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Inflatable Servo Actuators

By

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SUMMARY

The force v. pressure relationship of most fluid pressure servo actuators would be greatly improved if the whole wall surface of the working chamber were employed in energy transfer, instead of only the small area of a piston or vane.

Some ways of achieving this, by the inflation to cylindrical form of flat envelopes of flexible material, were investigated by the author during development of an artificial muscle system. This note records the performance of various prototype actuators and discusses possible applications.

One form, designated a "muscle-motor" actuator, has many possible uses in engineering. The advantages of such actuators lie chiefly in their extreme simplicity and cheapness, their flexibility in one plane even whilst working, the absence of sliding parts which enables dirty fluids to be used and virtually eliminates friction, and finally the improved force v. pressure characteristics.

These actuators are discussed mainly in a general engineering context, but some comments are included relative to the medical applications for which they were developed. The Appendix presents simple design formulae for muscle-motor actuators.

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1 INTRODUCTION

Whilst serving with the Ministry of Health between 1958 and 1961, the author carried out independent research into a practical artificial muscle system. This work, to be reported in the medical literature, showed the superiority of a closed hydraulic servo system, provided a simple actuator could be developed to give a large work output for a minimum of fluid pressure input. The present note considers this problem and its solution in detail.

It is well known that in the conventional actuator only a small portion of the working chamber area is used in doing work, i.e. a piston head or vane. If the whole wall area were made movable and harnessed to do work, the optimum force/pressure relationship would obviously result. To achieve this, the working chamber walls may be made from a flexible material, such as proofed textile or plastic film. Various ways can be devised to enable such chambers to do mechanical work. Three basic methods were investigated by the author and tests of prototypes using them are reported here.

Many situations arise in general engineering, and particularly in the aircraft field, where power-operation is desirable but the conventional hydraulic system is not justified on account of cost, complexity or risk of fire or explosion. This note is intended to stimulate thought on the use of low pressure, flexible actuators in such cases, and to suggest other instances where their unique characteristics could make them superior to the conventional ram or vane actuator. In particular, the form of actuator chosen as the muscle-motor in the author's artificial muscle system is discussed at length, since it is thought to be the most useful form of inflatable servo actuator for general engineering use. Schemes are suggested for overcoming the more obvious difficulties in applying such actuators. Simple formulae, by means of which any one lobe of such an actuator may be designed, are derived in the Appendix.

2 TESTS OF PROTOTYPE INFLATABLE ACTUATORS

The three types originated and tested all depend on the inflation to cylindrical tubes of flat rectangular envelopes made from an impermeable textile or plastic sheet. All three types are basically single-acting and designed to produce tensile force between fixed and moving anchorages. However, as in the case of skeletal muscle groups, two such actuators can be operated as mutual antagonists to give a double-acting system.

In all the tests described here, the working fluid was air at a supply pressure 50 lb/sq in, gauge. The air entered the manifold shown in Fig. 1a, serving the actuator under test, and was allowed to leak to atmosphere through a short length of high-pressure rubber tubing. The latter could be partially closed by a screwed clamp to give the required pressure in the manifold and actuator under test, as registered on the gauge shown. The latter was calibrated against an accurate manometer and found to have a maximum error of 0.4 lb/in^2 throughout the pressure range of the tests.

2.1 Displaced roller actuator

This relatively inefficient actuator is suitable for applications demanding a very long excursion, not necessarily in a straight line, but needing only a low force. An inflatable tube chamber slightly longer than the required stroke is attached along its length to a supporting base surface. The load is attached to the spindle of a roller which is constrained to travel along the flattened tube, pressing the latter firmly against the base surface and so sealing the tube along its line of contact with the roller. Inflation of the tube causes it to expand on the inlet side of the roller, creating a force on the face of the roller which pushes it along the tube and so moves the load. In this type of actuator the tube walls must be strong enough to resist the bursting force of the fluid at its maximum working pressure or alternatively they must be supported by an inelastic mesh covering.

The base surface which supports the working chamber tube, and against which the latter is sealed by the roller, may be flat or have any smooth curvature provided the roller can be accurately guided over it.

In the test prototype (Fig. 1b), the base surface was the outer curved surface of a drum. A yoke, turning on an axle through the centre of the drum, carried the roller spindle and was attached to a pulley over which the loading cable passed. The roller was faced with sponge rubber, which was compressed where it made contact with the working chamber tube to ensure efficient sealing of the latter. Better results might well have been obtained by spring loading of a rigid-faced roller to achieve the desired seal.

Figs. 1c and 1d show this actuator raising a load of 5.4 lb through 5.6 inches with a working pressure of 15.0 lb/sq in and a roller contact line width of 1.15 inches. The shape of the contact area between working chamber tube and roller was mapped by ink printing, and a strip technique used to calculate the force v. pressure relationship. The pressure required to raise 5.4 lb was thus calculated as 15.8 lb/sq in. giving good agreement with the measured value of 15.0 lb/sq in. No further work was carried out on this type of actuator following the above test made during November 1959.

A hoist using a similar principle, but having rollers on both sides of a freely suspended flattened tube rather than a rigid surface on one side, was devised independently in 1961 by F.T. Kiernan of Mechanical Engineering Dept., R.A.E., at R.D.E., Cardington. The rubberised fabric tube of this hoist is 9.5 inches wide and some 10 feet long, and is sandwiched between rollers 1.5 inches in diameter. A load of 150 lb can be raised readily by this hoist using a working pressure of 15 lb/in^2 (effective).

2.2 Expanding box actuator

This applies most directly the principle of utilising the whole working chamber wall at one time. A box is formed from rigid plates hinged together along their parallel edges and provided with suitable mechanism for moving a load. In the absence of fluid pressure within an impermeable, flexible liner to the box, the latter collapses under load into a flat envelope. The liner expands on admitting fluid pressure, forcing the rigid plates apart against the load's constraint until the actuator assumes the limiting form of a tube of polygonal section. The shape and size of this limiting tube form is fixed entirely by the number and dimensions of the rigid plates forming it.

The test model, shown in Fig. 2a, comprised six hinged plates. Of these, the two largest opposed plates each carried three axles, bearing pulleys at their extremities. A system of cords, anchored to a fixed crosshead at the fluid input end of the actuator, passed over these pulleys and terminated in a moving crosshead carrying a loading hook. The gearing is seen to be readily variable by lacing the loading cords in different patterns. The ends of the inflatable liner which were unsupported by the rigid plates were restrained against bursting by a stockinette sleeve tailored to fit the expanded shape of the actuator.

The plain journal pulleys used in the test model had very high friction thus giving poor performance for the actuator during its tests in November 1959. Figs. 2b and 2c show the actuator before and after admitting pressure against the weight carrier load of 0.4 lb. Owing to the high friction, a pressure of 3.3 lb/in^2 was needed to raise the load through 3.1 inches.

With rearranged loading cords giving a travel of 1.0 inches, the actuator is seen in Figs. 2d and 2e raising 40 lb with a working pressure of 12.0 lb/in^2. The cross sectional area of the fully-expanded working chamber was 1.09 sq in and the effective chamber length was 5.75 inches.

2.3 Muscle-motor actuator

In considering the various patterns of loading cords for the expanding box actuator it was thought of as comprising discreet elements along its length, each bearing loading pulleys over which the cords passed in zig-zag fashion. This suggested a similar arrangement, omitting the pulleys and having loading cords passing directly over inflatable chambers lying normal to the loading axis.

This woven construction was used for the first muscle-motor shown in Fig. 3a. Nine loading tapes formed the warp and six inflatable tubes formed the weft. It was apparent on first testing this actuator that at least 50% of the possible efficiency was being lost by expansion of the inflated tubes between the loading tapes. The obvious remedy was the use of sheet material in place of the loading tapes. This modification also simplified the dissipation of the concentrated end load into the full working width of the actuator.

Thus emerged the final form of the muscle-motor actuator, which comprises two sheets of flexible impervious material seamed together to produce a number of rectangular pockets or lobes lying normal to the loading axis (Fig. 3b). The lobes are supplied with fluid, either by a common duct formed along one margin of the actuator or by suitable ports between the lobes; alternatively it may be desirable to supply lobes individually, to improve reliability or response.

Admission of fluid pressure causes each lobe to distend until it reaches the limiting form of a circular section tube. This distension produces contraction of the actuator, creating a tensile force between its end attachments. The maximum contraction is determined by simple geometry. Consider a lobe of length, ℓ (measured along the loading axis), which inflates to a tube of diameter, d (Fig. 3b). Then $\ell = \pi d/2$. The contraction along the loading axis, expressed as a fraction of the rest length, ℓ is thus: $\frac{\ell - d}{\ell} = \frac{\pi d/2 - d}{\pi d/2} = \frac{\pi/2 - 1}{\pi/2} = 0.3634$. This maximum contraction of 36.34% of the rest length is a constant for any actuator of this type, irrespective of the number of lobes and of their angle relative to the loading axis. It is emphasised that no stretching of the lobe walls occurs, the whole action being a change of lobe shape from flat to circular section.

The author's attention has been drawn to unpublished experimental work by J.M. Rayne of R.A.E., using the inflation of discs (seamed at the periphery) into spheres to provide a tensile force. It can be shown, by equating surface areas, that such an actuator will give a maximum linear contraction (along any diameter) of 29.3% of the rest length.

For convenience of manufacture, the author's test model of the muscle-motor (Fig. 4a) was of 2 ply construction. Load bearing sheets of high quality fine linen were machine sewn to form lobes which were lined with plastic toy balloons. Each loading attachment was formed from two metal plates, riveted together so as to clamp a roughened circular rod around which the linen sheets were passed before assembly (Fig. 3b).

Tests of this model actuator were made during October 1959. Maximum contraction was first checked using only a nominal load of 0.8 lb to tension the actuator (Fig. 4b). Using a working pressure of 14.3 lb/in^2, the measured contraction was 35.7%, which is in good agreement with the value of 35.9% later calculated by the method of Appendix 1 and confirms the figure of 36.3% for zero load.

Tests were then made at ten fixed pressure settings up to a maximum working pressure of 14.25 lb/in^2 gauge. Load increments of 5 lb were applied up to a maximum load of 50 lb at all but the two lowest pressures. At each load increment the air leak to atmosphere was progressively reduced until the gauge indicated the desired pressure in the actuator. Contraction was measured by the scale seen in Fig. 4, which was set to zero initially with only the weight carrier in position. With the higher loads, slight stretch of the fabric and stitching (measured with the air supply turned off) necessitated a correction to the measured contraction. This was variable with load and never exceeded 0.1 inches (1.65% gauge length).

The results of these tests are presented in Fig. 5 as load v. contraction curves for each value of working pressure. Cross plotting of this family of curves produced those shown in Fig. 6, which correspond to isotonic and isometric operation respectively.

