DEVELOPMENT OF ARTIFICIAL RUBBER MUSCLES

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Summary

In mechanical simulation of the human extremities, the artificial muscle of rubber has been attracting considerable attention because of the enormous tension available compared with the weight when it is used as an actuator of the artificial extremities. These authors carried out studies of the rubber artificial muscle with a view to producing a handy nomograph from the standpoint of actual use of the rubber artificial muscle. At the same time a new type of rubber artificial muscle for rotation and flexure was developed.

Static and dynamic characteristics of the rubber artificial muscle were tested. Moreover, a factor effect graph was prepared for quantitative analysis of the effects of various factors (length and diameter of muscle, thickness of film, and distance between threads). These basic data made it possible to prepare a practical nomograph for design standards. If we are given such specifications as tensile force, shrinkage, and shrinkage time constant, we are now able to determine the length and diameter of the artificial muscle, the thickness of the film, the distance between threads, the number of knots, and the working air pressure.

Introduction

Nowadays there is a crying need for better ways of treating patients with amputation or paralysis of limbs resulting from traffic and industrial accidents as well as thalidomide babies. As one of the remedies offered from the medical fields, varied prostheses have been developed, and obviously the developers have to work in close cooperation with the engineers. In the engineering domain, a new science called biomechanics has been progressing in recent years with a view to analyzing the function and mechanism of the living body, especially that of a human being, aiming at the creation of a mechanical model of the living body.

The mechanism for controlling the living body is functionally divided into three major units: control, operation, and detection. In this research, the second factor of operation is taken up. While the operational factor is found in live muscles, the conventional artificial leg has been powered by a servomotor or a combination of pistons and cylinders, all adapted from known rigid machinery.

These machines, therefore, are too heavy and lack suppleness. Paying attention to the great potential of pliant machines having properties different from rigid ones, we have developed Poland-type rubber artificial muscles [1] powered by gas pressure. The rubber artificial muscle is characterized by light weight and pliability. Among other merits are easy handling, low cost, and the absence of sound, heat, and jarring noise during performance. In addition, certain manufacturing techniques can give the artificial muscle kinetic patterns different from mere linear motion ordinarily derived from the expansion and contraction of rubber, such as rotary and flexural motion. It is interesting to note that there are notable similarities between our creation and the natural muscle.

The objective of our experiment was to measure the static and dynamic characteristics of the rubber artificial muscle in order to determine quantitatively the factors affecting those characteristics in accordance with a proper design of experiments. On completion of the quantitative study, we were enabled to proceed to the preparation of nomographs which were useful in determining the specifications of a rubber artificial muscle which should satisfy given conditions.

The manufacturing details of the rubber artificial muscle are described in [2].

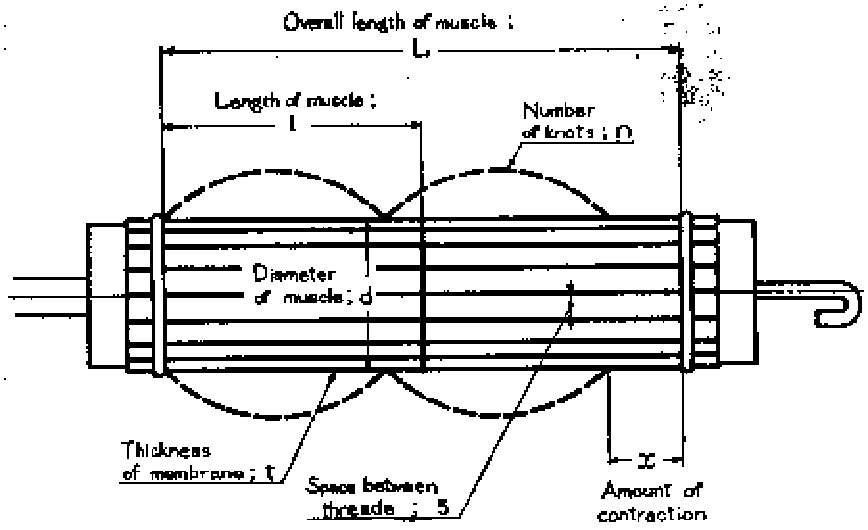

Fig. 1. Construction of rubber artificial muscle

Construction of Rubber Artificial Muscle

As illustrated in Figure 1, the basic idea consists of a rubber tube each end of which is equipped with a terminal through which gas can be introduced under pressure. The rubber tube is provided with threads in the axial direction. As the result, when the tube expands the axial elongation is checked, producing some amount of contraction and tension.

The properties of the rubber artificial muscle are affected by length of muscle (l), diameter of muscle (d), thickness of membrane (t), space between threads (s), and number of knots (n).

