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MUSCULAR CONTRACTION MIMICED BY MAGNETIC GELS

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The ability of magnetic-field-sensitive gels to undergo a quick controllable change of shape can be used to create an artificially designed system possessing sensor-' and actuator functions internally in the gel itself. The peculiar magneto-elastic properties may be used to create a wide range of motion and to control the shape change and movement, that are smooth and gentle similar to that observed in muscle. Magnetic field sensitive gels provide attractive means of actuation as artificial muscle for biomechanics and biomimetic applications.

INTRODUCTION

Since the muscle tissue consists of 80% multicomponent aqueous solution and 20% proteins that comprise the elastic material, it is not surprising that efforts to develop artificial muscle have been devoted to polymer gels.

Kuhn, Hargittai and Katchalsky were the first to realise that certain water swollen polymers can be chemically contracted like a muscle. Since their pioneering work various chemically active polymers, as well as their composites have been studied in order to develop an artificial muscle for biomechanics and technical applications. Several authors have given extensive reviews of these materials [1-3].

From an engineering point of view, muscles are soft and wet mechanical transducers, capable of performing their functions by quick and reversibly shortening in a process called unidirectional contraction. Forces internal to the muscle are derived from a special mechanism, which is designed to transform chemically bound energy into mechanical work or locomotion. During muscular contraction one end of the muscle remains fixed, while the other end moves towards to origin. Since the volume of muscle remains essentially unaltered, it also experiences an increase in diameter [4].

In the analyses of the mechanical behaviour of an isolated muscle it is customary to introduce two types of strains. Under load condition the muscle is first stretched passively before being stimulated to contract. This process is then followed by active contraction due to shortening of fibers. Therefore under load condition the muscular thickening may be considered as net effects of both passive and active strains taking place simultaneously.

When contraction takes place against a resistance, force is generated and mechanical work is released. When contraction occurs against the maximum resistance, maximum muscular force developes, but no measurable change in muscle length, as well as mechanical work, can be observed. This isometric contraction represents the largest force that a muscle can actively generate. Under no load condition the stimulation of muscle will cause it to contract to its smallest length without development of any active tension.

It must be mentioned that a simple Hooke's law can not describe the mechanical behaviour of an isolated muscle even in an unstimulated state [4]. The slope of stress-strain curve continuously increases as a result of strain hardening due to streching out of stiffer chains as the deformation continues from resting length to maximum extension.

To mimic the process of muscular contraction one must have a material, which can undergo a shape transformation and has similar mechanical properties like muscle. There are suitable materials, called polymer gels that largely satisfy these requirements. The development of artificial polymeric muscle relies upon the observation that changes in conformation induced by physical, chemical, or physicochemical stimuli can manifest themselves at a macroscopic level in terms of volume- or shape changes, or force generation. The passive-active nature of muscular contraction can not be realised by a traditional elastic material of which deformation depends only on the surface traction. In a material designed for artificial muscle application there must be a physical or chemical process that can generate mechanical stress inside the material independently on acting surface traction. This controllable "body force" must be able to determine the rate and measure of contraction even if the material is preloaded. It is also a requirement, that material should mimic the passive and active mechanism of muscle.

Development of an artificial muscle must face the task of reproducing at least three main characteristics of real muscle fibers: the high and fast contractility as well as a reliable control system. Electric or magnetic fields are the most practical stimuli from the point of view of signal control. Their coupling with elasticity may result in a powerful artificial muscle material.

The magnetic gel as a model of an artificial muscle

Magnetic field sensitive gels as we call them ferrogels are chemically cross-linked polymer networks swollen by a ferrofluid [5-11]. A ferrofluid or a magnetic fluid is a colloidal dispersion of monodomain magnetic particles with a typical size of about 10 nm [12].

In uniform magnetic field a ferrogel experiences no net force. When it is placed into a spatially non-uniform magnetic field, forces act on the magnetic particles, and the magnetic interactions are enhanced. The stronger field attracts the particles, and due to their small size and strong interactions with molecules of dispersing liquid and polymer chains they all move together. Changes in molecular conformation can accumulate and lead to shape changes..

The magnetic field drives and controls the displacement of the individual particles, and the final shape is set by the balance of magnetic and elastic interactions. The magnetic field sensitive gels can be made to bend and straighten, as well as elongated and contracted repeatedly many times without damaging the gel. The response time to obtain the new equilibrium shape was found to be less than a tenth of a second and seems to be independent of the size of the gel [8]. It must be mentioned that during deformation the volume of the gel does not change. When the magnetic field is eliminated, then the original shape of the gel is completely re-established. Fig. 1 demonstrates the unidirectional elongation and contraction of a ferrogel.

