Proc. of 5th Int. Symp. on External Control of Human Extremities, ETAN, Yugoslavia, Dubrovnik 1975.

A PROTOTYPE HYDRAULICALLY POWERED ARM PROSTHESIS

D.R. Broome, B.L. Davies and M. Lord

The multi-functional externally powered arm prostheses currently available in the U.K., suitable for fitting to children suffering from congenital deficiencies of both upper limbs are all powered by compressed carbon dioxide gas$^{(1),(2)}$. Arm articulation is accomplished by using three-way control valves in association with differential area piston actuators, or two three-way valves mounted back-to-back with double acting actuators, in closed loop position controlled servo-mechanisms.

Several advantages are associated with the use of hydraulic fluid as the powering medium for such devices$^{(3),(4)}$. These mainly accrue from the relative compressibility of the two media. The virtually incompressible nature of hydraulic fluid results in safe operation of systems at higher working pressures and consequently results in better power to weight ratios. Thus hydraulically powered position control systems, designed to conform to the prosthetic requirements of safety, compactness and lightness, are able to meet load, response and stability specifications which exceed the capabilities of their pneumatic counterparts. The output stiffness of hydraulic servos is also much greater, which decreases their disturbance by external loads.

The construction of a hydraulically powered arm prosthesis has not been possible to date due to lack of a suitable power source. However, recent successful development of a prototype miniature, hydraulic power unit indicates that portable hydraulically powered systems are viable$^{(5),(6),(7)}$. Energy storage for this hydraulic supply is accomplished by electric batteries which offer great advantages in ease of recharging or replacement compared with compressed carbon dioxide storage cylinders. This should make such a system polular in the United States where, due to the logistic difficulties of supplying gas cylinders, most externally powered prostheses are actuated by electric motors.

Although satisfactory for low power levels, such as powered grip and wrist rotation, electric actuation of motions requiring high power levels such as shoulder elevation would incur penalties of weight and poor dynamic performance. For this reason no multi-degree-of-freedom prosthetic arm system has been totally based on electric motor actuators.

Other areas of difficulty in implementing a hydraulic arm prosthesis include the development of suitable control valve and actuator systems (8), (9), (10) and the adaptation of suitable terminal devices to make them compatible with the arm structure and hydraulic power.

This paper describes the hydraulic prosthesis constructed at University College London. It should be stressed that this project is aimed at producing a prototype hydraulic arm and that the arm will not be used for clinical trials, but could form the basis of a system which, suitably modified to permit small batch production, could be used by bilateral dysmelics.

ARM STRUCTURE

In collaboration with Professor D.C. Simpson of the Princess Margaret Rose Orthopaedic Hospital, Edinburgh, the Series II Mark I arm has been used to assess the hydraulic actuation and, to this end, a set of arm components has been supplied by Professor Simpson and assembled at U.C.L. The arm structure with valve actuators, terminal device, and power pack is shown in Fig.1, less its cosmetic covers. The kinematics of this mechanism have been well described by Professor Simpson and his associates$^{(11)}$, but may be explained with reference to the detailed photographs of Figs.2 and 3 as follows: The arm utilizes a spherical coordinate system of r, θ, ϕ, to position the terminal device in space. The reach actuator,Fig.2, which controls the r coordinate, produces a coupled rotation about both elbow and shoulder to produce a linear extension of the terminal device from the shoulder. The shoulder elevation actuator, Fig.3, lifts the whole arm about a horizontal axis through the shoulder (θ), and the shoulder rotation actuator, Fig.3, produces a rotation of the arm structure about a vertical axis through the shoulder (ϕ) by means of the bevel gear mechanism in the shoulder gear box. Orientation of the terminal device is accomplished by a wrist rotation system similar to the shoulder rotation and a passive link coupled to the shoulder elevation drive system causes the hand axis to remain in a constant attitude with reference to the shoulder as the arm is articulated. Finally the terminal device is fitted with active prehension.

This arm is one of the few gas power multi-functional arms which have been in extended clinical use and lends itself to conversion to hydraulic actuation because of its robust construction and component accessibility. Also, the considerable clinical experience of this system at the Princess Margaret Rose Orthopaedic Hospital should permit a direct comparison between hydraulic and pneumatic power based on the same arm prosthesis.

PORTABLE POWER SUPPLY

Preliminary work on a portable hydraulic power unit was reported at the last Dubrovnik Symposium(6) Since that time, efforts have been directed at making the unit smaller and more efficient. Figs.4 and 5 show the present arrangement of the power unit.

A 12 V battery pack, consisting of 1.1 Ah rechargeable nickel cadmium cells, is used as a primary energy reservoir sufficient to meet the anticipated energy demands for a whole day. The battery powers a dc permanent magnet Maxon motor rated at 20 W. This drives a miniature radial pintle pump via a special 3:1 ratio gearbox. The motor, pump and gearbox are totally immersed in a low pressure reservoir to give both thermal and acoustic insulation. The fluid in the unit is a vegetable oil, also used in face creams, chosen to avoid toxic or carcinogenic effects. The pressurized oil at 30×10^5 N/m^2 (450 lbf/in^2) is supplied via a 10 μm filter and non-return valve, to a liquifiable gas charged accumulator where it is stored.

The accumulator is specially designed to store a large quantity of energy in a small volume. A mixture of liquifiable gases, chosen to have an appropriate vapour pressure at room temperature, is contained in a reservoir. The gas is separated from the hydraulic fluid by a rolling diaphragm which is reinforced by a sliding piston. When the accumulator is charged with oil the liquifiable gas is compressed from the mixture phase to a liquid which occupies a smaller volume. The state of charge of the accumulator is monitored by a switch which senses the piston position. In addition a sub-miniature pressure switch cuts out the motor if the pressure should rise too high. A bursting disc is also included as a safety device. In this way the relatively small pump can be driven intermittently at about 11 watts output and yet, by storing energy in the accumulator, peak power demand can also be met.