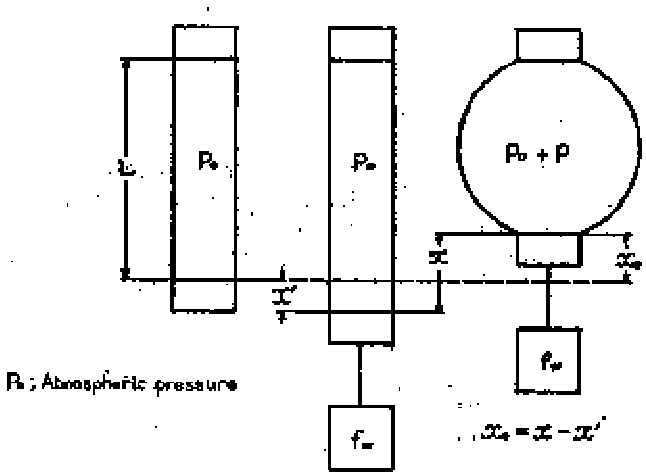

Fig. 2. Amount of contraction

The overall length of muscle is found by $l \times n = L$. By examining how the properties of the artificial muscle are affected by the above variables, we can plot a nomograph which serves as the basis for design work. In addition, the specifications of a rubber artificial muscle is represented by the following matrix:

$$L[l, d, t, s]_n \rightarrow 200^L[100^l, 30^{\varnothing}, 0.75^t, 6^s]_2$$

wherein the unit of all numerals except n is millimeter.

Now the amount of contraction of the rubber artificial muscle may be given in two ways depending upon the choice of the standard. As shown in Figure 2, when the rubber artificial muscle is loaded in its natural state, an elongation of x' occurs. For this reason, contraction may be defined either in terms of the amount of contraction, x, including said elongation, or in terms of the amount of contraction, x_0, starting from the natural lenght. In the following pages, distinction will be made by designating x or x_0. The same is true of contraction ratio x/L and x_0/L.

Static Characteristic of Rubber Artificial Muscle

This characteristic was measured separately isotonically and isometrically. Isotonicity implies here the relation between pressure p and amount of contraction x under a constant load tension f_W; isometricity is the relation between pressure p and tension produced f for the contraction amount $x_0=0$. This differentiation was necessary because the control system is twofold, and the former corresponds to the displacement control and the latter to the force control.

Prior to the measurement, the rubber artificial muscle was operated about three times to stabilize the rubber membrane.

Static Characteristics in Isotonicity

Figure 3 shows a portion of the p-x graph in the isotonic condition. It is seen here that hysteresis decreases with increased loading and considerable improvement can be made if the length of muscle *l* is reduced by increasing the number of knots n. Secondly, the slope Δx/Δp is decreased with smaller muscle length tending to become linear. On the basis of these graphic data, a factor effect graph on pressure may be drawn as in Figure 4. This graph represents how the specifications of the rubber artificial muscle affect the pressure related to the static characteristic, with greater effect expressed by higher gradient (within the range of

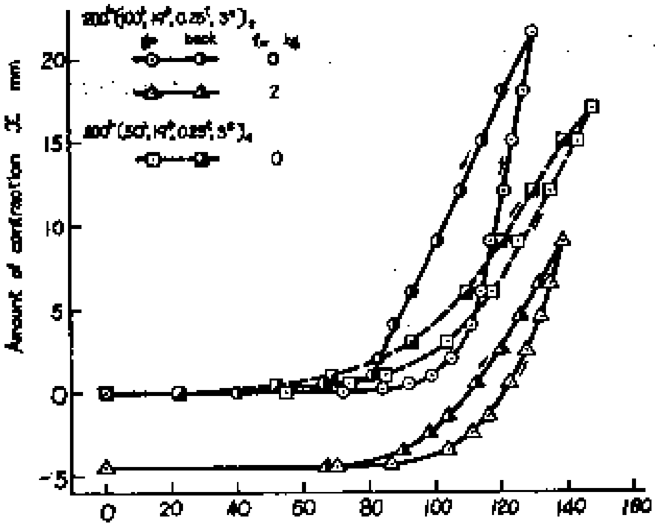

Fig. 3. Static characteristic in isotonicity

this experiment). A similar factor effect graph was prepared with regard to hysteresis, with the finding that the length of muscle produced an overwhelmingly great effect compared with any other factor, so that the hysteresis became smaller with the decrease of *l* For the sake of comparison, an f_{w-x} graph was drawn with the