3 CHARACTERISTICS OF TWO ACTUATOR TYPES TESTED

3.1 Displaced-roller actuator

This type of actuator does not have the improved force v. pressure relationship since its working area, only part of the roller face, is comparable to the piston area of a conventional ram actuator. For many applications, however, the displaced-roller has the following advantages:

(a) unlimited stroke length,

(b) ability to conform to three dimensional changes of shape along the working stroke,

(c) extreme simplicity and cheapness of manufacture, as no high tolerance work needed.

(d) completely enclosed working fluid, hence no glands exposing fluid on moving element: this permits dangerous, corrosive or dirty fluids to be used.

This type of actuator is readily made double-acting by providing fluid supply pipes to both ends of the working chamber tube, exactly as in a conventional ram actuator.

Suitable applications for displaced-roller actuators are those requiring long stroke and ability to follow curved paths. Thus, a suitable aircraft application might be in the operation of roller-shutter bomb doors or cargo hatches. Similarly, the complex high-lift flap systems now being incorporated in some S.T.O.L. aircraft could usefully employ such actuators. In each case, the working tubes would be submerged in the roller guides supporting the moving surfaces.

Aircraft catapults using steam for ship-borne aircraft or gas for land-based aircraft or missiles in the field might be based on such actuators. A water-filled actuator exhausting through a restricted orifice would also provide a ready means of arresting aircraft landing runs. For such applications, the form of actuator developed by M.E. Department, R.A.E., using rollers either side of a plain flattened tube would probably be superior to the author's prototype. In this group of applications the advantages of the displaced roller actuator over the present steam catapult and hydraulic rams are in the elimination of glands and long seals, extreme cheapness and flexibility of design, together with portability.

In general engineering, the likeliest applications are to the remote operations of doors, particularly where these must travel along curved tracks, or to mechanical handling systems where a cheap and crude means of moving pallets along complicated routes is needed.

The response time of the displaced-roller actuator is similar to that of the comparable conventional ram and increases directly with stroke length.

3.2 Expanding box actuator

The optimum force v. pressure relation is obtainable with this type of actuator when its limiting inflated form approximates closely to that of a circular cylinder. This suggests surrounding the inflatable chamber with a "squirrel cage" of narrow rectangular plates pivotally carried by iris-diaphragm mechanisms on circular end plates. The rectangular plates would carry the loading cables in suitable fairleads on their outer edges; these cables form spiral windings tending to collapse the unit when under load.

Such a design would utilise the fluid pressure at optimum efficiency, but the mechanical complexity could well outweigh this advantage, so that an actuator more comparable to the prototype of Fig. 2 might be superior.

The main problem with this type of actuator is to minimise friction between the loading cables and the moving plates to which the load is transferred. The use of sintered P.T.F.E.* fairleads or needle rollers are possible ways of overcoming this problem.

As in the conventional actuator the force v. pressure relationship is substantially independent of stroke length, but in the case of the expanding-box actuator it is essentially surface area rather than cross sectional area which is concerned in this relationship.

In common with the other actuators described in this Note, the expanding-box type has the working fluid totally enclosed and glands are eliminated. Response of the actuator is rapid (provided friction is kept low), since the movement of the loading cords is usually much greater than that of the plates carrying them. It follows that response depends largely on the gearing, changing of which is intrinsically simple with designs similar to that of Fig. 2.

4 CHARACTERISTICS OF MUSCLE-MOTOR ACTUATOR

4.1 Design considerations

During the earliest part of its contraction this actuator behaves similarly to a toggle mechanism in that, theoretically, an infinitely large load is applied by an infinitely small lateral force (which implies, in this case, infinitely small fluid pressure). The axial component of the tension in the lobe walls falls rapidly, however, as the contraction continues. The relationship between axial force and degree of contraction is calculated in Appendix 1, the resultant curve appearing as Fig.7.

The product of axial force and contraction from the axial rest length is a measure of the work done by the actuator. This product, plotted

* Polytetrafluoroethylene.

against contraction in Fig. 8b, is seen to have a maximum value at a contraction of 11.5%. Over the range 6.5% to 17% contraction, the work done is within 90% of the maximum value and this range may be considered the optimum working range. Mechanisms for use with this actuator should therefore be designed to work over this contraction range as far as possible.

The volume of fluid filling a lobe of the actuator is another parameter which varies with contraction, the relationship being derived in Appendix 1 and plotted in Fig 8a. From considerations of response time and power supply, the aim should be to keep fluid volume to the minimum.

Division of fluid volume by the "force exerted" parameter of Fig. 7, for all values of contraction, produces the term V/F, plotted against contraction in Fig. 8b. This term, which represents the supply power requirement for a given force is seen to increase only slowly with contraction, up to some 20% contraction, after which it rises steeply.

This confirms the previously derived optimum working range and makes it clear that the muscle-motor actuator is best suited to short stroke applications unless gearing up is acceptable.

Coupling together of two muscle-motors, having suitable power take-off at their joined ends and their outer ends "earthed", provides a double-acting actuator. In most applications, however, it will be preferable to use two separate motors acting in opposed sense on some common linkage.

For some specialised applications it may be desirable to connect, by suitable piping, two identical muscle-motors as the transmitting and receiving ends respectively of a leakproof hydrostatic transmission system. Consideration of such a system shows that the non-linearity effects of each actuator are mutually exaggerated and that the optimum working point of the system is where each motor has a volume equal to half that of a fully contracted motor. This occurs at a contraction of 4.15% of the rest length, with operating force at the transmitter unit equal to the load at the receiver (since the pressure is common to both units). Thus conditions are essentially linear over only 5% of the receiver contraction range and, for constant receiver load W, the transmitter force required varies from 0.23W at 1% contraction to 1.69W at 6% contraction of the receiver unit. With such a configuration, much of the contraction range of the transmitter unit is traversed before any appreciable deflection of the load is achieved: commencing at full contraction of 36.34%, the transmitter must be extended down to a contraction of 10.7% to give a receiver contraction of only 1%, and further to 3.9% for a receiver contraction of 6%.

These facts suggest that, where a muscle-motor forms the receiver of a hydrostatic transmission system, the transmitter should be of the squeeze-bulb type. The bulb volume of this transmitter should greatly exceed the volume of the fully-contracted muscle-motor, mechanical limit stops being provided to protect the latter from over inflation. Such systems form an important group of applications for the muscle-motor, being completely sealed and leakproof and free from mechanical friction due to the absence of sliding parts.

Where the force output of a muscle-motor actuator is required to be linear over the whole range of movement, the characteristic of the supply must be adapted to be the reverse of the pressure volume characteristics of the actuator or, alternatively, non-linear gearing is required between the actuator and its load.

Response of the muscle-motor is variable within wide limits. The volume of fluid required for a given contraction may be decreased by using a larger number of lobes, with a corresponding decrease in the length (ℓ)

of each. A major effect on response will result from feeding each lobe of the actuator from a separate supply pipe.

Where a large load is to be handled and space for a large surface area muscle-motor is not available, smaller ones may be stacked so that they act in parallel. A convenient geometrical arrangement here is that adjacent motors are displaced by $\frac{1}{2}\ell$, so that the lobes of each motor lie in the grooves between neighbouring motor lobes. In such a situation, the use of a conventional actuator may be more practical if the 100% sealing and minimal friction qualities of the muscle-motor are not essential.

Within the same muscle-motor, lobes may be of varying size and/or inclination to the loading axis and supplied by independent fluid pressure sources. In this manner graduations of force and contraction to suit specific applications may be obtained with minimum effort.

4.2 Engineering applications

The applications for which the muscle-motor form of actuator is suited may be linked to its four main characteristics:

(a) dependence of force on surface rather than cross-sectional area,

(b) ability to conform to curved stroke paths whilst moving and under load,

(c) freedom from sliding parts and hence from sliding friction,

(d) freedom from leaks since the system is positively sealed from its environment.

In the aircraft field, hovercraft and some modern V/S.T.O.L. aircraft require large quantities of air to be distributed through their structure in suitable ducts. Thus a ready working fluid is available for muscle-motors employed to vary blowing nozzle configurations, or to move flaps, flexible curtains and the like during hovering or low forward speed applications.

The awkwardly shaped free spaces of undercarriage wells and those between tail pipes and structure of the airframe must frequently house actuators for undercarriage retraction and nozzle area control respectively. The ability of the muscle-motor to perform on a curved path suggests it may be used to advantage here. To prevent excessive friction on the motor surface, rods having their ends supported in suitable curved guide channels may be built into the motor along the inter-lobe seams. Alternatively the motor may be surrounded by a liquid-filled flexible bag and protected thereby in the same way that the human lung is protected from the ribs' abrasive action by the pleural sac. In the particular case of tail-pipe nozzle actuation, the surrounding cooling-air stream, which is usually provided by compressor bleed, might well be used as the working fluid source, providing a degree of feedback potential.

The control of flow in ducts carrying "cold" air in aircraft might perhaps be carried out by making portions of the duct flexible and incorporating muscle-motor lobes in these regions. Using the flow in the duct as the working fluid, changes of duct area would be effected by the motor constricting the duct in the manner of a sphincter muscle. Control of such a "valve" might be by a very small servo-valve, governing the admission of duct flow air to the motor through a diaphragm pressure-balance servo. An automatic flow control system is a further possibility using this principle.

In those pressurised flying suits using pressures as high as 3 to 5 lb/in^2 a large physical effort may be needed to move the limbs or to prevent hyperextension in emergencies. If muscle-motors were built into the appropriate aspects of the limb envelopes, the use of the suit pressurising air as the working fluid would give power assistance directly proportional to the internal pressure and hence to the load.

In conjunction with bottles of compressed gas the muscle-motor would provide a very cheap but reliable one-shot emergency power system for such duties as mechanical lock operation, canopy or dinghy release. For such applications, the very small bulk of the motor, together with its complete mobility whilst in the collapsed, inoperative state might constitute definite advantages.

The foregoing examples are all of applications where precise positioning of the load is unimportant, or where positional control may be exercised by a mechanical linkage which is independent of load application. For many applications of muscle-motors using a gaseous working fluid, stiffness requirements may make separate positional linkages essential, though the author's experience with crude, home-made motors suggests that this is unlikely.

In dealing with conventional hydraulic systems the large forces obtainable with high pressures often make designers use small movements. Thus precise positioning is here important, but the danger is that its importance may be over emphasised where manual monitoring of position is possible. Before irreversible powered primary flying controls became common, boosted manual power was often used, the boosting power being provided either by aerodynamic servo tabs or by hydraulic jacks. Since the pilot still felt the same force gradients for given aircraft movements at a given speed, it was found that the position of the control column within its range of movement was unimportant.

