HENDON PNEUMATIC POWER UNITS AND CONTROLS  
FOR PROSTHESSES AND SPLINTS  

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The success of Marquardt’s gas-powered prosthesis (Marquardt and Haefner 1955) had aroused general interest before the thalidomide tragedy in 1962. The urgent need for functional prostheses not needing strong controlling movements, and giving at least three powered movements, has further stimulated research, so that work in this field is growing rapidly in many countries. The programme begun in 1959 at the Centre for Muscle Substitutes, West Hendon (formerly the Institute of Orthopaedics Poliomyelitis Centre), now includes both pneumatic and electric systems. This paper is concerned with pneumatic systems.  

PREVIOUS PNEUMATIC MOTORS  

A study of motors existing in 1959 and 1960 revealed that there were already several kinds with widely differing performances apparently related only to the earlier needs for powered movement. For instance, the “McKibben muscle” (Snelson and Conry 1958) arose from the need for a very light weight simple motor providing an on/off pinch grip for the hand of a poliomyelitic patient, whereas the desire for a precisely controlled rotation system for the wrist and elbow of a prosthesis led to the design of Kiessling’s double-acting motor in 1960. However, the shape of Kiessling’s elbow bender prevented its use in an elbow splint, which was the first need of patients at this centre. Single-acting systems with a spring return were too jerky and too wasteful of gas because, at each pneumatic stroke, the piston had to overcome the load on the limb as well as to compress the return spring. The return spring returning had not only to overcome the internal friction of the motor but also to extend the joint powerfully enough to satisfy the occasional extreme of the user’s demands. In a double-acting system forcible extension can be produced when required without the need for high gas consumption with every stroke. Further, Marquardt’s bellows system did not fit on to splints easily. At that time the problem was to make a flat, long motor, light yet with a fairly high torque and a smooth action, equally controllable in both directions. The torque had to be the same at all positions because a direct lift against gravity was not the only action needed. The fact that the torque does not decrease at the extremes of movement has enabled one patient to dig and swim wearing his splint. It should be remembered that the greatest pull that can be derived economically from the piston movement is so much less than that of the natural biceps and triceps that, if the mechanical disadvantages of the elbow were reproduced, the resulting movement would be very weak near its limits.  

HENDON PNEUMATIC MOTORS (ACTUATORS) AND THEIR APPLICATIONS  

Hendon twin cylinder motors—The above considerations led us to the following basic design. All the Hendon actuators except the “pat-a-cake” are, in effect, double-acting, with the antagonist pistons of the two cylinders connected by a cable running round a pulley (Fig. 1). Gas is admitted first into the driving cylinder. Movement of the pistons and cable and rotation of the pulley then occur smoothly as the gas from the previous stroke is released from the opposite, now controlling, cylinder. This gives an even torque at all positions in both directions.
Figure 1.—The basic twin cylinder pneumatic motor. A portion has been cut away to show one piston.

Figure 2.—The conventional elbow splint fitted with a twin cylinder unit and a built-in valve. The pulley and its cover are mounted on the lateral side-iron.

Figure 3.
A twin cylinder unit with a lateral side-iron only, in use on a blind patient with a partial brachial plexus lesion.
Experimental splint to lie on the medial aspect of the right arm. The flexing cylinder lies opposite the forearm, the extending cylinder opposite the upper arm. The material is duralumin with a polythene gutter.

A three-motor unit consisting of a large twin cylinder unit for elbow bending with a smaller twin cylinder unit, driving bevels for hook rotation, interdigitated at the other end. The positive closing hook is of Heidelberg design. Figure 6—Bilateral three-motor forearm units on an 8-year-old boy with phocomelia.
With little alteration of design, the present system provides various torques and ranges of movement because these depend only on pulley size and the length of otherwise standard cylinders. Practical applications of the twin cylinder method comprise actuators for both prostheses and splints (Bottomley, Kinnier Wilson and Nightingale 1963).

Splint motors—For lightness and best performance from the whole appliance the motor must be fully integrated into the prosthesis or splint. One early experimental splint had the cylinders and pulley mounted on the lateral side-iron. Because there was no corresponding pull on the medial side-iron the two elbow-joint bearings ceased to be coaxial, and movement became jerky (Fig. 2). Subsequently the pulley and ball-race bearing were mounted on a pillar fastened to the cylinder end plate. Because this withstands asymmetrical forces, it is now possible to do away with the medial side-iron completely, using instead a Velcro sling fixed to the simple cranked lateral forearm side-iron to move the wrist (Fig. 3) (Kinnier Wilson 1962). In the latest version the cylinders themselves act as the side-iron (Fig. 4). Its action is the same as with previous models but the motor has been "unfolded."

Prostheses motors—Experience with the improved performance of the pillar motor led to its experimental application for prostheses. A three-motor adult prosthesis (shown at the British Medical Association Scientific Meeting in July 1962) had an elbow bender in the upper arm, a wrist turner (comprising the basic motor with 90-degree bevel gears to change the axis of rotation) and a standard Roehampton hook opened by the McKibben "muscle." A smaller version of this, without powered wrist rotation and with hook opening powered by a piston-cylinder system operating through a Bowden cable, was fitted bilaterally to a seven-year-old boy with phocomelia in November 1962. This was the first gas-powered prosthesis to be fitted in Britain. He has worn the prosthesis or improved versions ever since.