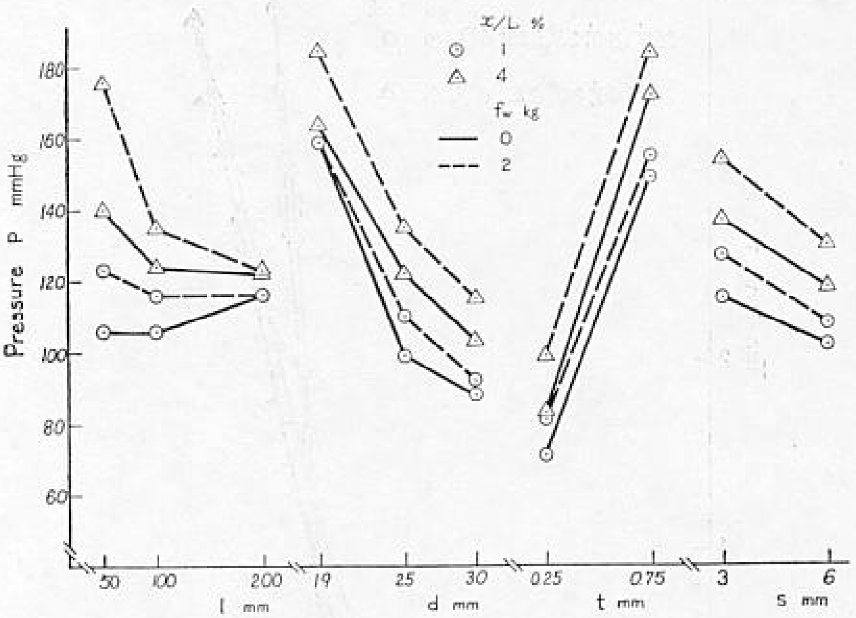

Fig. 4. Factor effect graph in isotonicity

pressure p used as parameter. Then it was known that larger fluctuations against loading occurred for smaller length of muscle *l*, smaller thickness of membrane t, and larger space between threads s.

In order to obtain qualitative information on the efficiency and the amount of air consumption, the volumetric change ΔV of the rubber artificial muscle in isotonicity was measured. As the result, it was verified that efficiency η could be heightened by smaller l, smaller t, and largers. In addition, the input work was denoted by $\int Vdp$ and the output work by fx, and efficiency η, was defined as the ratio between the two.

Static Characteristics in Isometricity

Figure 5 demonstrates a portion of the p-f graph in isometricity. Though hysteresis is observed here, isometricity is not conspicuous. When a factor effect graph was drawn with respect to pressure, the result showed a tendency almost identical to that of Figure 4. As for the gradient of $\Delta f/\Delta p$, it was disclosed that the length of muscle l acted as a major determinant factor, and $\Delta f/\Delta p$ declined with the decrease of l.

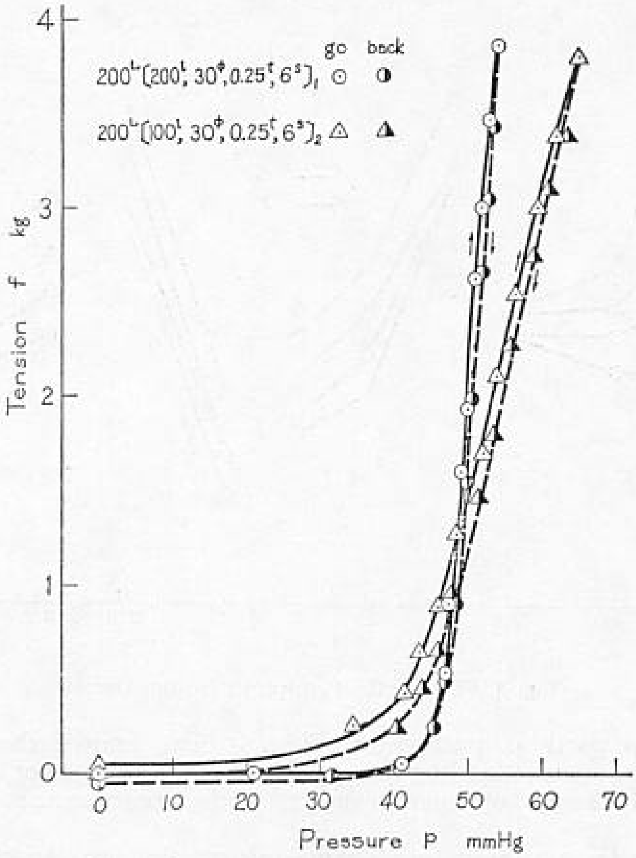

Fig. 5. Static characteristic in isometricity

Dynamic Characteristic of Rubber Artificial Muscle

The response of the rubber artificial muscle when it was given pressure steps by the on-off action of the solenoid valve was recorded separately for isotonicity and isometricity.

Dynamic Characteristic in Isotonicity and Isometricity

Figure 6 gives the transcription of the response curve in isotonicity on a semi-logarithmic scale. It is illustrated that in the beginning, pressure p varies linearly and contraction x begins to respond quadratically after the lapse of dead time, but the time constant increases halfway. This phenomenon may be explained as follows. Since the rubber artificial muscle does not expand before the bias pressure is reached, the pressure gives a linear response, but as expansion starts, the capacity increases and the response is retarded. Nearly the same response was obtained in the experiment for isometricity.