As control surface hinge moments continued to increase, it became more difficult to obtain adequate stiffness with boosted manual controls and emphasis shifted to irreversible power systems. Here control column position is important since it determines "stick force" due to the spring feel systems commonly used (though often modified by an input of force proportional to dynamic pressure).

It is suggested that the use of muscle-motors fed with ram air and used as power boosters to manual control may actually raise the threshold of hinge-moment at which such power boosted systems can operate. This is because the power can be applied along the whole spanwise extent of a control surface, rather than at one or two points and torsional stiffness of the control surface is thus effectively increased.

Thus, in such a system, control column movement would admit ram air independently to every lobe of large sheet muscle-motor actuators, located under the fixed surface skin and extending over most of its chordwise extent for the full spanwise length of the control surface. The muscle-motors (two, for opposed deflections of the control surface) would be continuously attached to the control surface at its maximum thickness. Use of a large number of lobes would reduce the contracted muscle-motor thickness and simultaneously improve response, besides providing a high degree of immunity to battle-damage. The principal problem to be investigated in considering such a design would undoubtedly be stiffness, on which the whole feasibility would depend.

A similar system to that just described would almost certainly be suitable for providing cheap power steering for small ships, with water as the working fluid. A hydrostatic transmission system with squeeze-bulb type transmitters operated by the ship's wheel and muscle-motor actuators driving the rudder is a further possibility.

Such hydrostatic transmission systems, using either water or conventional hydraulic fluids would form the majority of applications for muscle-motors in the general engineering fields. Thus, in automobiles they might be used for accelerator, brake and clutch linkages and for applications such as window winding for which power-operation is at present an expensive luxury. Similarly in cases where the application of "automation" to existing plant is only marginally justified on a cost basis, the extreme cheapness and simplicity of such actuators might well influence their acceptance.

5 MEDICAL APPLICATIONS OF MUSCLE-MOTOR ACTUATOR

As shown in Fig. 4c, the prototype of this actuator is producing 350 lb tension per square inch of resting cross sectional area. This compares favourably with an average value of 140 lb/in^2 for human skeletal muscle during optimum contraction, and thus shows that the actuator can satisfy power needs for operating all types of artificial limbs and "flail" appliances for paralysed limbs.

Fig. 9 compares the length/tension characteristics of living muscle (similar to human skeletal muscle) and those of the muscle-motor actuator. These are seen to be virtually identical over the contraction range 18% to 32%. Living muscle can, however, contract to nearly 50% of its rest length when in isolation, compared with the 36% maximum of the motor. This has no great significance however, as muscles rarely contract by more than 12% "in vivo", this contraction being usually over the optimum range of some 5% to 17% rest length.

For contractions less than 18% the muscle-motor actuator can develop tension tending to infinity, but this is dependent on the provision of an adequate supply of working fluid at a high enough pressure and on its walls being formed from a material of sufficient strength. In the author's prosthetic muscle system, fluid supply is from a pump; owing to the large number of design parameters, it would be a simple matter to arrange for the muscle-motor tension to duplicate that of living muscle over the range 0 to 18% contraction.

Thus the muscle motor actuator can readily be made a true physiological copy of a human muscle group over a practical excursion. By suitable design of its lobe configuration, it can also duplicate the flexibility and the bulging property, under load, of human muscle. Consequently, if formed from an inert material such as the "Terylene" already used for surgical implants, such an actuator might well perform satisfactorily as an internal prosthesis. This would involve implanting also the fluid pressure generator and making provision for it to be fed with the necessary electrical signal. The latter would be difficult, but not impossible, as demonstrated by such devices as artificial pacemakers for hearts.

Alternatively, restoration of function to a paralysed limb might be by external use of the muscle motor(s) connected to the limb by a conventional flail appliance or by cineplastic tunnels. In such cases there are no surgical problems, only those of obtaining the necessary control by use of the myo-electric currents still sensible at the limb.

Muscle-motor actuators may be used for many functions in connection with external prostheses for amputated limbs. Supply of working fluid, usually water or a hydraulic fluid, may be by a fluid pressure generator controlled by stump action-currents in the way already described. The method used is to be discussed separately in a medical publication when the whole question of artificial muscle will be considered in detail. The most common use for muscle-motor actuators in artificial limbs will be for powering hands or terminal applicances to forearms, more particularly in the case of the double arm amputee. Where the complication of control by myo-electric currents is undesirable, such forearm "muscles" may obtain their fluid pressure supply from squeeze-bulb type transmitters embodied in a conventional limb harness or within the wall of an arm socket.

This principle of sealed circuit, hydrostatic transmission between a squeeze-bulb transmitter and a muscle-motor actuator has many possibilities in the medical field, owing to its similarity to some physiological systems. As a further example, a difficulty with artificial hands is the provision of tactile feedback. This might be readily obtained by the use of a pump-bulb in a thumb or finger tip pad, connected to a muscle motor by flexible tubing, so as to produce a pressure stimulus on the stump skin through a simple lever stylus. Such a stimulus would be applied to a site whose cutaneous innervation was common with that of the missing digits.

6 CONCLUSIONS

Some forms of servo actuator have been described which depend on the inflation of flat envelopes of flexible material to essentially cylindrical form. One particular type has been shown to have a large number of possible applications in aeronautical and general engineering in addition to the medical role for which it was designed.

Such actuators work at lower pressures than conventional fluid pressure servos since, to a first approximation, their force output is dependent on their surface area rather than their cross sectional area.

In their medical role of internal or external muscle prostheses, such actuators are shown to duplicate the length/tension characteristics of live muscle under active contraction and to have a similar optimum working range of contraction.

The necessary design formulae for such actuators have been derived in the Appendix to this Note.

It is considered that the extreme simplicity and economy of these actuators entitles them to consideration as alternatives to conventional fluid pressure actuators in any low-pressure fluid servo system.

APPENDIX 1

1 DESIGN OF MUSCLE-MOTOR ACTUATOR LOBE

For most applications, the actuator will comprise a number of similar lobes, each of rectangular shape and having the dimensions shown in Appendix 1 Fig. 1a.

To complete a design it is necessary to know:-

(i) The force, F exerted by the lobe having internal fluid pressure, p acting on it's walls.

(ii) The volume of fluid contained by the lobe.

Both these quantities vary with the amount of contraction, x (Appendix 1 Fig. 1c), which is conveniently expressed as a fraction of the rest length, ℓ of the lobe.

2 TO DETERMINE FORCE (F)

Consider the surface element dS (Appendix 1 Fig. 1b) having the width, w, into the paper.

Then T is the tension in the surface
p is the fluid pressure
R is the radius of curvature of the element.

Since T is everywhere tangential to the surface, tangential resolution shows that it is everywhere constant.

Now

$$\frac{p.w.dS}{T} = \sin d\theta$$

(which, in the limit, is equal to $d\theta$).

Therefore $$T\, d\,\theta = p.w.dS\ .$$

But

$$dS = R\, d\,\theta\ .$$

Therefore $$T = p.w.R\ . \tag{1}$$

Now T, p and w are all constant for the given configuration. Hence R is constant, showing that the surface is an arc of a circle. Referring to Appendix 1 Fig. 1c we see that

$$F = 2\ T \cos\theta$$

and

$$\ell = R.2\ \theta\ .$$

Therefore $$F = 2\ p\ w\ R \cos\theta \text{ (from 1)}\ .$$

But $$R = \ell/2\theta$$

therefore $$F = p\ w\ \ell \cos\theta/\theta$$

or
$$\frac{F}{p\,w\,\ell} = \frac{\cos\theta}{\theta} \tag{2}$$

Now
$$b/R = \sin\theta\ ,$$

therefore
$$b = R\sin\theta = \ell\sin\theta/2\theta$$

therefore
$$2b = \ell\sin\theta/\theta\quad . \tag{3}$$

Contraction $x = \ell - 2b$, therefore $2b = \ell - x$.

Therefore from 3, we have

$$\frac{\ell - x}{\ell} = \frac{\sin\theta}{\theta}$$

or

$$1 - \frac{x}{\ell} = \frac{\sin\theta}{\theta}\quad . \tag{4}$$

The dimensionless force and contraction terms, $\frac{F}{p\,w\,\ell}$ and $\frac{x}{\ell}$ respectively, have been calculated for values of θ from 0^{o} to 90^{o} and are plotted against each other in Fig. 7, to provide a design curve for all actuator lobes of this form. This obviates the intermediate step of evaluating θ and to further simplify design without loss of accuracy, normal curve fitting techniques were used to find the law of the above curve. This was determined as

$$\frac{F}{p\,w\,\ell} = \frac{1.1212}{\left(\frac{x}{\ell}\right)^{0.344}} - 1.5842\quad . \tag{5}$$

By use of this law F may be determined to an accuracy of 0.6% for values of $\frac{x}{\ell}$ within the optimum working range of Fig. 8b.

3 TO DETERMINE FLUID CONTENTS OF LOBE

Considering Appendix 1, Fig. 1c, let shaded area = Z.

Therefore Z = Area of Sector AECO - Area of Triangle AOC.

Therefore
$$Z = \frac{\ell R}{2} - 2\left(\frac{Ry}{2}\right) = \frac{\ell R}{2} - Ry\ . \tag{6}$$

But $R = \frac{\ell}{2\theta}$ and $y = b\cos\theta$.

Therefore substituting in 6,

$$Z = \frac{\ell^2}{4\theta} - \frac{\ell b\cos\theta}{2\theta}\quad . \tag{7}$$

Now $b = \frac{\ell - x}{2}$ therefore substitution in 7 gives:-

$$Z = \frac{\ell^2}{4\theta} - \frac{(\ell^2 - \ell x)\cos\theta}{4\theta}$$

and division throughout by ℓ^2 gives:-

$$\frac{Z}{\ell^2} = \frac{1 - \cos\theta\left(1 - \frac{x}{\ell}\right)}{4\theta} \quad . \qquad (8)$$

Now the lobe cross section area = 2Z, and it's width is w, thus the lobe fluid contents volume, V = 2 Z w.