The advantages associated with the high bulk modulus of hydraulic systems can only be realised if no air is present in the lines. This is of particular importance when the low pressure reservior is not vented, as small bubbles of gas may be accumulated. Such bubbles may not only be entrained during assembly, but can result from liquifiable gas slowly passing through the accumulator diaphragm which acts as a semi-permeable membrane. This problem has been minimised by the addition of a gas bleed valve.

It is envisaged that the power unit will be located in the upper section of an associated passive arm or, where this is not possible, be strapped on the prosthetic harness. The battery pack is designed to fit on a waist strap.

VALVE AND ACTUATOR SYSTEM

It was necessary to develop hydraulic valves and actuators satisfying the stringent requirements of size, weight, energy constraints, etc., peculiar to prosthetic applications as no commercially available components could be found. For example, the smallest commercially available electrohydraulic valve, the Series 30 Moog has a quiescent power drain from its flapper-nozzle first stage which exceeds the continuous rated flow of the portable power pack. The design philosophy has been to adopt standard, accepted engineering practice and conventional, proven systems wherever possible, and to develop miniaturised versions of the required components, thus avoiding lengthy development programmes. The valve developed was a miniaturisation of a standard four-way spool valve. The spool valve design is shown schematically in Fig.6 and can be inserted in to a bore in the actuator body and all the necessary hydraulic connections made by internal drillings within the composite actuation unit. The only connections required are those of hydraulic supply and drain and these can be made to the actuator body. Miniature screwed connectors have been designed and made for this purpose.

The resulting actuation unit is very compact and has the advantage that valve replacement due to wear or malfunction can be facilitated without disturbing any hydraulic connection. This design also eliminates the mechanical feedback linkage normally required since, as the actuator responds to spool displacements, the actuator body moves and shuts off the valve by moving the valve sleeve relative to its spool, thus providing a one-to-one position feedback. Several types of this sleeved valve were produced, the main variations being in port dimensions, radial location and spool land widths. They all demonstrated satisfactory flow, no-load and load test behaviour. The geometry was varied in an attempt to reduce the effect of dynamic pressure imbalance forces to a minimum and hence obtain as low a spool operating force as possible.

A further problem present in the miniature hydraulic servo-system is that, owing to the relatively low stall capabilities of the hydraulic actuators suitable for prosthetic use which arise from energy expenditure criteria, it is possible to subject the prosthesis to external loads which are far greater than system stall. These loads could easily arise from the patient leaning heavily on the arm or from accidentally falling on the structure. The effect would thus be to cause large pressure rises in the actuator and would probably result in linkage distortion or failure. This is unlike pneumatic systems, where the low bulk modulus of the actuating media would yield to considerable external loads by compression of the gas. It is therefore necessary to include in the actuator design over-pressure relief valves which would permit blow off from one side of the cylinder to the other when external loads become excessive. Miniature relief valves have been made and tested to be compatible with the actuation system. Fig.7 gives an exploded view of the largest actuation unit providing the shoulder elevation function. Each actuation system has been designed to have the same stroke as its pneumatic counterpart, thus retaining the same ranges of motion and overall kinematics. The actuator area determines the load torque capability and the saturation angular velocity for each articulation and, for a fixed system pressure and valve flow, the relative magnitude of each depends on the chosen area. For example, a larger area at the shoulder provides the increased stall forces required to lift the whole arm but results in a lower maximum velocity. A smaller area is selected for the elbow where a lower stall capability and faster velocity are desired. The limiting factor is again an energy constraint from the power pack which imposes a maximum available valve flow at the system pressure. The valves and actuators were designed to obtain similar stall capabilities to the comparable pneumatic system and some test results are discussed in the section on system performance.

TERMINAL DEVICE

The functional requirements for the terminal device are quite distinct from those of the other articulations of the prosthesis. Whereas the main function of the structure comprising the r, θ, ϕ, system is to position the terminal device in space and is therefore best served by position-control actuation, the terminal device itself is designed to grip objects and is essentially more concerned with prehension force than finger position. The use of force servo-mechanisms, i.e. a prehension force proportional to the control site effort, is known to be effective in facilitating the manipulation of delicate objects by a device capable of exerting high forces. The concept has been utilised in gas-powered systems by the use of pressure-demand valves, the grip force being proportional to the force at the control site exerted by the valve(12), and in electrically-powered systems by the transduction of electromyographic signal levels or from the muscle bulge at the control site(13)

The question arises as to whether hydraulic power is suited to this particular force servo application. We have available the electric power supply which normally drives the power pack and which could be utilized directly to drive an electrically-powered terminal device. The 50% loss of energy in the conversion from electric to hydraulic power must be weighed against any advantages of a hydraulic terminal device. However, there are two exploitable aspects of the hydraulic actuation in this instance - the higher power/weight ratio and the absence of additional noise. The former should allow a considerable percentage weight-saving on powered hooks where the bulk of the weight resides in the actuator, but perhaps less on a hand for which a high proportion of the weight is in the cosmetic structure. With regard to noise levels, electrical terminal devices in general produce a disconcerting whirring, whereas the hydraulic hand will cause no localised noise.

A survey of available electric hands showed two to be suitably light and powerful, these being the Myobock and the Fidelity. The Myobock hand weighs 442 g with its cosmetic glove, has a prehension force of 90 N (20 lbf) and a closing speed of 70 mm/s (2.8 in/s)$^{(14)}$, the Fidelity hand is comparable$^{(15)}$. No power consumption is quoted for these hands in terms which would allow a comparison with hydraulics. Based on the 0.6 litre/min flow rate at 30 bar (450 lbf/in^2) used for the main valve/actuator assembly, a few simple calculations indicate that this performance can be matched with hydraulics.

One further consideration has to be taken into account in the design of any terminal device and that is the aspect of interchangeability of cosmetically-pleasing hands with more functional hooks or special purpose applicances. This imposes a problem in hydraulics in that the power line cannot be disconnected without an unacceptable loss of hydraulic fluid. In order to circumvent this problem, it is necessary to place the actuation unit inboard on the arm structure and to transmit the drive through to the terminal device by a mechanical linkage. This proves to have its advantages, for whereas before each terminal device required its own motor, now only one actuator is needed. Thus a whole range of normally body-powered terminal devices can be used with slight modifications to accept the linkage drive rather than a cable attachment.