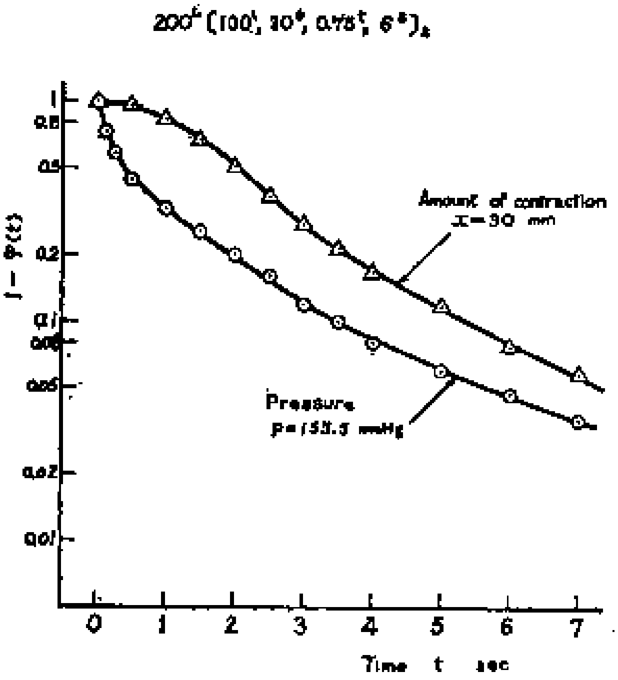

Fig. 6. Dynamic characteristic in isotonicity

If the time constant Tx is read when the response curve of the amount of isotonic contraction approximates linearity, the resultant factor effect graph is as shown in Figure 7. Here are noted large effects of the overall length of muscle L, the number of knots n, and the interaction of the two factors L×n. This interaction varies the gradient at n = 2, 4. A similar tendency is given in isometricity. In addition, the dead time Tx' in isotonicity is smaller for larger load f_w.

In the next place, the time constants Tx and Tf in isotonic and isometric contractions, respectively, vary with the pressure applied as input. The variation is smaller as the pressure climbs, and Tx and Tf tend to converge upon definite values.

Conclusion

It is known from Figure 7 that the time constant Tx is smaller when the length of muscle l is smaller, the thickness of membrane t is larger, and the space between threads s is smaller. With all the conditions taken into account, we can say that the resistance factors are large. The larger the resistance factors, the higher the coefficiency of elasticity of the rubber membrane, drawing close to rigidity in extreme cases. Then the rubber artificial muscle inherently equipped with large resistance factors will lose its pliability as a component of a flexible machine, and instead will take on the property of quick response which is characteristic of a rigid machine.

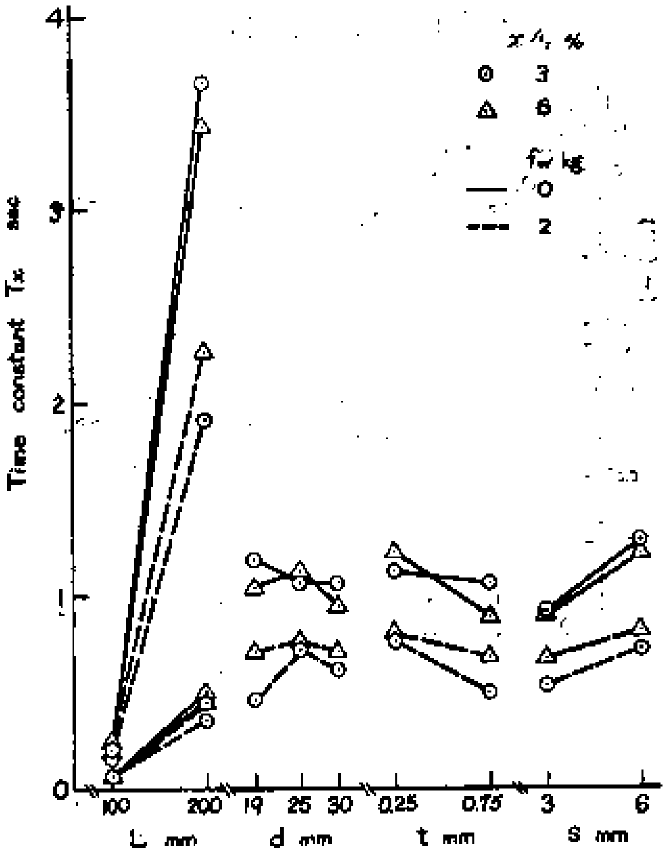

Fig. 7. Factor effect graph in time constant Tx

On the other hand, the dead time Tx' in isotonic contraction is largely affected by the load f_w. The dead time is enormous when the rubber is not loaded, and the time becomes shorter with increasing load. This is considered to be due to the fact that the chain-forming giant molecules between rubber molecules in the rubber membrane are stretched by loading, and the dead time is reduced proportionately. For another reason, it is also conceivable that the resistance of the rubber membrane is lowered by being stretched, and its expansion is all the more facilitated. Besides, the dead time can be eliminated if bias pressure is constantly applied on the working rubber tube.

Nomograph

In case the rubber artificial muscle is incorporated into the system as an actuator, the choice of a rubber artificial muscle of appropriate specifications is necessary to give full play to the performance desired in the system. The preparation of a nomograph which diagrammatically facilitates the selection was one of the ultimate goals of the measurements of both static and dynamic characteristics in this experiment.