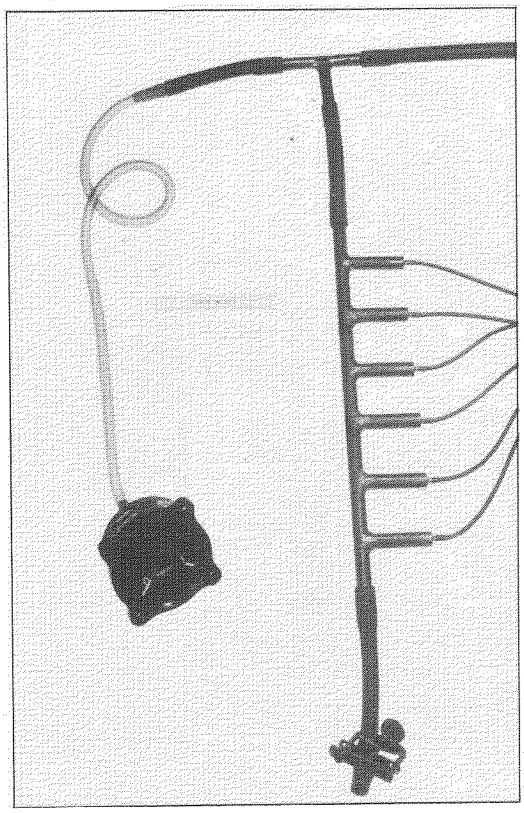
Substitution in 8 then gives:-

$$\frac{V}{w\ell^2} = \frac{1 - \cos\theta\left(1 - \frac{x}{\ell}\right)}{2\theta} \qquad (9)$$

This dimensionless expression for volume was evaluated for values of θ from 0° to 90° and is presented as a function of contraction, (x/ℓ) in Fig. 8a. The application of normal curve fitting methods showed that the law of the above curve could be given as the difference between two terms, thus:-

$$\frac{V}{w\ell^2} = 0.83176\sqrt{\frac{x}{\ell}} - 0.73569\left(\frac{x}{\ell} + 0.00422\right)^{1.390} \qquad (10)$$

This law enables V to be determined to an accuracy of 0.25% for values of x/ℓ within the optimum working range of Fig. 8b.



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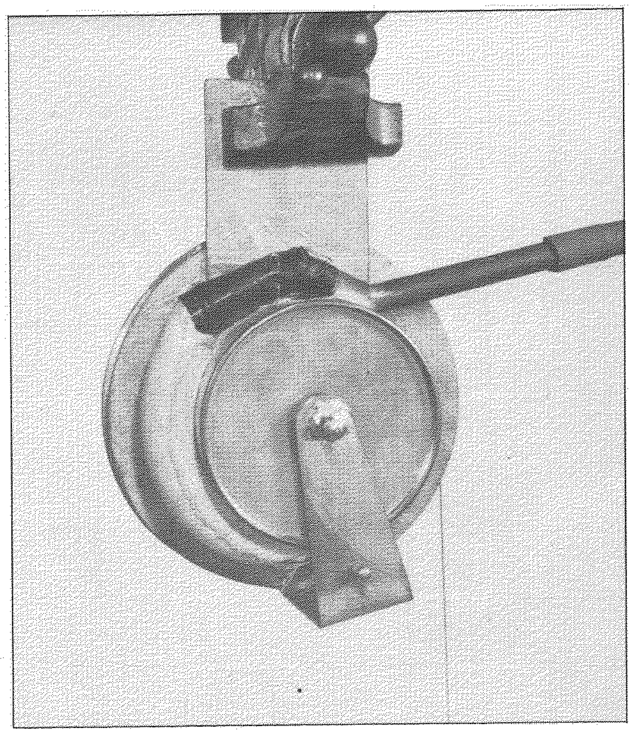

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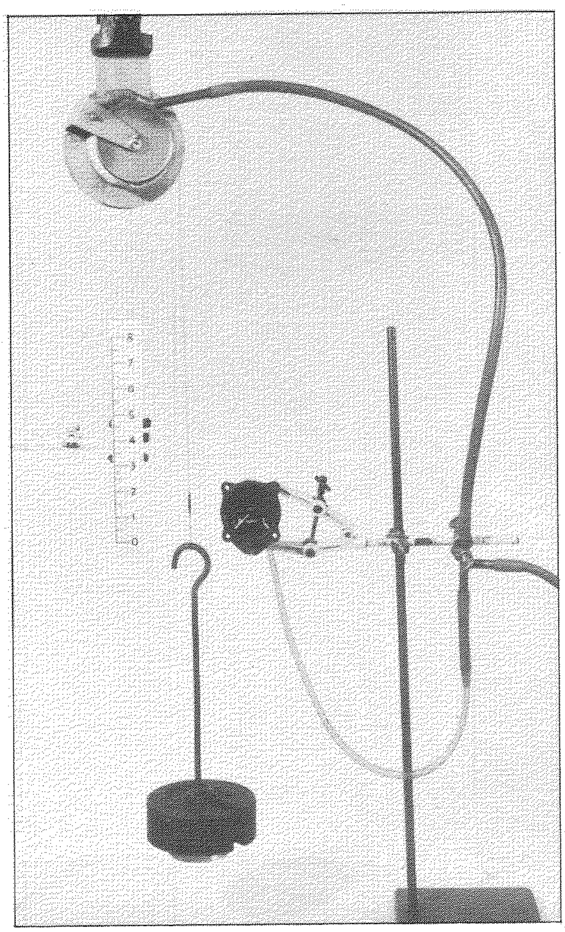

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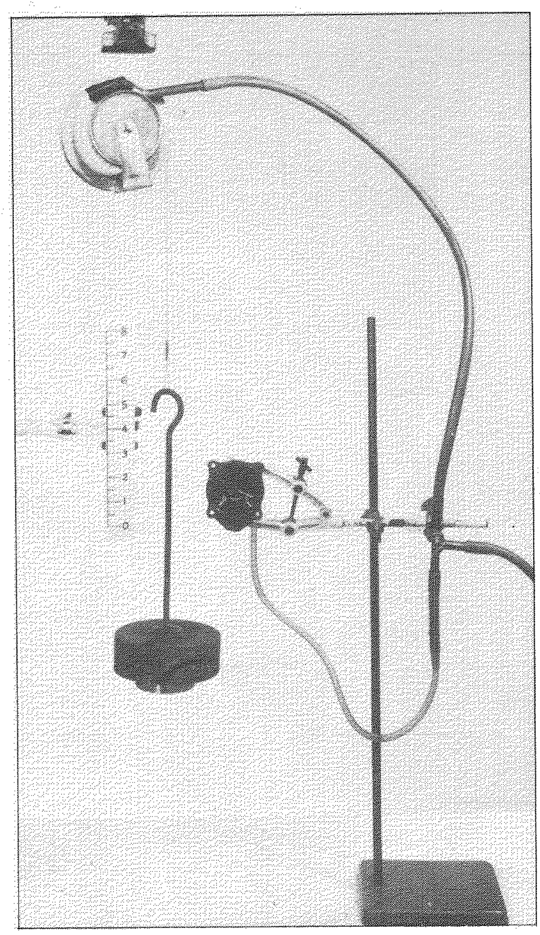

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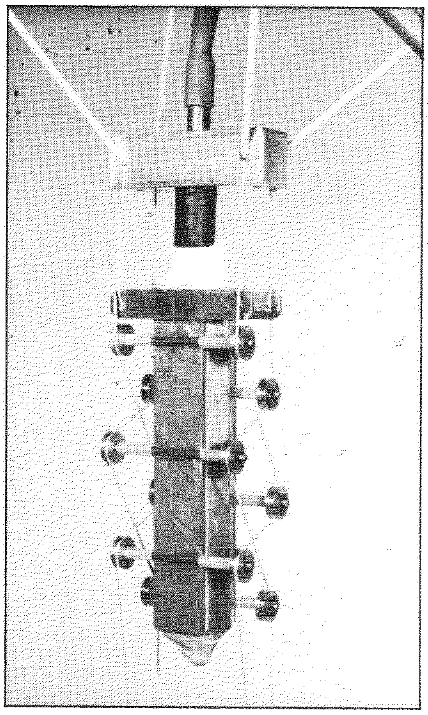

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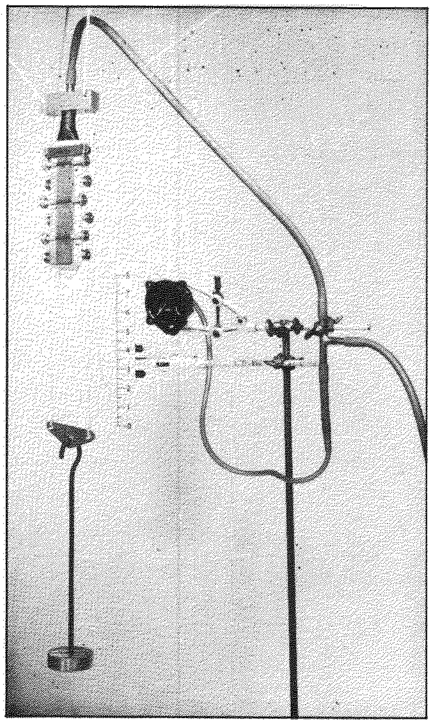

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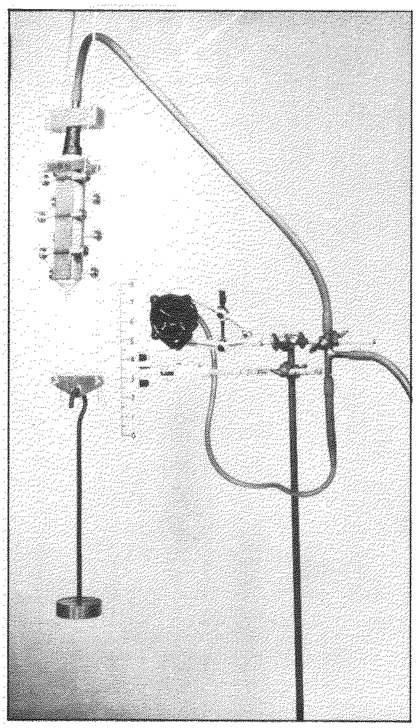

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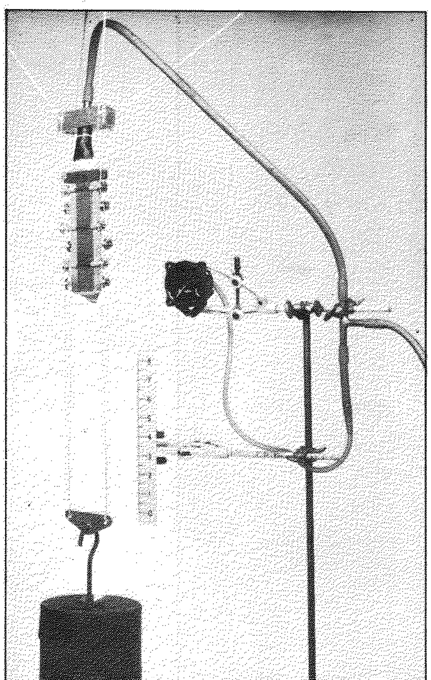