The hydraulic hand currently attached to the prosthesis is based on Otto Bock components in order to be compatible with the extensive Bock range of terminal devices. Fig.8 shows an exploded view of the wrist and hand assembly. The wrist block which was used in the Simpson pneumatic arm, both to transmit gas and to orientate the arm, has been modified to house the hydraulic actuator proximal to the wrist adaptor. The wrist adaptor is a Bock design which was modified by B.R.A.D.U. to reduce weight. The hydraulic actuator piston rod passes through the centre of the adaptor and is connected to a Bock

System Pneumatik hand from which the actuator has been removed. Existing body powered terminal devices could also be readily adapted to this form of hydraulic actuation.

Prehension is obtained by opening a pressure demand valve so that oil is supplied to one side the hydraulic actuator. The return stroke is spring powered as in the original Bock hand.

The hand is intended for use by an older child and has been designed with a maximum grip force of 45 N (10 lbf) and closes at a rate of 80 mm/s (3 in/s). Although the relationship between the control site force and grip force is non-linear due to valve hysteresis, sufficient sensitivity is obtained to enable the user to hold a paper cup without crushing it.

The mechanical drive produces a force of 360 N (80 lbf) through a stroke of 15 mm (0.6 in) and could be adapted easily to connect with many voluntary opening and closing terminal devices. The total weight of the wrist block (50 g), wrist adaptor (44 g) and hand with glove is 440 g. This must be compared with an estimated electric system weight of 520 g, comprising 440 g for the hand with glove and an additional 30 g for the block and adaptor. A weight saving of 15% has been gained and this is an important consideration for the total arm prosthesis as the hand weight deducts directly from the payload or, conversely, necessitates a proportional increase in the size of all the main actuators for a given lifting capacity.

SYSTEM PERFORMANCE

Several tests have been conducted on the prototype arm. These include measuring the response of the three main positioning actuators of r, θ, ϕ, to full sweeps of the input controls. A typical response of the shoulder elevation actuator is presented in Fig.9 and from this the straight line portion of the curve yields a saturation angular velocity, lifting the arm alone, of 2.2 rad/s. This is increased to 3.2 rad/s when the arm is lowered at full valve opening. Also the transition from rest to full speed and vice versa is seen to be smooth with no oscillatory behaviour which demonstrates the dynamic stability of the hydraulic servo-mechanisms.

Other tests were designed to investigate the stall loads on each arm function and, typically, the elbow reach system was capable of lifting the equivalent of over 1 kg placed in a prosthetic hand weighing 0.5 kg. Another important property of any manipulating device is its positional resolution and tests showed that it was possible to position the hand to within about 10 mm on the reach function (i.e. to about 2%). This will not cause any real problems to the patient as final accurate positioning is usually accomplished by trunk movements.

However, several factors contribute to this loss of accuracy, such as the backlash of the linkage gearboxes, stiction effects in the actuators and linkage and the poor characteristics of the Bowden cable input signalling system. Further positional inaccuracies occur when the arm is mounted on a harness of a patient due to the additional flexibility which is introduced. Distortion of the shoulder gearbox due to wear causes a marked loss in torque efficiency as the arm loading is increased; this was measured at about 90% at low loads, but fell to below 60% for half stall load at input.

Tests have been conducted to examine the compatability of the prosthetic arm system and the portable power unit. These reveal that the size of the pump and accumulator is adequate to permit coordinated articulations involving the simultaneous use of several degrees of freedom. That is, when the system is operated at the maximum rate for control of coordinated motions the accumulator is not drained, and the pump maintains the accumulator in a charged state. Also the overall efficiency of the system with a 1.8 Ah, 12 volt battery pack is sufficient to provide power for an anticipated day's activity.

CONCLUDING REMARKS

A hydraulically powered total arm system has now been constructed which demonstrates that hydraulic power is now feasible for prostheses. Not only is the hydraulic power unit small enough and light enough to be carried in the upper section of a body poweredarm, but also miniature valves and actuators have been constructed which can be fitted into an arm framework and control precisely the positions of the arm drive linkages. The use of hydraulics has revealed that there are now problems with the arm framework itself, particularly the shoulder flexion motion which can be very heavily loaded, which is susceptible to backlash and has poor mechanical efficiency. An alternative arm framework which may be less prone to these problems is currently being investigated with a view to powering it hydraulically. This is the B.R.A.D.U. 'radius vector' arm produced at Roehampton, England, which has a powered reach motion, wrist rotation and prehension. However, the design of an arm framework could be simplified further if miniature rotary hydraulic actuators were available, minimising inefficiencies in the transmittion of motion. It is hoped to investigate such actuators inthe future.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the continuing support of the Department of Health and Social Security in the development of this system and the advice and encouragement of Professor T.H. Lambert and Dr. R.M. Davies of the Department of Mechanical Engineering, University College London.

REFERENCES

1. The design and development of an experimental externally powered prosthetic system. M.R.C. Powered Limbs Unit, West Hendon Hospital (1970).

2. Simpson, D.C. An externally powered prosthesis for the complete arm. Bio.Med. Eng., 4, pp.106-110.

3. Davies, R.M. and Lambert, T.H. Dynamic characteristics of pneumatic, electric and hydraulic actuation of prosthetic and orthotic devices. 2nd Int. Symp. on External Control of Human Extremities, Dubrovnik (1966).

4. Davies, R.M. and Lambert, T.H. The design of an hydraulically powered arm prosthesis. 4th Int. Symp. on External Control of Human Extremities, Dubrovnik (1972).

5. Davies, B.L. A prototype portable hydraulic power supply for prosthetic applications. Human Locomotor Engineering, I.Mech.E. Conf. Brighton (1971)

6. Davies, B.L. and Davies, R.M. Portable power units for hydraulic prostheses. 4th Int. Symp. on External Control of Human Extremities, Dubrovnik (1972).