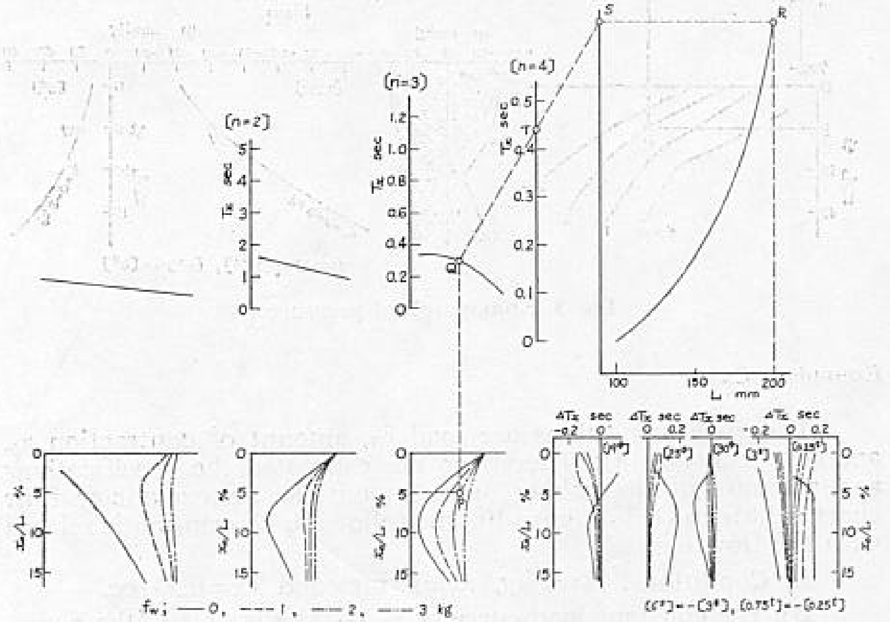

Fig. 8. Nomograph of time constant

Detailed process in preparing the nomograph is not described here, but basically the nomograph can be prepared by extending the data in the above-mentioned factor effect graphs in Figures 4 and 7. The nomograph of time constant is given in Figure 8, and that of pressure in Figure 9.

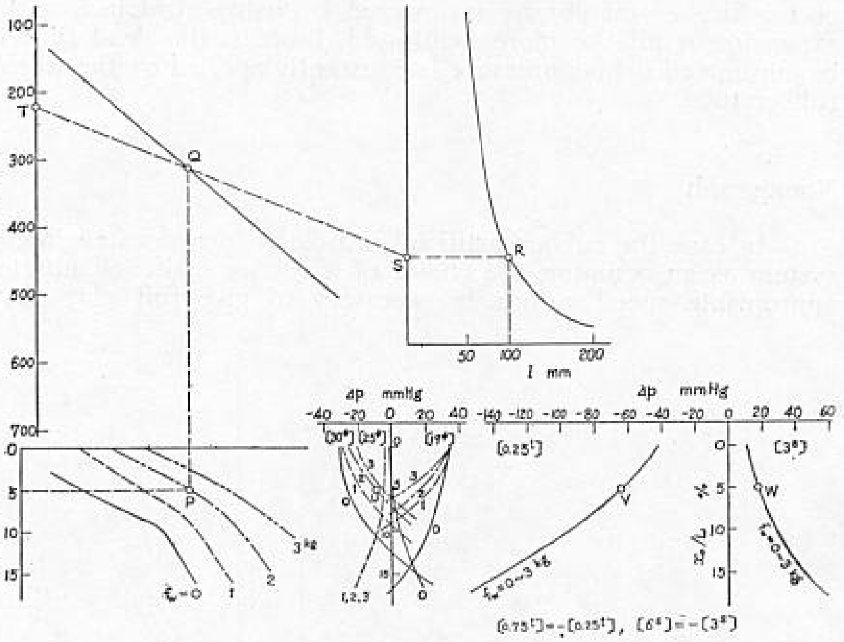

Fig. 9. Nomograph of pressure

Exemplary Case

The given conditions are load f_W, amount of contraction x_0, and time constant Tx. Therefrom are estimated the specifications and pressure of the rubber artificial muscle. An exemplary flow chart is illustrated in Figure 10. The following description is related with the flow chart.

A) Conditions: $f_W=2$ kg, $x_0=10$ mm and $Tx=0.50$ sec.

B) The constant load curve of f_W — 2 kg is noted (the nomograph of time constant).

C) Attention is given to the number of knots n=2, 3 and 4 in the reversed order, i.e., starting from 4.

D) When an arbitrary value is given to the overall length of muscle L at n=4, the contraction ratio x_0/L can be calculated from $x_0=10$ mm. From the value of x_0/L and $f_W=2$ kg, the point which corresponds to the point P can be plotted, and this point produces another point Q if transferred onto the auxiliary axis of coordinates.

From the value of L in this case, on the other hand, point R → point S is plotted and point S is connected with point Q by a straight line, whose intersection with the time axis is designated as point T. L is varied so that the time constant Txn at point T may come closest to the conditional value $Tx=0.50$ sec. The points P, Q, R, S and T in Figure 8 are all provided through the above procedure.