Placing the elbow bender in the "anatomically obvious" position in the upper arm is wasteful of space and precludes its use in prostheses for patients with long stump upper arm amputations. The elbow bender can, however, be placed in the forearm, as a brachioradialis substitute, with the pulley fixed and the motor moving. If a wrist turner is interlocked from the opposite end space and weight can be saved.

The present design of a three-motor forearm unit (Fig. 5) provides powered elbow flexion and extension, wrist rotation, and a power-closing hook of Heidelberg design which is supplied with gas through the spindle of the final bevel. These forearm motor units have been fitted to two patients with idiopathic dysmelia (Fig. 6).

The twin-cylinder system is capable of fine controlled movements. But the very young child needs a much simpler system to start with, until he has learnt that arms can be made to move to some purpose. Following Marquardt, the first powered prosthesis exhibited provides bilateral medial rotation of the upper arm just above the elbow. For synchronous action of the two arms one single-acting motor pulls two Bowden cables, each of which terminates round a pulley at the elbow (Fig. 7). Each pulley has a coil spring for return action fastened
Curves showing the air flow-rate through two poppet valves and the Hendon O-ring plotted against plunger movement. The tendency for poppet valves of this type to "run away" is clearly shown.

Diagram of the principle of operation of the Hendon valve. In the mid-position the O-rings block both cylinder ports giving a positive lock.
to the lower part of the elbow mechanism by the standard screw. The system, fitted to some thirty children, uses child-size elbow friction locks made by Messrs Hugh Steeper Ltd. of Roehampton, virtually unaltered.

**THE HENDON VALVE**

Good control is next in importance to a small light power unit. The speed of movement must be understandably related to the valve lever movement, preferably in a linear way to enable slow or fast speeds to be selected at will. Smooth starting of the movement is also essential for if there is a jerk at the outset predicting the final speed is impossible and positional inaccuracy inevitable.

Because of static friction in the motor and transmission, pneumatic motors will not move until a differential pressure has been developed between the cylinder and atmosphere for single-acting systems, and between both cylinders for double-acting systems. Jerk is inevitable if the static friction exceeds the dynamic friction, but this can be prevented by the use of modern lubricants.

Valve characteristics are, however, more important than static friction. We tried three types of industrial valve which, though large, seemed capable of being made smaller. The first two were spool valves. The type in which the moving spool was sealed with O-rings developed very high static friction which could not be abolished by lubrication after being left for one or two hours. The other type used a finely ground spool running in a body, both of stainless steel. Though this could be controlled by light pressure it could not be made bubble-tight without a marked increase in stiffness. Though these objections were of no importance in industrial use they were significant for our purposes.

Poppet valves such as are used in car tyres, though airtight and relatively light to operate, did not have a steady flow response to lever movement. This was because the valves had very light return springs; when the gas flow rose to a certain figure back pressure was exerted on the disc of the poppet itself, opening it still further without any corresponding movement of the lever (Fig. 8).

The rudimentary digits of some patients with phocomelia, which could only exert a force of 60 grammes through one centimetre, had only about a quarter of the strength necessary to operate the lightest valve that was commercially available. Accordingly, a balanced valve was developed which is shown in Figure 9. This needs a force of only 30 grammes to move it through its full travel of one centimetre. In practice, the centralising springs for adults are made heavier than this because they find it difficult to feel a resistance of 30 grammes against a lever without actively concentrating on it all the time it is in use. The reasons for the lightness of operation are that there are only two very small O-rings, that the system is balanced, and that the plunger and O-rings on one side are driven by the line gas pressure, so that the wearer only has to overcome the friction of the other O-ring.

This valve has a virtually linear flow response to lever movement (Fig. 8). Moreover, it is a double change-over valve which is not only completely airtight but also has no point in the operation where all three orifices are interconnected. Provision is also made for a feed through to the next valve, avoiding a T-piece.
Unlike poppet valves, which may need quick jabs, the valve is worked by a smooth action of the control movement. This makes it possible to extend the principle (described elsewhere in this issue by McKenzie) of using as a control movement part of the whole desired movement. With this system learning times as short as three days in a child of eleven months, and ten minutes in a child of fifteen months, have been achieved with some applications of the pat-a-cake system. The girl in Figure 10 successfully cut and ate her lunch ten minutes after first putting on the complete splint and valve.

A pneumatic servo system is also under trial. With this the valve body is mounted on the moving (forearm) part of the splint or prosthesis, with the lever movement arranged so that upward movement of the lever tip causes upward movement of the forearm and so of the valve body. As soon as the lever movement stops, the body of the valve begins to “catch up” and lever-valve body relationship is returned to the “off” position. A control system is thus provided which makes the change in position of the arm proportional to the change in position of the lever. There is no doubt that other types of servo mechanism will prove worthy of trial as time goes on.

Until recently we were not sure how to assess the merit of a powered limb quantitatively. With increasing knowledge of what parameters to measure, it is correspondingly easier to define and to fulfil a performance specification. There seems no doubt that the continued interchange of information between centres will result in progressive development of apparatus that will be available to clinicians.

SUMMARY
1. The Hendon motor and the Hendon valve are described.

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REFERENCES