7. Davies, B.L. A portable hydraulic power unit for prostheses. Eng. in Med., 1, 2, pp.41-49, (1972).

8. Broome, D.R. and Gilham, W.R. Prototype spool valve for use in hydraulically powered arm prostheses. Med. and Bio. Eng., 10, 6, p.796.

9. Broome, D.R. and Lambert, T.H. Valves and actuators for hydraulically powered prostheses. 4th Int. Symp. on External Control of Human Extremities, Dubrovnik (1972).

10. Broome, D.R. Transients in hydraulic position of heavy loads. Proc. 4th Canadian Congress of Applied Mechanics, Montreal, Canada, pp.839-840 (1973).

11. Simpson, D.C. and Kenworthy, G. The design of a complete arm prosthesis. Bio-Med. Eng., 8, 2, pp.56-59, (1973).

12. Bottomley, A.H. A pressure demand ~~valve~~ for use in the control of powered prostheses. Bio.Med. Eng., (October, 1966).

13. Experiences and observation with Myobock 1. Orthopadie Technik 12, p.337 (1970).

14. Piezer, E. External power in prosthetics, orthotics and orthopaedic aids. Prosthetics. Intl., 4, 1, (1971).

15. Fidelity VA-NU American myoelectric hand system. Fidelity Electronics, Ltd., brochure, Chicago, Illinois 60639, U.S.A.

CAPTIONS

Fig.1 Overall view of arm system with pack.

Fig.2 Elbow joint showing reach and shoulder elevation actuators.

Fig.3 Shoulder joint showing shoulder elevation and rotation actuators.

Fig.4 Details of the latest power pack.

Fig.5 Block diagram of power pack details.

Fig.6 Final sleeved valve schematic.

Fig.7 Exploded view of components of shoulder elevation actuator.

Fig.8 Terminal device.

Fig.9 Response of shoulder elevation actuator to a full sweep of the input control. Scales: 20° per division, 0.2s per division.

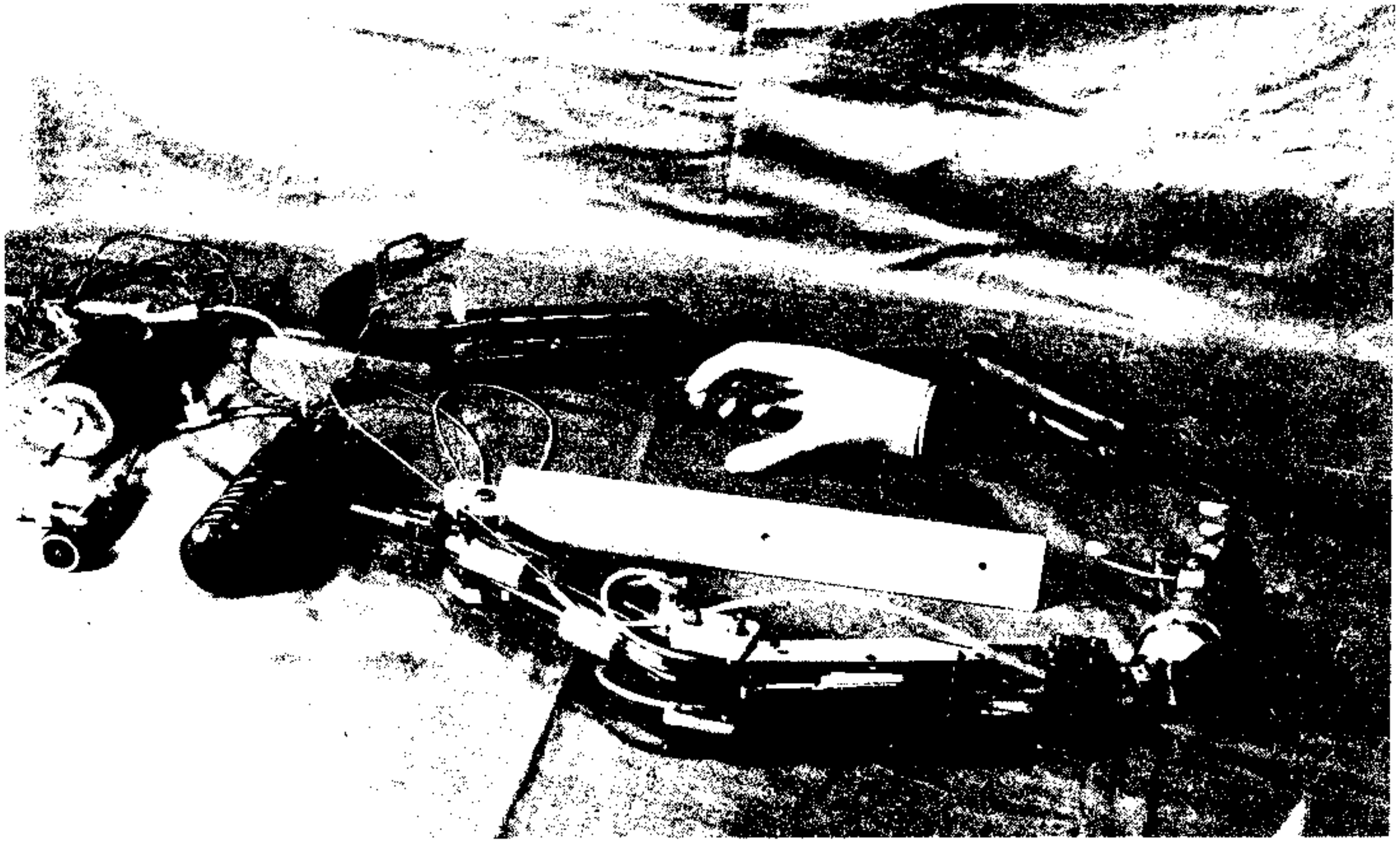

Fig. 1.