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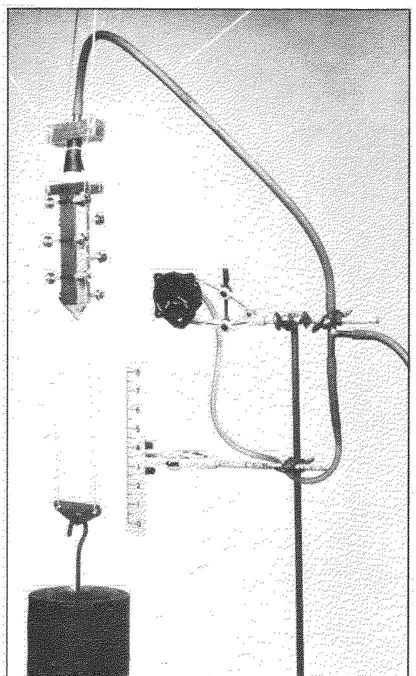

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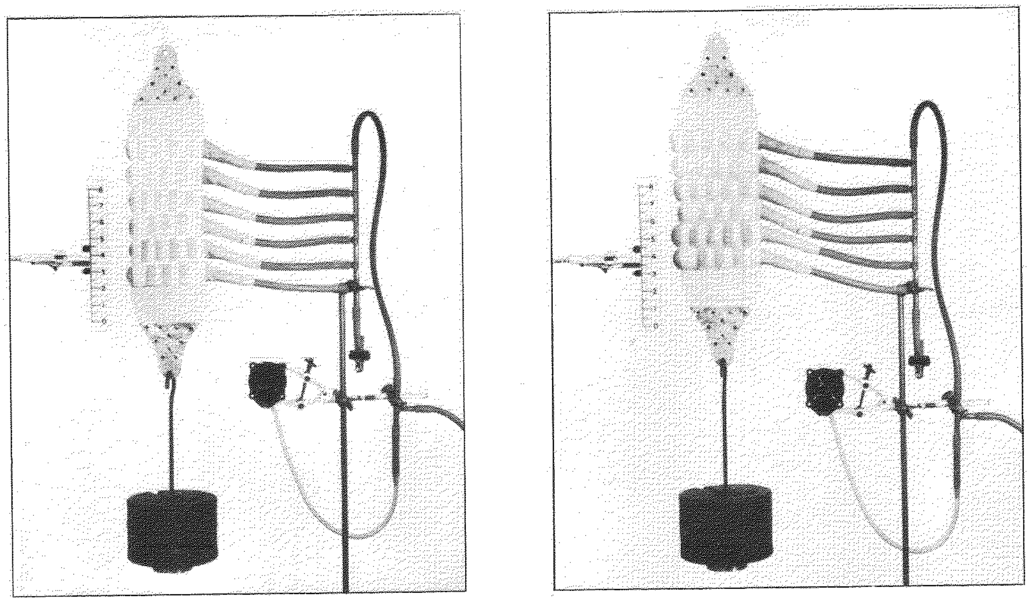
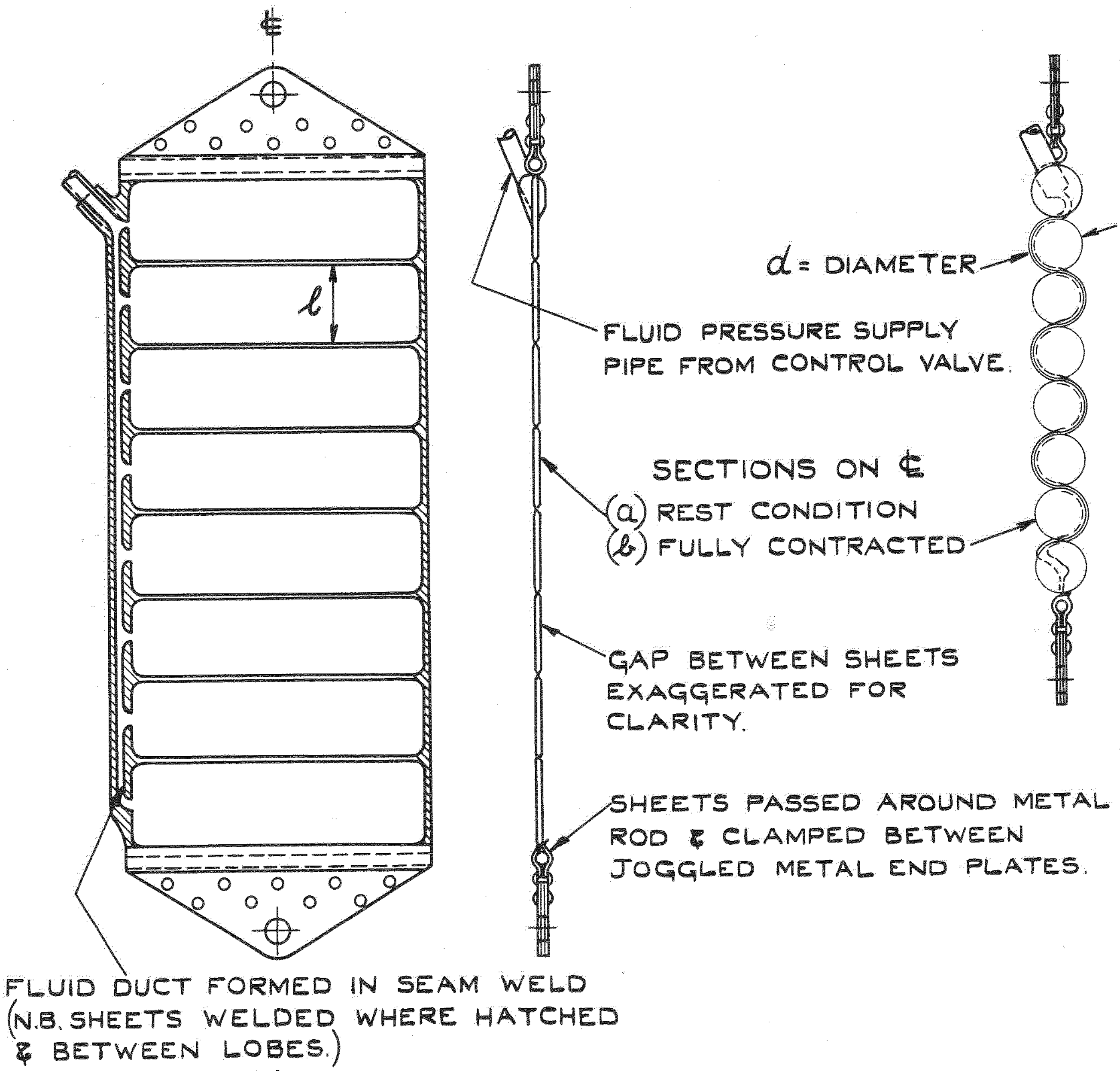
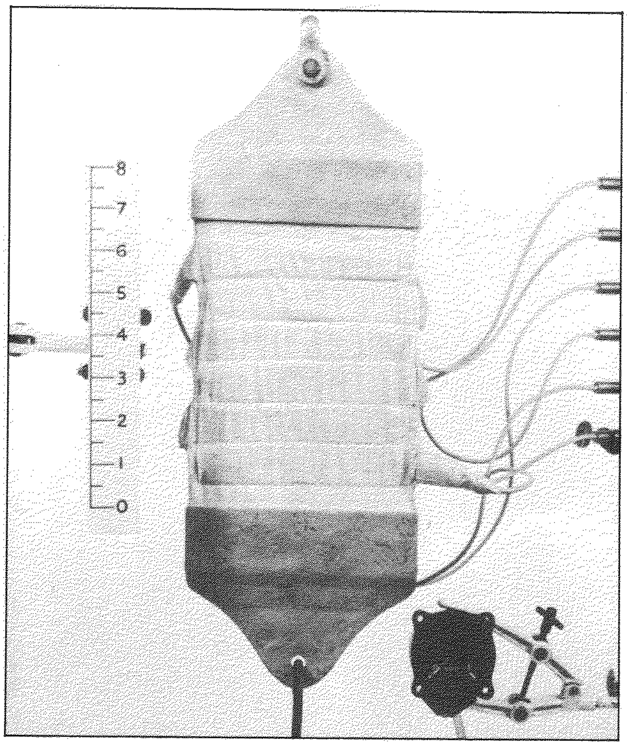


(a) FIRST MUSCLE-MOTOR ACTUATOR.



(b) DESIGN OF TYPICAL MUSCLE-MOTOR



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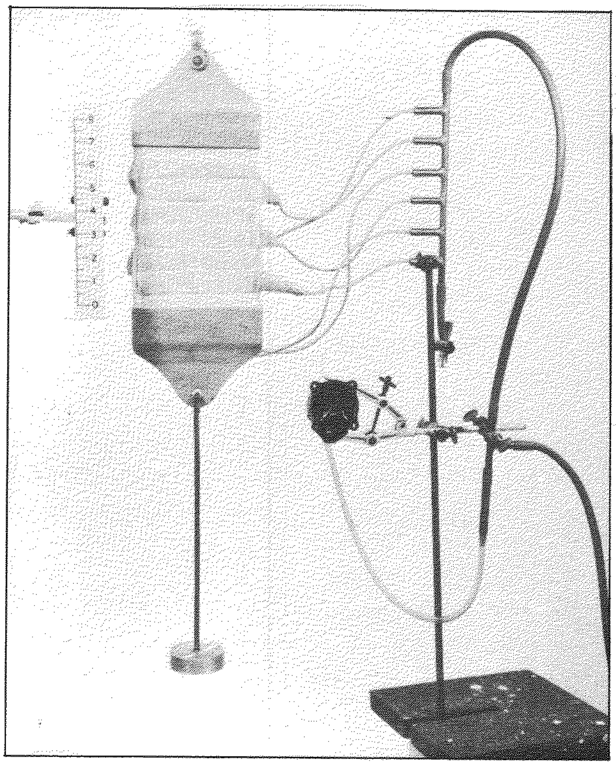

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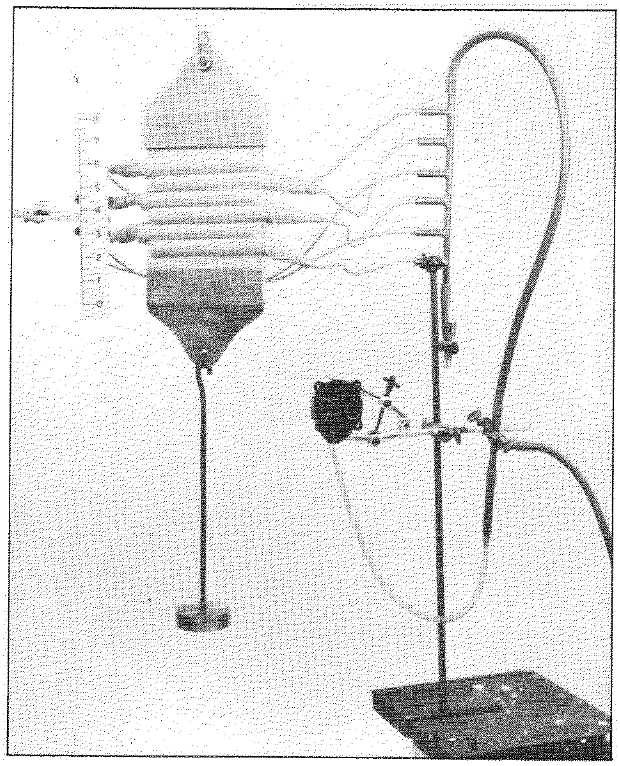

