13 pounds (512 grammes), which is about the same as the present gas bottles, can store 34 watt hours of energy. That is 90,400 foot pounds, which is 8.6 times the theoretical maximum stored in 150 grammes of carbon dioxide; so for the same store weight, the carbon dioxide system provides 4,800 foot pounds whereas the electrically driven hydraulic system should provide 18,000 foot pounds. Apart from the fact that the life of the system is improved, the accumulators have the advantage that they can be recharged in twelve hours by the user, whereas the gas bottles have to be supplied from a central depot.

The alternative—using electric motors and gearing to drive each joint—may seem to be even more advantageous. A well designed gear train should have an efficiency of 80 per cent or more, and the overall efficiency of the motor and gear train should be about 40 per cent. So far as energy utilisation is concerned, therefore, this is the best system, but it has been shown that the electro-hydraulic system would have an adequate life between rechargings, so that other considerations must be taken into account.

Electric motors are noisy and heavy. An arm containing three motors would be very heavy and very noisy. If an electro-hydraulic system were used the motor pump and reservoir could be carried on the body inside acoustic packing. The arm would contain the necessary actuators and control valves. The hydraulic control system would be rather complex, but even so the electro-hydraulic system might be preferable to any other. Mr Kalyanvala's work on small pumps should indicate whether such a system is likely to be practicable.

When only one joint actuation is required there is obviously no point in using hydraulics. The motor can be acoustically packed and the gear train can be carefully designed to be as quiet as possible. With suitable gears the starting torque should be about 150 pound inches and the torque when the forearm is moving at 30 revolutions per minute (150 degrees in '83 second) should be about 45 pound inches.

The starting torque and speed of movement are much greater than those produced by the present carbon dioxide systems but the running torque is much less. Test will show whether this is significant in practice.

The control system also presents problems. A simple position control system in which the motor current flows through the control potentiometers is not possible because the starting current is of the order of 30 amperes, and the power dissipated in the potentiometers would be excessive. To overcome this difficulty a control system incorporating a multi-vibrator and switch could be used. The multi-vibrator and switch, being transistorised, would be of negligible size and weight. In order to investigate the possibilities of such a system, one is being made at Lanchester College of Technology, Coventry, and performance tests began early in 1965.

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