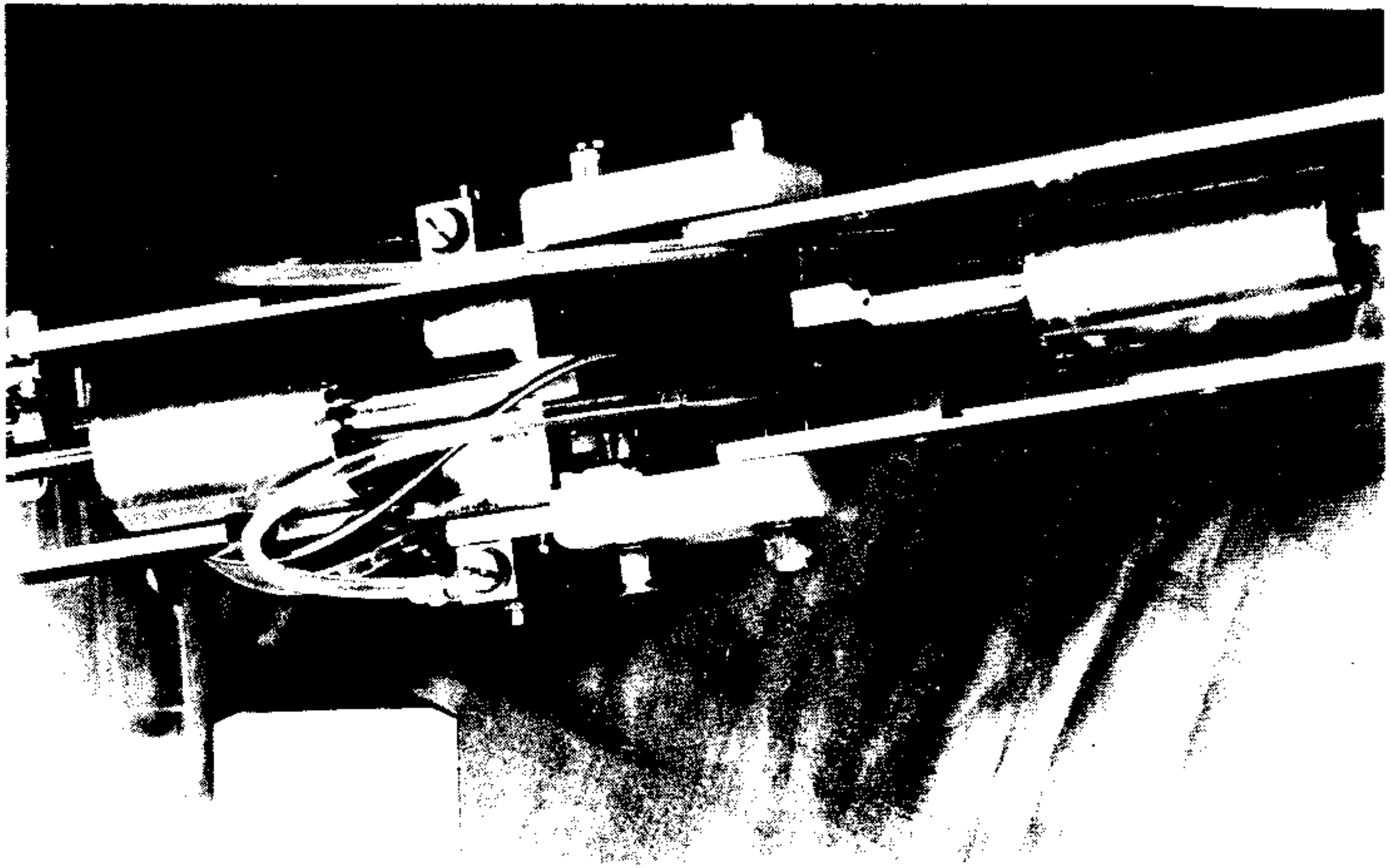

Fig. 2.