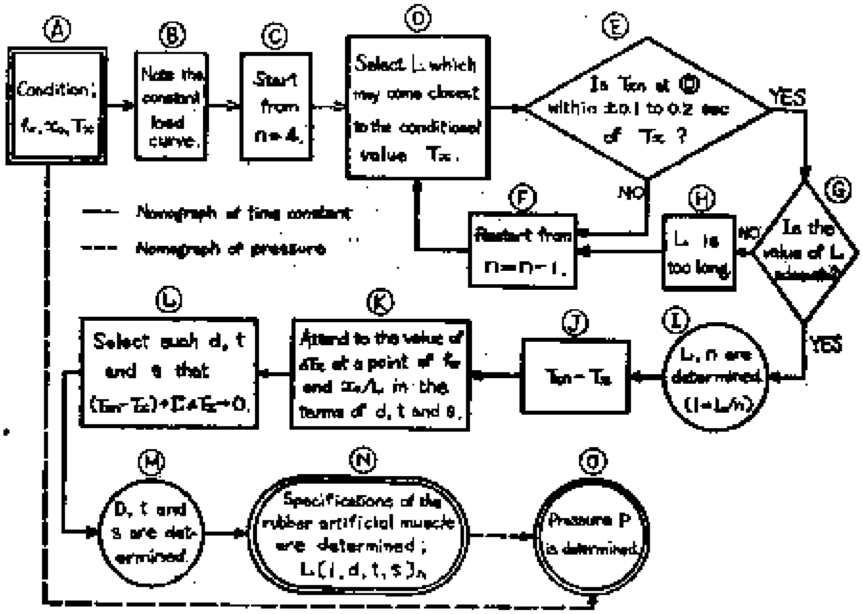

Fig. 10. Exemplary flow chart of nomograph

E) At point T the time constant $Txn=0.44$ sec. within plus/minus 0.1 to 0.2 sec of $Tx=0.50$ sec. Thus we are ready to proceed to (G). In case the time constant is outside the above range, the same procedure is performed in the term $n=4-1=3$.

G) At this stage $L=200$ mm. With this value assumed to be adequate, we proceed to the following:

I) Eventually it is determined that $L=200$ mm and $n=4$. The length per knob, namely, the length of muscle $l=L/n=50$ mm.

J) Then $Txn-Tx=0.44-0.50=-0.06$ sec.

K) Attention is called to the value of ΔTx at a point where $f_w=2$ kg and $x_0/L=5\%$ in the correction terms of d, t and s.

L) Now inasmuch as the values of ΔTx at 19^{θ}, 0.25^{t} and 6^{s} are −0.03, +0.05 and +0.05 sec, $(Txn-Tx)+\Sigma\Delta Tx=-0.06-0.03+$ $+0.05+0.05=+0.01$ sec which is closest to nought.

M) From the above it is determined that $d=19^{\varnothing}$, $t=0.25$ and $s=6$ mm.

N) Based on the foregoing, the specifications of the rubber artificial muscle are determined as follows:

$$200^{L}[50^{l}, 19^{\varnothing}, 0.25^{t}, 6^{s}]_{4}$$

The rubber artificial muscle with the specifications closest to the experimental values is as follows:

$$200^{L}[50^{l}, 30^{\varnothing}, 0.25^{t}, 6^{s}]_{4}$$

Though the value of d is given differently as $19^{\varnothing}$ and $30^{\varnothing}$, the value of ΔTx for both is nearly the same at $f_W=2$ kg and $x_0/L=5\%$ in the d term of the nomograph. In consequence, the above rubber artificial muscle should satisfy the conditions. Then the experimental value is read at $Tx=0.48$ sec, when the pressure $p=144$ mm Hg. The time constant is almost identical if 0.48 sec is compared with 0.50 sec.

As for the pressure, the pressure for $200^{L}[50^{l}, 30^{\varnothing}, 0.25^{t}, 6^{s}]_{4}$ is read to compare with the experimental value. O) With respect to the nomograph for the pressure, the working pressure P at $f_W=2$ kg and $x_0/L=5\%$ in the rubber artificial muscle $200^{L}[50^{l}, 30^{\varnothing}, 0.25^{t}, 6^{s}]_{4}$ can be represented by the point T on the pressure coordinates by connecting, similarly to the procedure for the time constant nomograph, point P with Q, point R with point S, and point Q with point S. Hence the reading is $P_1=222$ mmHg.

Then d, t and s are plotted as points U, V and W, while the values of ΔP are respectively $\Delta Pd=-10$, $\Delta Pt=-64$ and $\Delta Ps=-18$ mmHg. The above leads to the estimation that

$$P=P_1+\Delta Pd+\Delta Pt+\Delta Ps=222-10-64-18=130 \text{ mmHg}$$

The above value can be considered close to the experimental value of 114 mmHg.

Comparison between Estimated Value and Experimental Value

An attempt was made to use the nomograph in reverse of the above example. Namely, the time constant Tx and the concurrent pressure P in an arbitrary state of the experimental rubber artificial muscle were estimated from the nomograph. As the result, it was revealed that 50% of the experimental value came within plus/minus 10% of the estimated time constant Tx, and the percentage rose to about 80% within plus/minus 15%. On the other hand, about 60% of the experimental value came within plus/minus 20% of the estimated pressure P, and slightly more than 70% within plus/minus 25%. After all, it can be stated that the time constant Tx and the pressure P estimated from the nomograph have ranges of error of roughly plus/minus 15% and plus/minus 25%, respectively. It is conjectured that these errors are partly due to the averaging of the fluctuation of individual measured values in the factor effect graph, and partly due to the approximation of various curves in the nomograph prepared from the averaged values.