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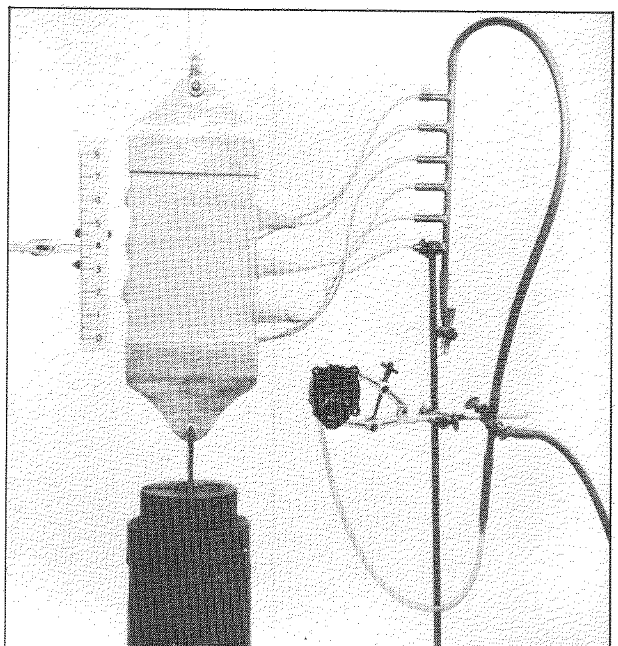

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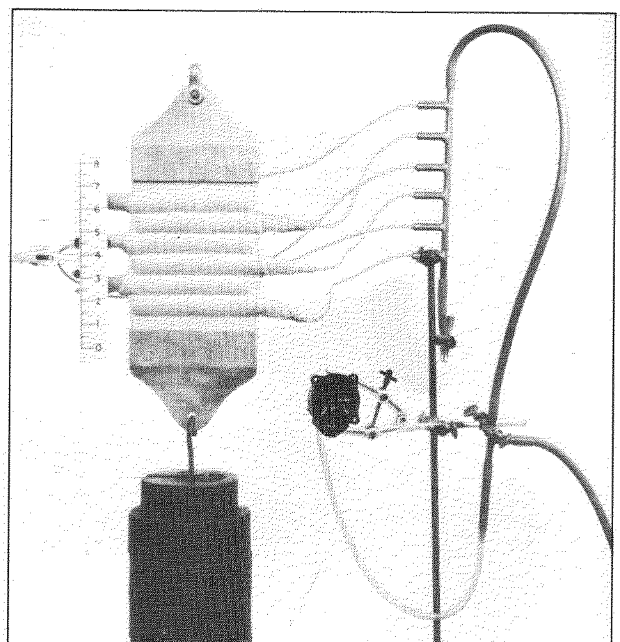

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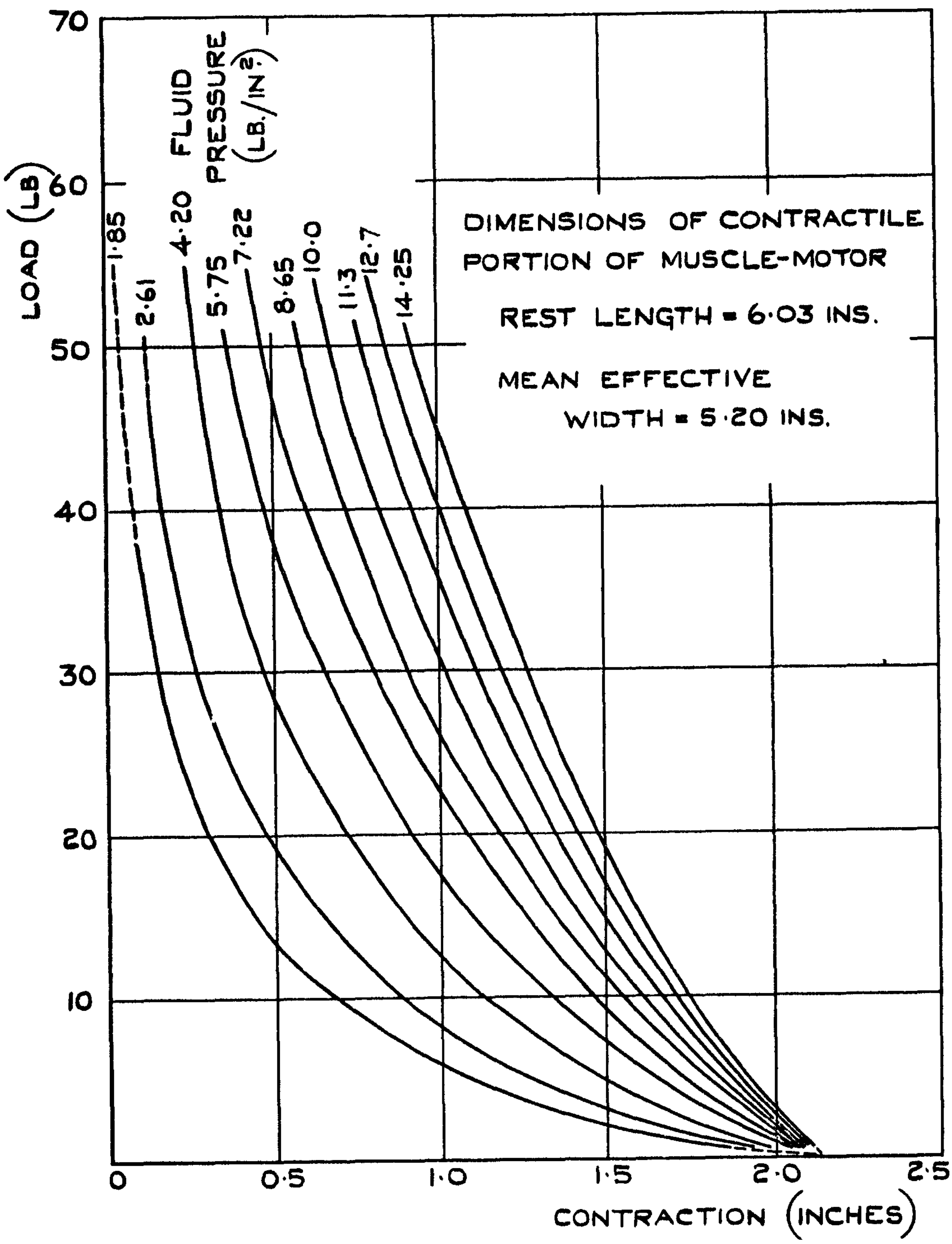
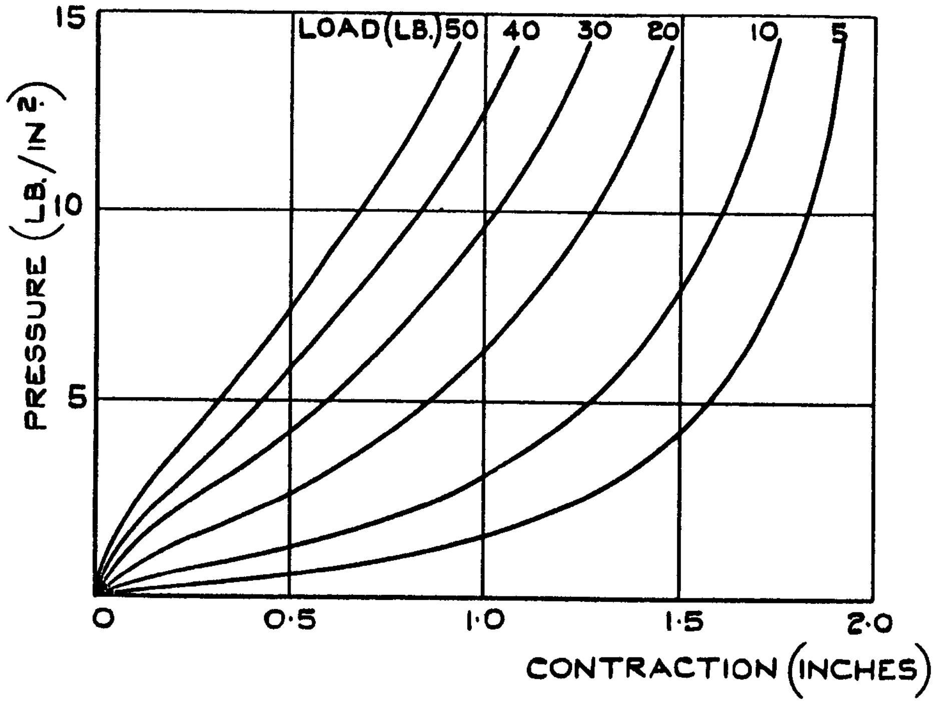
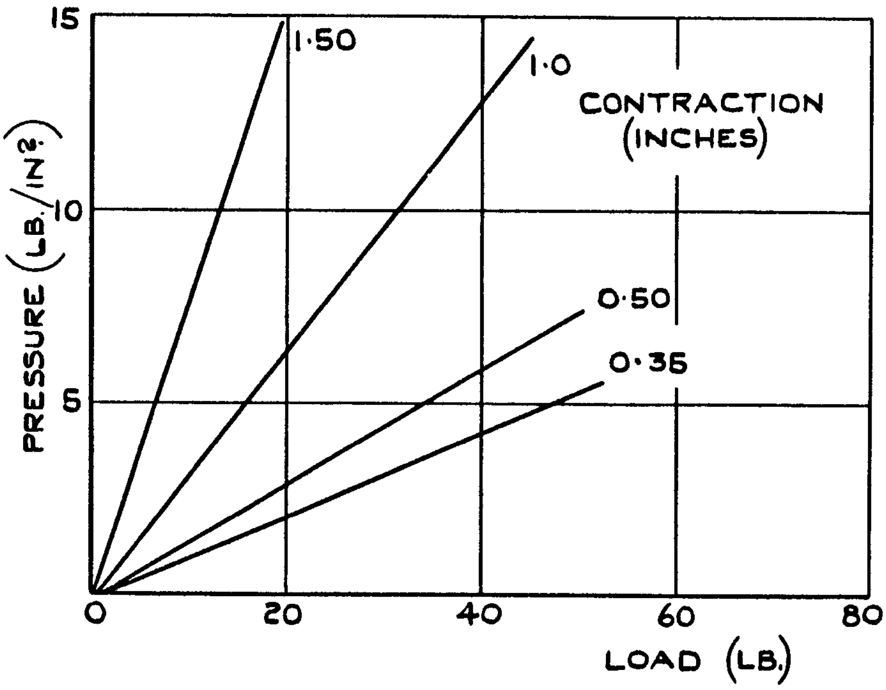


FIG.5. MUSCLE-MOTOR TEST RESULTS.
(LOAD v. CONTRACTION)



(a) ISOTONIC OPERATION–PRESSURE v. CONTRACTION.