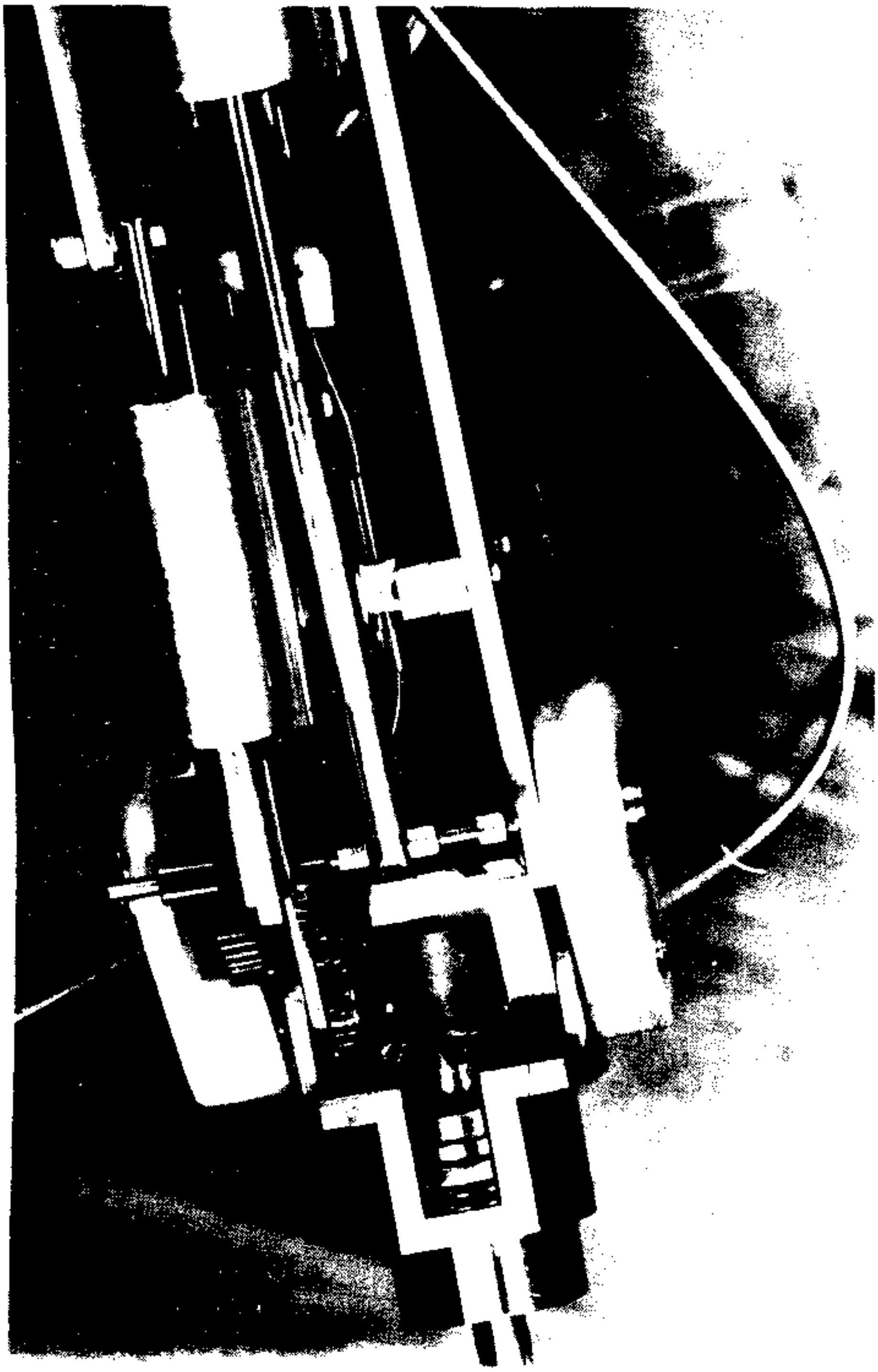

Fig. 3.

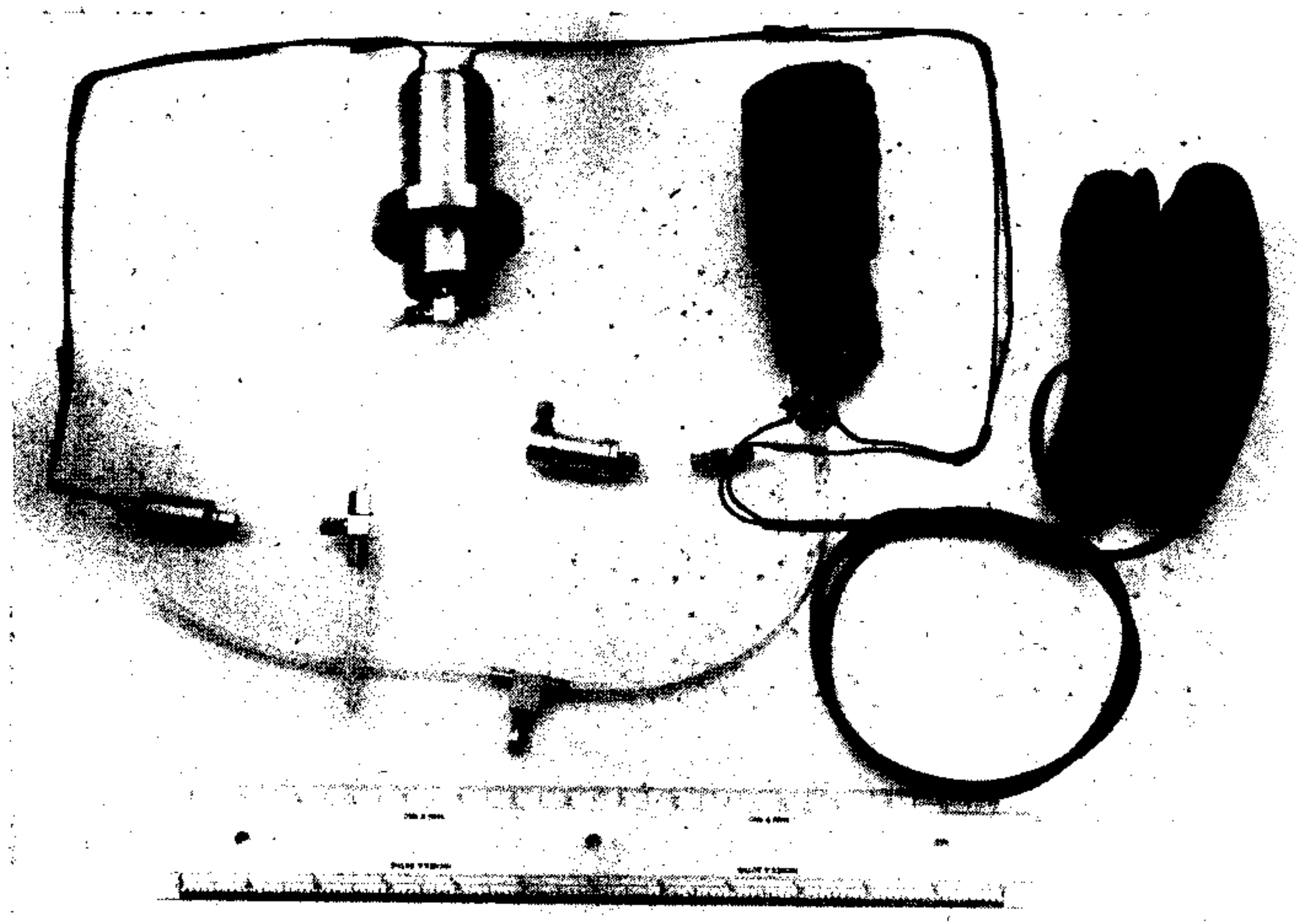

Fig. 4.