Degree of Freedom in Determining Specifications

With conditions given, it is possible to determine the specifications from the nomograph generally in the three case of $n=2, 3, 4$. In other words, the number of degrees of freedom is 3. Hence three different kinds of rubber artificial muscle can be determined, but the major difference in their shapes lies in the overall length of muscle L, which increases with the value of n. Therefore, if an approximate value of L is given beforehand, the degree of freedom becomes 1. On the other hand, in the term of L of the flow chart, d, t and s are to be selected. In this selection, the values of d, t, and s that meet $(Txn-Tx)+\Sigma\,\Delta Tx \rightarrow 0$ are not necessarily single. It may be that the closest value to zero is no doubt single, but practically if values somewhat close to 0 are available, the rubber artificial muscle may meet the conditions. In this sense, it can be said that a fairly high degree of freedom is obtained.

Development of a New Type of Artificial Muscle

By adding a structural improvement to the previous straight-moving rubber artificial muscle, we tentatively manufactured new artificial muscles of the rotary type and the flexural type.

The rotary artificial muscle consists, as illustrated, of a spirally laid thread, which generates rotary angle and torque when compressed air is introduced, for the thread tends to assume a position parallel to the axis.

The flexural artificial muscle is a variant of the straight-moving artificial muscle with its membrane varied in thickness, with one side thicker than the other. The difference in resistance between the two sides manifests as a flexural angle and a bending moment. But this artificial muscle is exceedingly weak against bending moment.

Conclusions

Live Muscle vs. Rubber Artificial Muscle

Now the rubber artificial muscle is compared with the muscle in the living body. The rubber artificial muscle produces contractile tension and a certain volume of contraction by the strength of compressed gas. At this time, the strained rubber membrane would regain its original form, thus producing elasticity, and at the same time a stationary state is maintained because of a dynamic equilibrium with the pressure of the gas. Moreover, the contraction of a live muscle is performed by the transmission of stimulus, which action is supposed to find its mechanical counterpart in the opening and closing of the solenoid valve in the rubber artificial muscle.

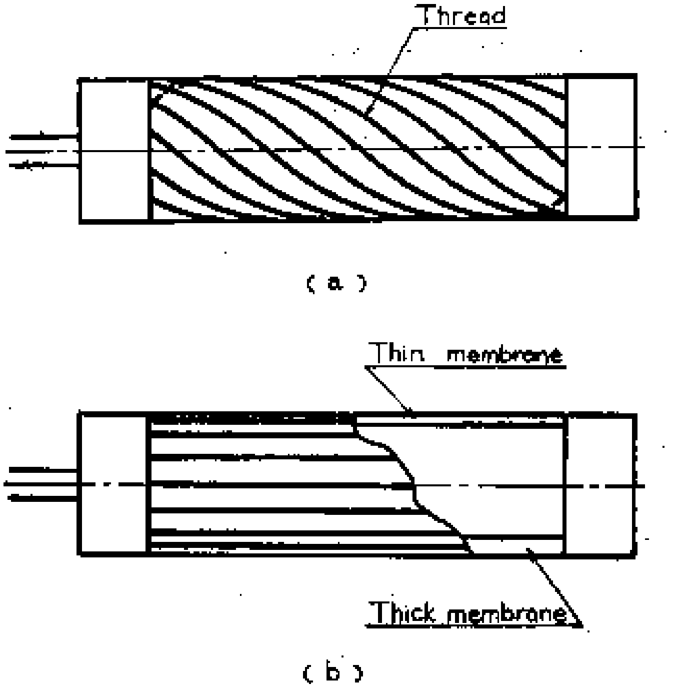

Fig. 11. New type of artificial muscle
(a) artificial muscle of the rotary type
(b) artificial muscle of the flexural type

Natural Muscle	Artificial Muscle
Elastic factors	Elasticity of rubber membrane
Contraction factors	Pressure and volume of gas
Stimulation	Opening and closing of solenoid valve

Effects of Specifications of Rubber Artificial Muscle on Varied Characteristics

Here is a summary of the effects of the specifications of rubber artificial muscle on the isotonicity and isometricity of dynamic and static characteristics, and on efficiency and air consumption. The specifications are classified as follows:

Capacity factors:	Length of muscle l and diameter of muscle d
Resistance factors:	Length of muscle l, thickness of membrane t, and density of threads l/S

In the above, the space between threads is replaced by the density of threads l/S, and L and n are shown compositely by the length of muscle $l = L/n$.

The above items are summed up in Table 1. In this table, the part marked [—] indicates insignificant or negligible change.

Concerning the relations among the items in the table, the same tendency is shown by items (2) and (3) since great contractibility in the rubber artificial muscle represents the ease of occurrence of tension. Since this is related with the smallness of time constants Tx and Tf, the tendency is similar to that of items (8) and (9). Furthermore, as bias pressure is related with dead times Tx' and Tf', there is a similarity among items (1), (10), and (11).