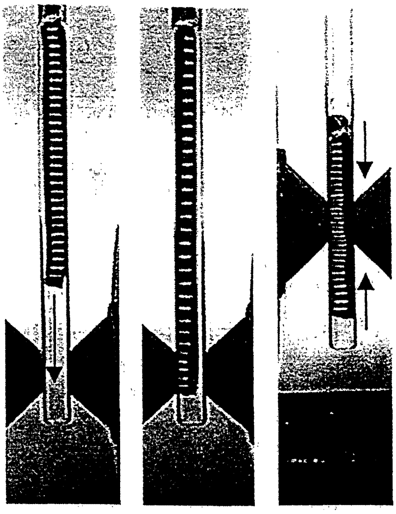


Fig. 1 Elongation and contraction of a magnetic field sensitive gel
a) no external field, b) and c) nonuniform magnetic field
The arrows indicate the direction of the magnetic force

In order to mimic muscular contraction we have studied the unidirectional shortening of ferrogel samples excited by nonhomogeneous magnetic field. A cylindrical gel sample was suspended in water vertically between planparallel poles of an electromagnet. The position of the top surface of the gel was fixed and the highest field strength was located at this point. The steady current intensity in the solenoid-based electromagnet was varied in order to produce different magnetic field distribution. The maximum magnetic field strength (magnetic flux density) of 300 mT developed at the upper part of the gel and disappeared within 120 mm along the axis of cylindrical gel sample. It is worth mentioning that 300 mT is a field strength which is less than the field strength measured at the surface of common permanent magnets. Due to the field gradient directed from bottom to top along the gel axis, contraction occurs. Stimulation of magnetic gel under no-load condition will cause it to contract to its smaller length without development of any mechanical tension. It was found that significant contraction can be induced by moderate magnetic field gradient. The measure of this atonic (no-load) contraction strongly depends on the structure of the magnetic gel as well as on the distribution of magnetic field along the axis of the gel. Since the highest magnetic field strength can be controlled by the intensity of the steady current flowing through the electromagnet, it is possible to realise different degree of contraction. The contractile activity of magnetic gels can be used to lift a load, consequently to produce work. A nonmagnetic load (lead) of variable mass was connected to the lower end of the gel. A CCD camera that provides us the displacement of the lower part of the gel with an accuracy of 0.01 mm monitored the contraction of the gel.

In the presence of a load the gel elongates (passive strain). When an external magnetic field is created, as a consequence, a contraction (active strain) takes place. If the mass of the load is not too high, the net effect is a significant contraction. Fig.2 shows the active deformation of a magnetic field sensitive gel under a load. It can be seen that the magnetic stimulus results in a significant decrease in the length of the gel. When the field is turned off, the gel stretches again.

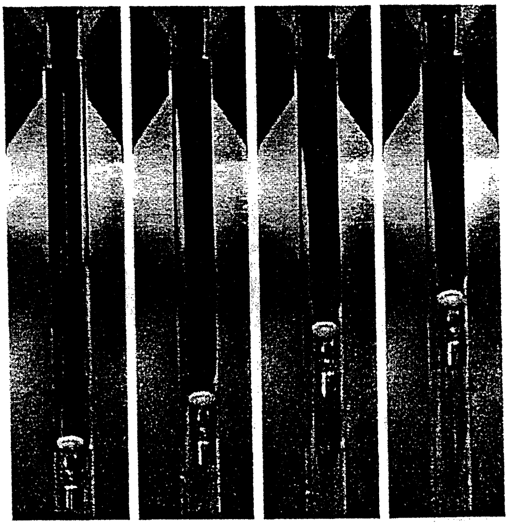


Fig. 2 Active strain developes in a ferrogel due to nonuniform magnetic field
The field gradient increases from left to right.

We have determined the work done by the ferrogel as a function of load. These results can be seen in Fig.3.a Depending on the mass of load the work varies in wide range. With increasing load the work first increases, then passes through a maximum and finally begins to decrease.

Control of pseudomuscular contraction

We consider here a vertically suspended cylindrical ferrogel by means of which a non-magnetic load can be lifted up. The position of the upper surface of the gel is fixed.

First the gel is preloaded with a mass, *M*. As a consequence a passive strain, λ_M developes. The magnitude of the extension due to the passive strain can be calculated on the basis of rubber elasticity theory [6,11]:

$$\lambda_M^3 - \alpha\lambda_M^2 - 1 = 0 \qquad (1)$$

In this equation it was assumed that the Gaussian network behaviour could be used as an approximation. The dimensionless quantity, α includes the ratio of nominal stress, σ_n and the modulus, G. The nominal stress due to the load of mass of M, can be given as Mg/a_0, where g represents the gravitational constant and a_0 denotes the undeformed cross-sectional area of the gel at rest.

$$\alpha = \frac{\sigma_n}{G} = \frac{Mg}{a_0 G} \qquad (2)$$

Eqs. 1 and 2 tell us how the deformation ratio depends on the applied mechanical stress and the modulus. It is obvious that in the presence of a load, the gel elongates, $\lambda_M \rangle 1$.