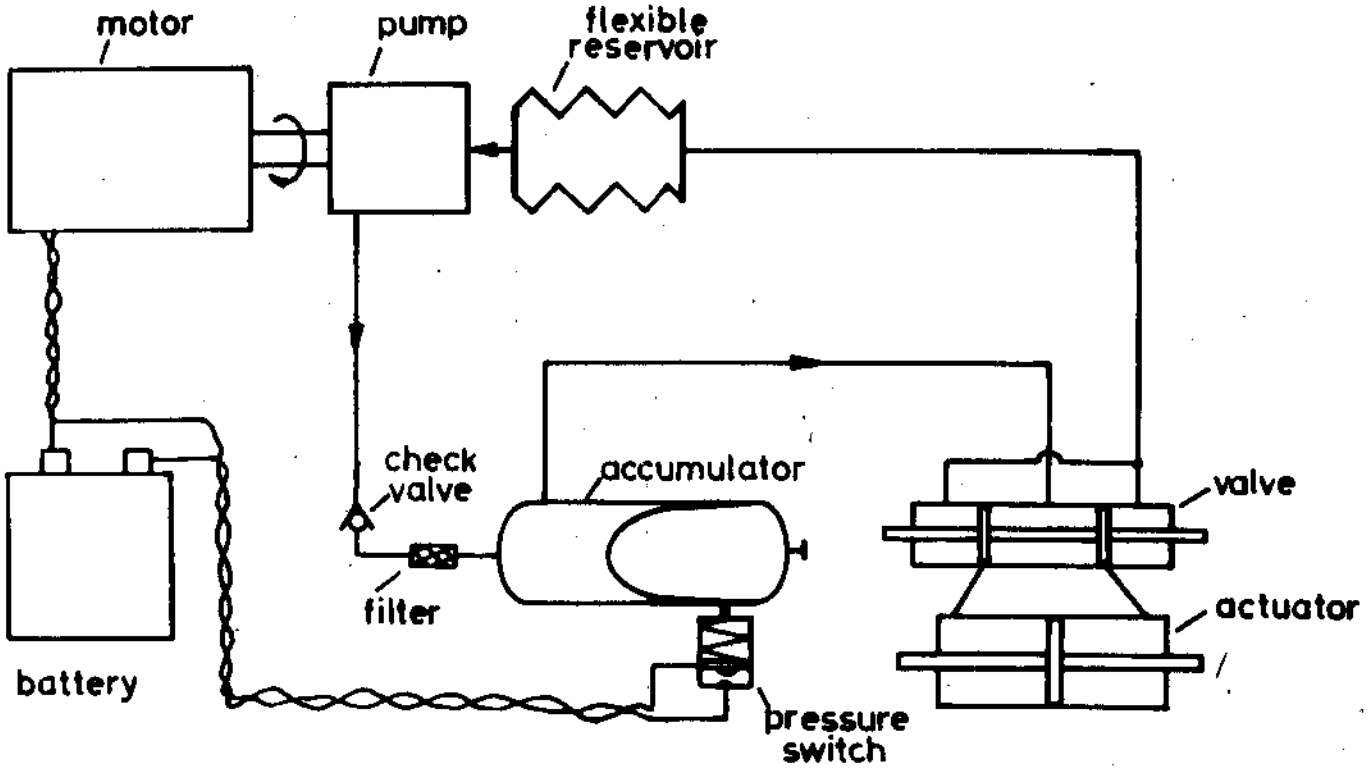
motor
pump
flexible reservoir
check valve
accumulator
valve
filter
actuator
battery
pressure switch

Fig. 5.

SCALE 4:1

SPOOL VALVE ASSEMBLY

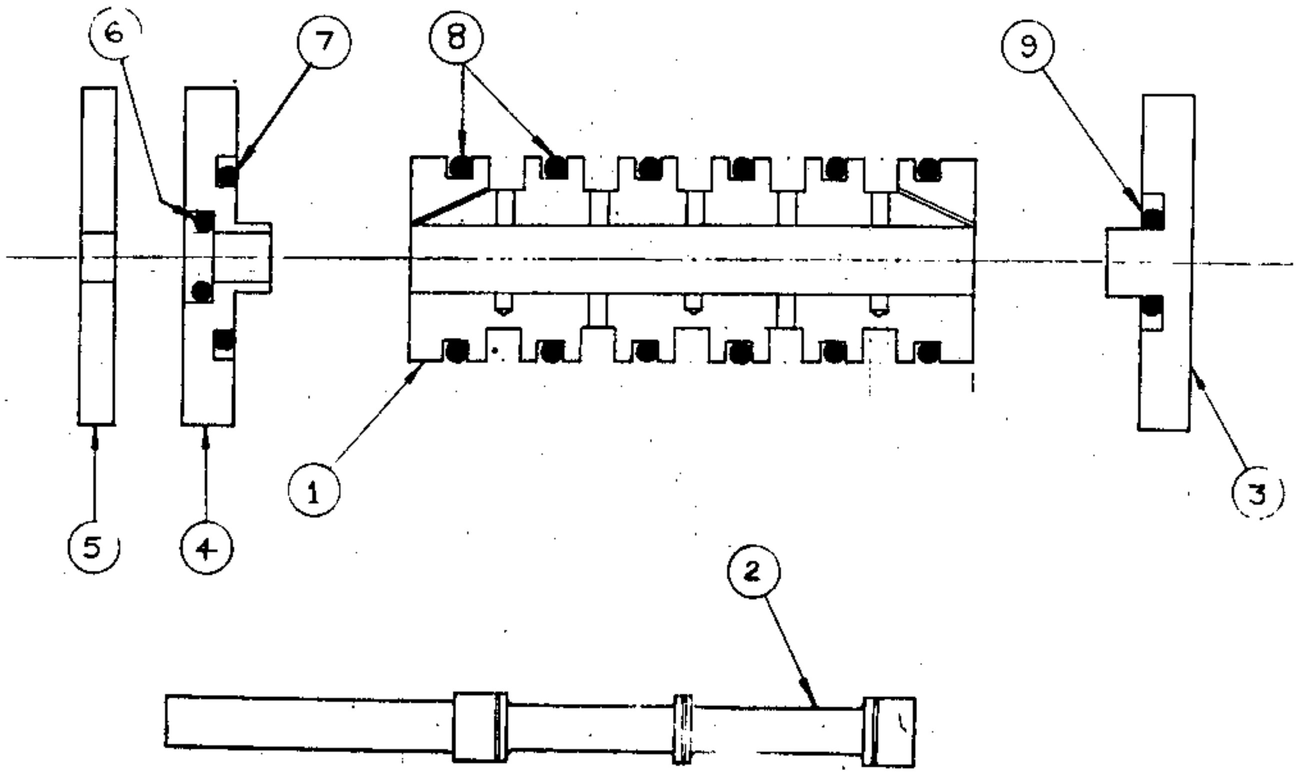

Fig. 6.