(b) ISOMETRIC OPERATION – PRESSURE v. LOAD.

FIG. 6. MUSCLE–MOTOR TEST RESULTS.
(ISOTONIC & ISOMETRIC CROSS-PLOTS.)

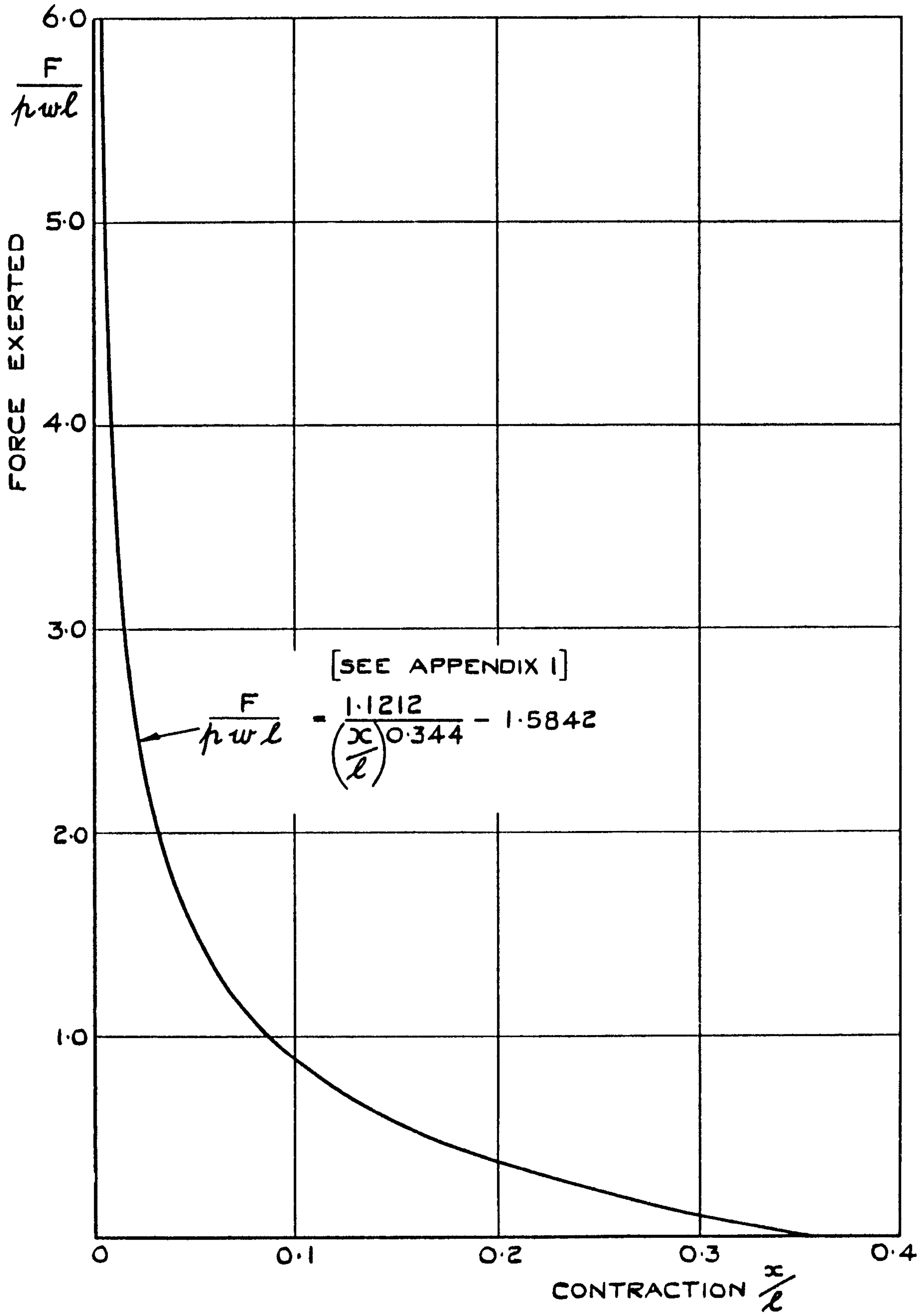
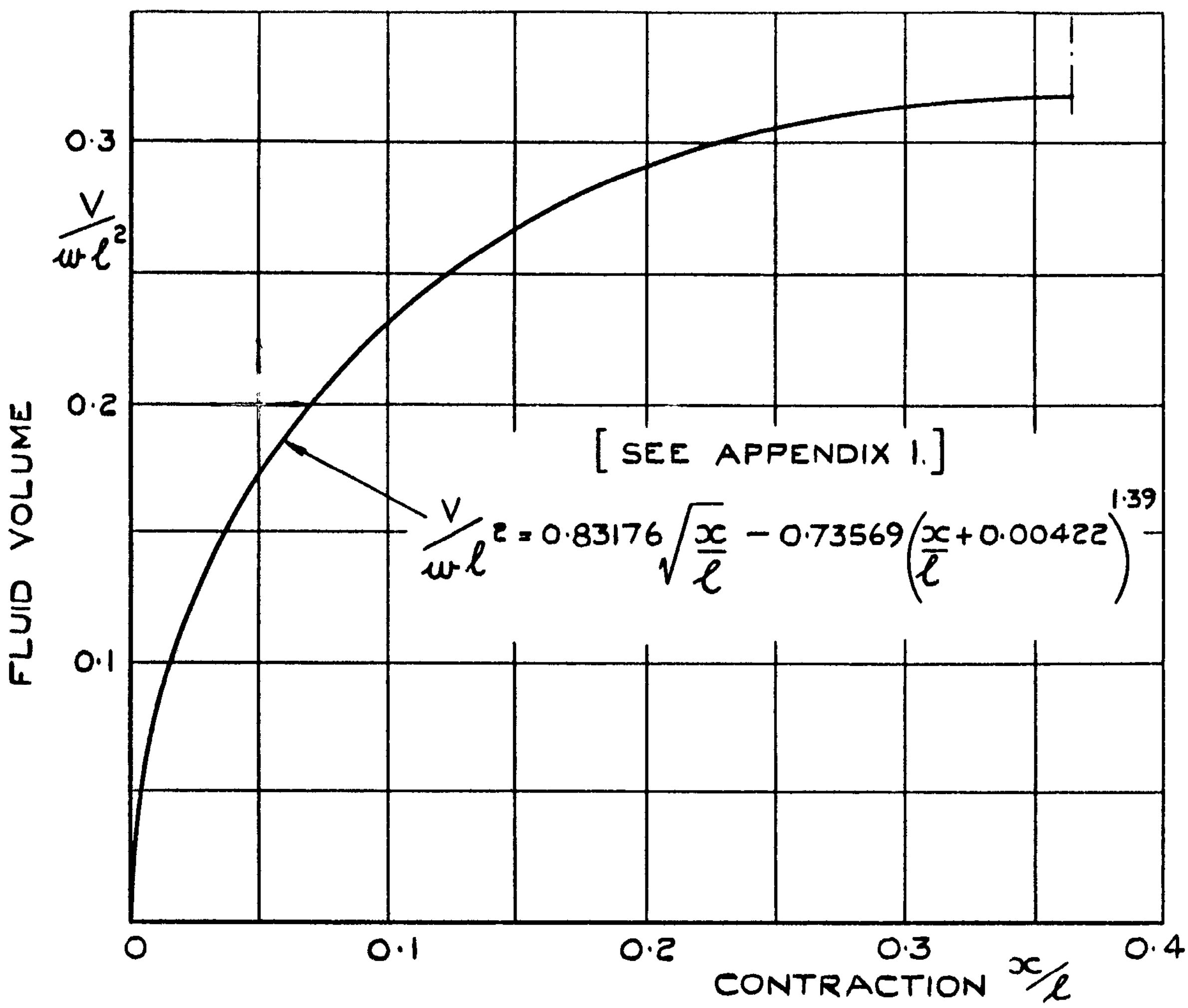
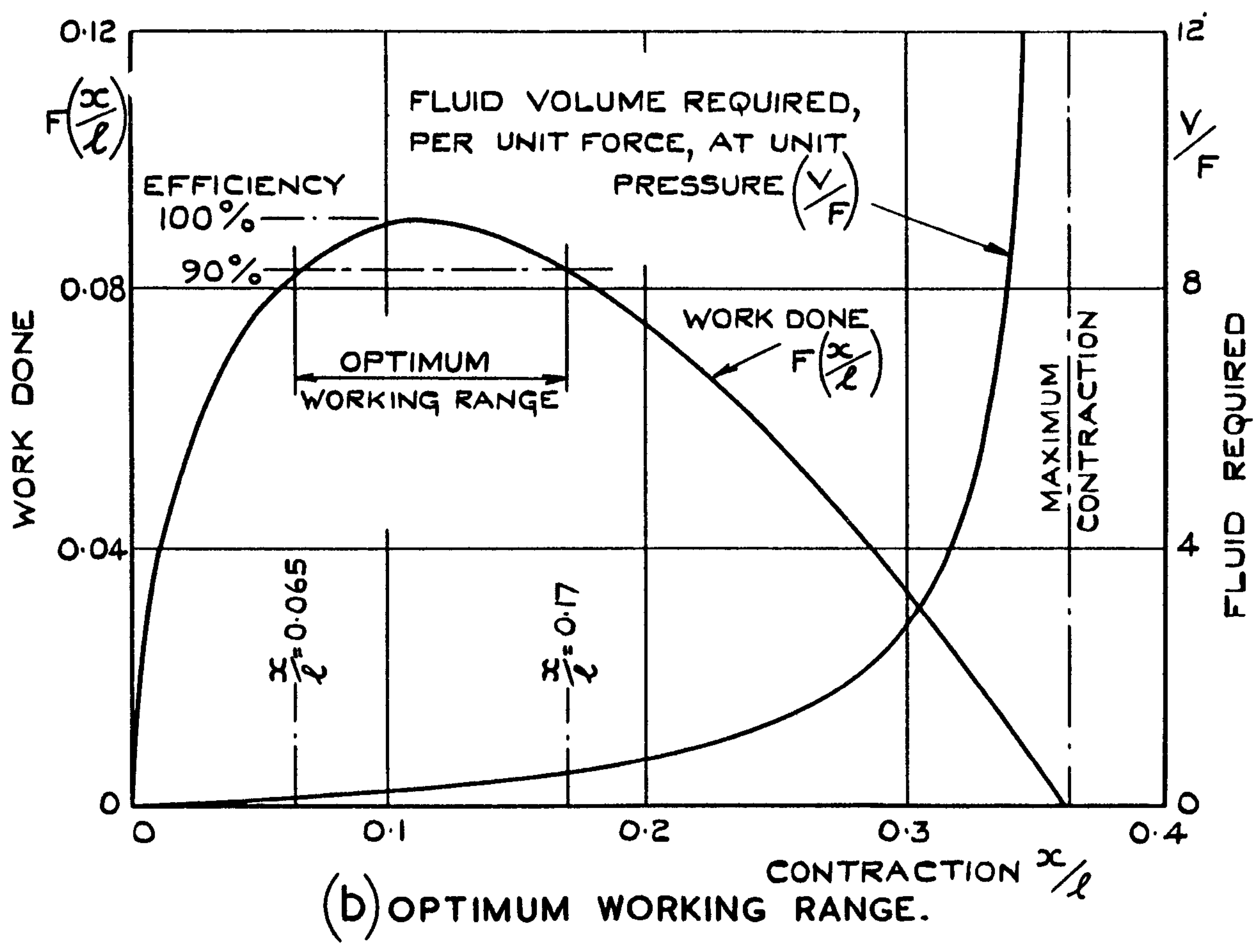