When a nonuniform external magnetic field is applied the strain changes to $\lambda_{M,H}$ which can now be considered as the overall strain.

Considering homogeneous deformation, linear relationship between magnetisation and magnetic field strength as well as assuming additivity of the mechanical and magnetic stresses we arrive:

$$\lambda^3_{M,H} - \alpha\lambda^2_{M,H} - \beta\left(H_h^2 - H_m^2\right)\lambda_{M,H} - 1 = 0 \qquad (3)$$

where H_h and H_m denote the magnetic field strength at the bottom and the top of a ferrogel cylinder, respectively. β can be considered as the stimulation coefficient defined as:

$$\beta = \frac{\mu_0 \chi}{2G} \qquad (4)$$

where μ_0 and χ denotes the permeability of the vacuum and the magnetic susceptibility, respectively. The overall strain can be obtained from Eq.3 by numerical solution. In order to solve Eq.3 one needs to know the magnetic field distribution. H_h denotes the field strength at the lower end of the magnetic gel. During contraction this value keeps on changing according to the field distribution. Let us assume that the magnetic field strength varies along the gel axis, z as

$$H(z) = H_{\max} \cdot e^{-\gamma|z|} \qquad (5)$$

where γ is a characteristic constant for the field distribution and $H_{\max}$ is proportional to the steady current, $H_{\max} = k_I \cdot I$. These assumptions are satisfactorily fulfilled by our experimental arrangement. One can relate the coordinate, z to the variable, $\lambda_{M,H}$ according to

$$z = z_0 + h_0\left(1 - \lambda_{M,H}\right) \qquad (6)$$

where h_0 denotes the undeformed length of the magnetic gel and z_0 stands for the position of the upper surface of the gel. Taking into account the magnetic field distribution H_h can be expressed as follows:

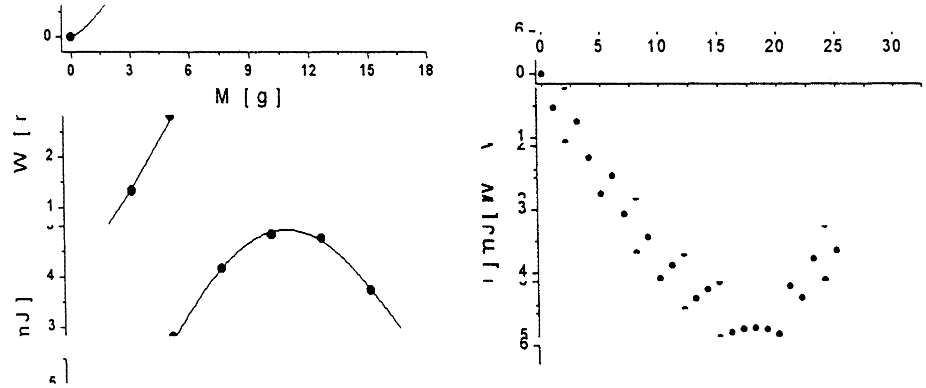
$$H_h = H(\lambda_{M,H}) = H_{\max} \cdot e^{-\gamma\left|z_0 + h_0(1-\lambda_{M,H})\right|} \qquad (7)$$

Combination of Eqs. 3 and 7 makes possible to carry out a numerical solution to get $\lambda_{M,H}$. The mechanical work can be calculated as follow:

$$W = Mg\Delta h = Mgh_0(\lambda_{M,H} - 1) \qquad (8)$$

where Δh represents the displacement of the load.

We have calculated the mechanical work as a function of magnetic field streng at different applied loads. These results are shown in Fig.3.b. It is obvious that the mechanical work strongly depends on the applied load. One can see that at small loads the work increases with the load. M = 18 g represents the highest mechanical work. It is also seen, that above a certain value, if the load is comparatively heavy, the work decreases with increasing mass. When comparing the calculated dependence with the experimental results it may be concluded that our analysis provides the general character of this dependence. It is worth to mention that any other experimental situation can be studied with aid of Eqs.3-8.



a

b

Fig.3 Mechanical work released by a ferrogel as a function of load.
a) experimental results, b) calculated by Eqs. 3-8

Conclusion

Magnetic field sensitive polymer gels have been prepared by introducing magnetic particles of colloidal size into chemically cross-linked polyvinyl alcohol hydrogels. These gels represent a new class of stimuli responsive gels. The influence of nonuniform field has been studied. Significant contraction can be realised by magnetic gels. The unique magnetoelastic properties make them possible to mimic muscular contraction

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