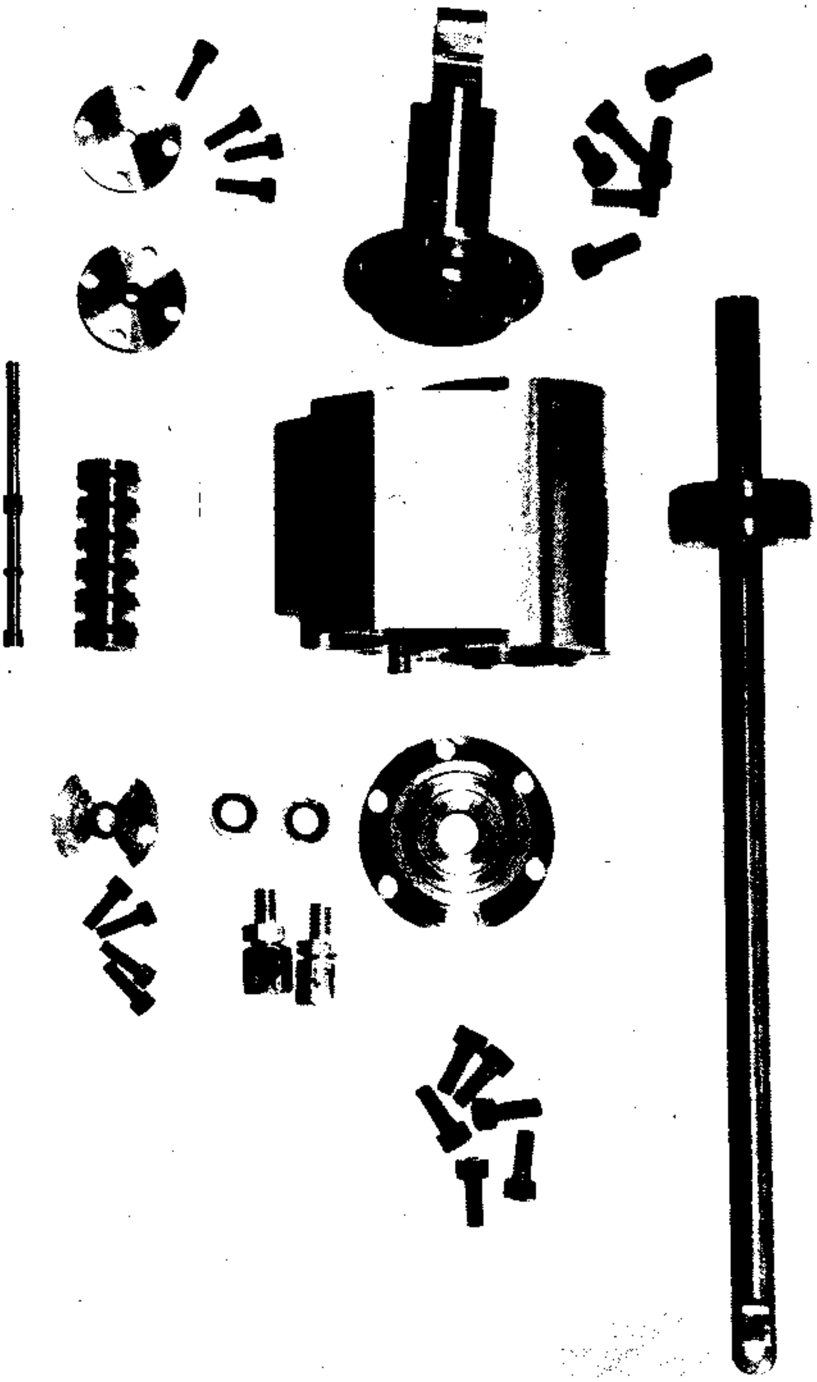

Fig. 8.

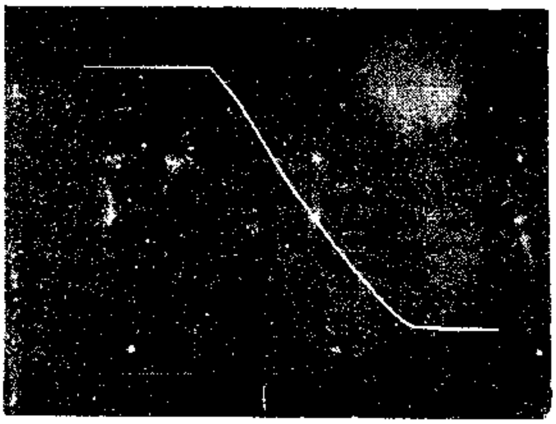

Fig. 9.

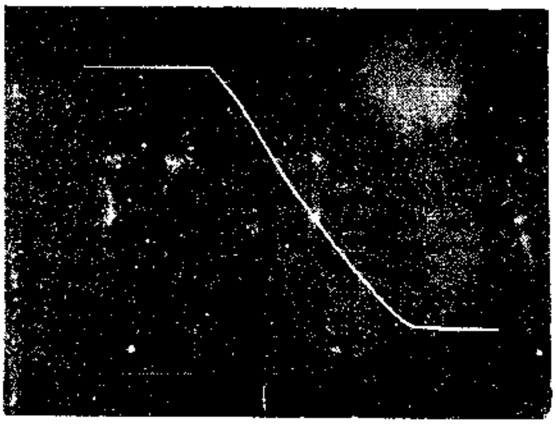

Fig. 9.