FIG. 7. MUSCLE-MOTOR LOBE DESIGN CURVE.

(FORCE v CONTRACTION)



(a) WORKING FLUID REQUIRED.



(b) OPTIMUM WORKING RANGE.

FIG. 8. MUSCLE-MOTOR LOBE DESIGN CURVES.

(WORKING FLUID REQUIRED & OPTIMUM WORKING RANGE)

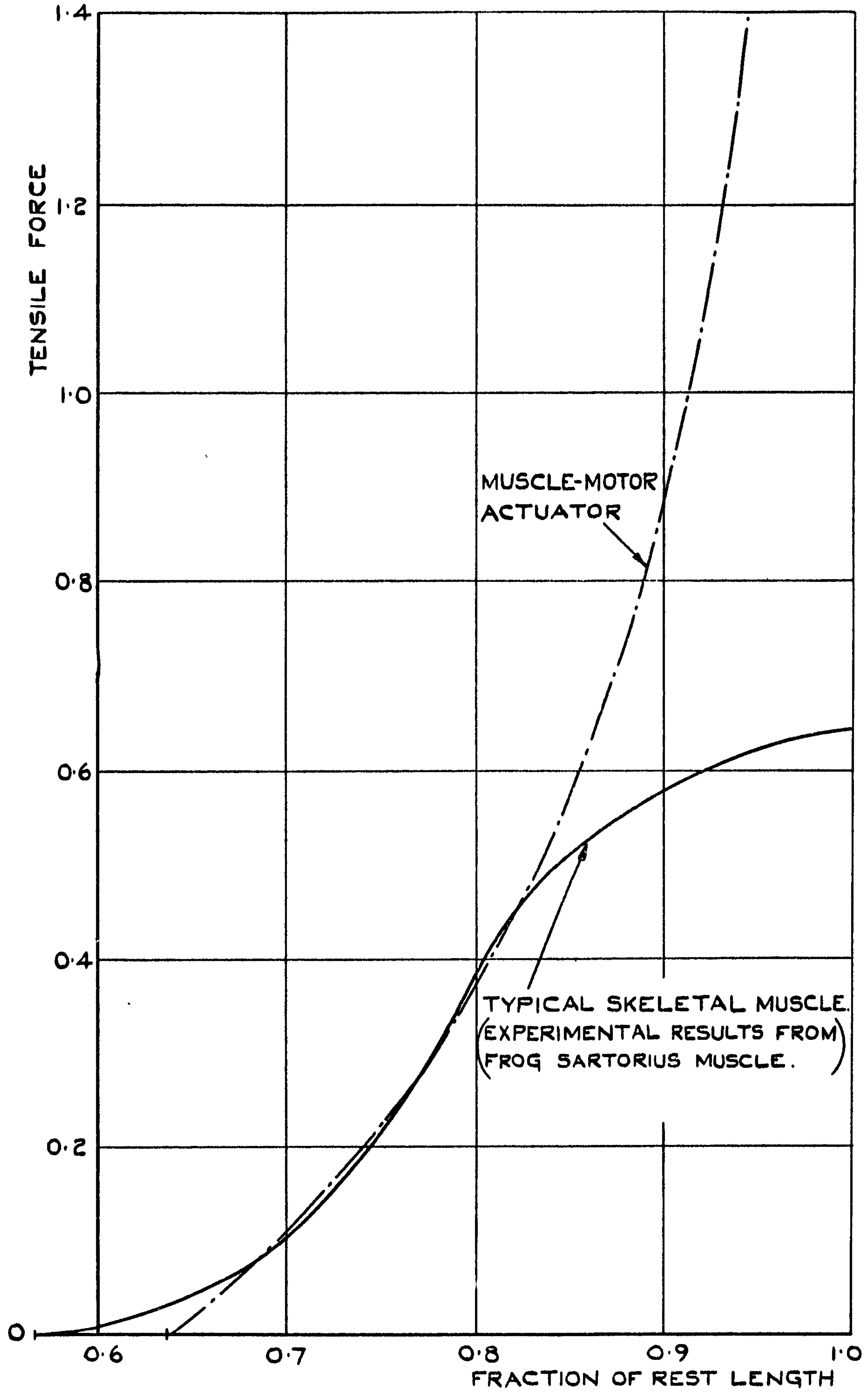


FIG. 9. LENGTH/TENSION COMPARISON OF LIVING & ARTIFICIAL MUSCLE-MOTORS.

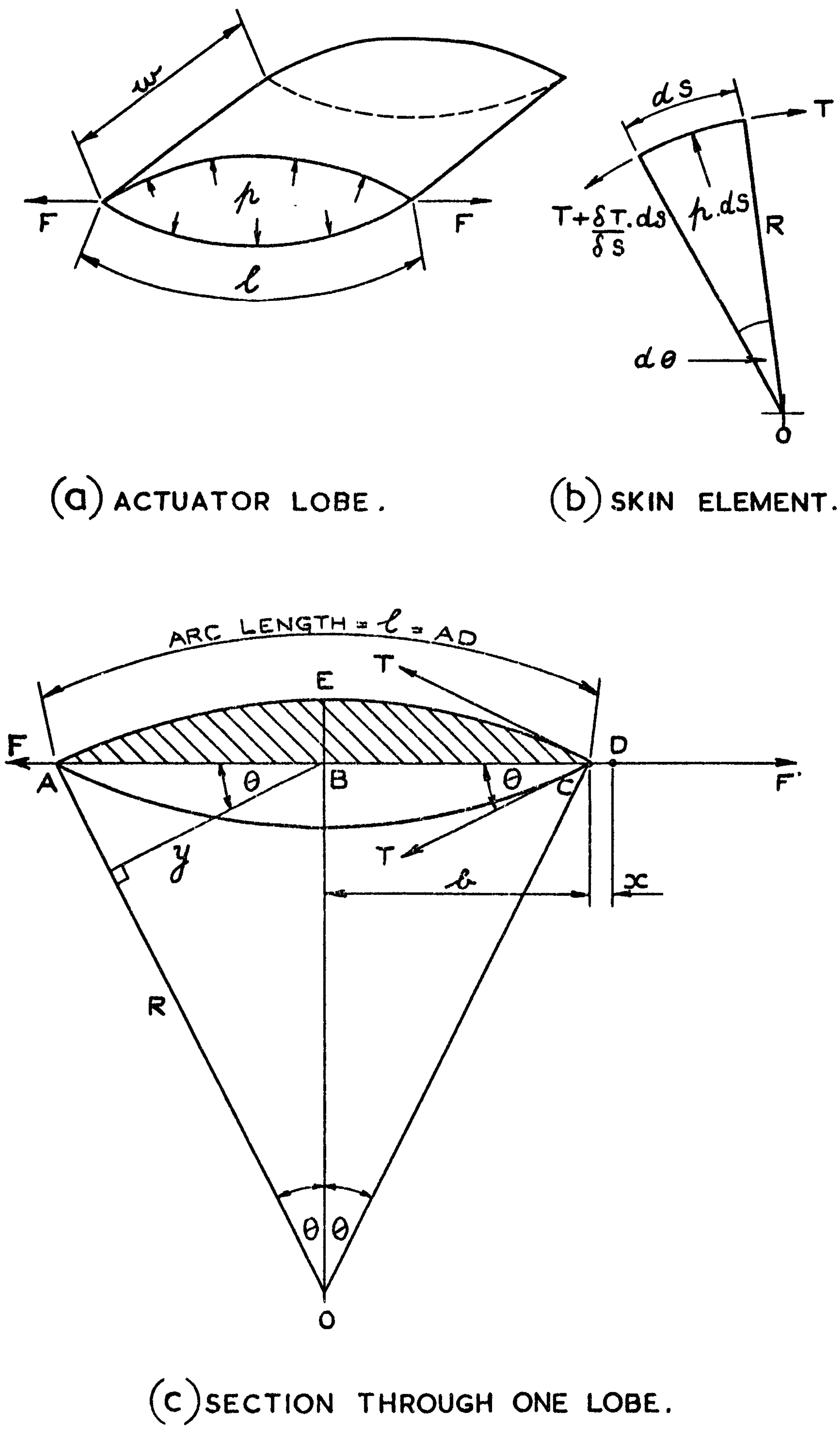


FIG. I. DESIGN DATA FOR MUSCLE MOTOR ACTUATOR.

A.R.C. C.P. No. 671 — 621-526: 615.477.2

INFLATABLE SERVO ACTUATORS. Mettam, A.R. Aug., 1962.

The force v. pressure relationship of most fluid pressure servo actuators would be greatly improved if the whole wall surface of the working chamber were employed in energy transfer, instead of only the small area of a piston or vane.

Some ways of achieving this, by the inflation to cylindrical form of flat envelopes of flexible material, were investigated by the author during development of an artificial muscle system. This note records the performance of various prototype actuators and discusses possible applications.

One form, designated a "muscle-motor" actuator, has many possible uses in engineering. The advantages of such actuators lie chiefly in their extreme simplicity and cheapness, their flexibility in one plane

(Over)

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These actuators are discussed mainly in a general engineering context, but some comments are included relative to the medical applications for which they were developed. The Appendix presents simple design formulae for muscle-motor actuators.

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