Effects of Muscle Length

If the length of the muscle l is reduced, the following advantages will be gained:

Bias pressure	Decrease
Hysteresis	"
Efficiency	Increase
Air consumption	Decrease
Time constants Tx, Tf	"
Dead times Tx', Tf'	"

As opposed to the appearance of the above merits, $\Delta(x/L)/\Delta f_w$ increases as l becomes smaller, enhancing the susceptibility to the load. In view of this shortcoming, it is necessary to make a proper choice of l depending upon the property of the load installed in the system.

Properties of Muscle Length

The length of muscle l has properties related with both capacity factors and resistance factors. Accordingly, it appears probable that the effects on each characteristic of the rubber artificial muscle vary with the ratio between the two groups of factors. The relationship between the magnitude of the two groups of factors and the length of muscle l is assumed to be as shown in

Figure 12. So it is true that the advantages are increased by making *l* smaller, but there exists a certain limit to it. If this limit is surpassed, such problems as the decrease of efficiency and the decrease of the maximum contraction ratio will arise due to the increase of the resistance factors. Thus Table 1 illustrates a general tendency within the limits of this experiment.

Table 1. Effects of the specifications of rubber artificial muscle on every characteristic

Factor	Specifications of artificial muscle			
Item	l — larger	d — larger	t — larger	l/s — larger
(1) Bias pressure	Increase	Decrease	Increase	Increase
(2) $\Delta(x/L)/\Delta P$	"	Increase	Decrease	Decrease
(3) $\Delta f/\Delta P$	"	"	"	"
(4) $\Delta(x/L)/\Delta f_w$	Decrease	Decrease	"	"
(5) Hysteresis	Increase	—	—	—
(6) Efficiency	Decrease	—	Decrease	Decrease
(7) Air consumption	Increase	—	Increase	Increase
(8) Time constant of contraction amount, Tx	"	—	Decrease	Decrease
(9) Time constant of tension, Tf	"	—	Increase	"
(10) Dead time, Tx'	"	—	"	"
(11) Dead time, Tf'	"	Decrease	"	—

Table 2. Effects on every characteristic on output side

Factor	Output side	
Item	f — larger	x — larger
(1) Hysteresis	Decrease	—
(2) Time constant of contraction amount, Tx	"	Increase Decrease
(3) Time constant of tension, Tf	"	—
(4) Dead time of contraction amount, Tx'	"	Decrease
(5) Efficiency	Increase Decrease	Increase Decrease

Effects on Each Characteristic on the Output Side

A discussion was made above of the effects on each characteristic as viewed from the specifications of the rubber artificial muscle (Table 1). Here are presented major effects in terms of the output factors (tension f and amount of contraction x). In the illustration, increase → decrease signifies that there is a local maximum in between.

Postscript

In addition to the foregoing essential description of the rubber artificial muscle, we would like to mention the fact that painstaking work was involved in securing a definite thickness of the membrane and a definite property in the manufacture of the rubber artificial muscle, since the condition of the rubber liquid kept changing from moment to moment.

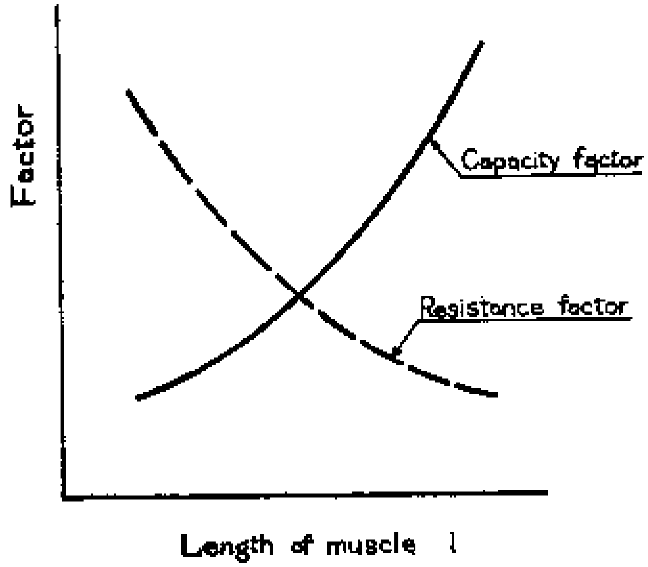

Fig. 12. Properties of muscle length l

The characteristics of the resultant rubber artificial muscle were used by preparing nomographs as the groundwork for designing and adequate product in accordance with a well-calculated design of experiments. However, as the experimental conditions were restricted within certain ranges, the scope of the nomograph had to be limited. Therefore, it is an urgent need to accumulate more data to establish the more extensive standards for design.

It was keenly felt, moreover, that the optimum shape and the optimum condition had to be quantitatively controlled so that they could be incorporated in the nomograph. On the other hand, the present thesis is concerned solely with natural characteristics of the output elements with the power source constant, but attention must also be paid to the effectual characteristics.

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