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Soft Linear Actuator Utilizing Electrically Vibrating Threads

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***Abstract*— Various soft actuators have been developed in the past, achieving flexible motion. However, soft actuators that combine high force and high work have not yet been realized. The ratchet movement between actin and myosin, which causes muscle contraction in living organisms, could potentially lead to such high-efficiency soft actuators. In this paper, we describe a thread-based soft linear actuator inspired by this biological principle. The mechanism of this actuator utilizes the interaction between threads and objects to generate motion. Multiple units could be stacked to produce high force when used as a contracting actuator. To verify the principle of the proposed mechanism, we conducted transport experiments. The object placed on the threads was successfully transported at a speed of 2.2 mm/min.**

***Index Terms*— Soft actuator, transport mechanism, conductive thread, electrostatic force**

I. INTRODUCTION

One of the important roles of robots is to be useful to humans by substituting human labor and even performing tasks that are impossible for human power. Until now, robots have been responsible for substituting human work in industry through great strength and precise control. The robotic arms used in factories are the main example of this. These robots are capable of performing tasks with precise control of a few millimeters and with forces tens of times greater than human power.

People's expectations for robots have increased, and now their active participation is desired not only in industry but also in settings where they work alongside humans, such as in care-giving and medical robots. Robots that work closely with humans require even greater safety than industrial robot arms. In such scenarios, rather than the precision pursued by conventional robots, moderate flexibility like that of biological bodies becomes important [1]. In fact, there are many examples where making the robot itself flexible has allowed the body's flexibility to adapt to objects and the surrounding environment [2][3][4]. Robots that utilize their own softness are called soft robots and have been actively researched in recent years. The ambiguous movements of soft robots, in contrast to conventional robots composed of rigid bodies, are crucial for realizing robots that can work closely with humans.

Soft robots are composed of flexible bodies, flexible actuators, flexible sensors, and so on. Soft actuators are crucial in determining the movements of robots that work closely with humans. Among soft actuators, those aimed at mimicking biological muscles are called artificial muscles [5]. These include pneumatic McKibben-type artificial muscles [6], Ionic polymer metal composite (IPMC) driven by low voltage [7], Dielectric elastomer actuator (DEA) driven by static electricity using high voltage [8], Hydraulically amplified self-healing electrostatic actuators (HASEL) which combines fluid and DEA [9], and Shape Memory Arroy (SMA) [10] coils and another actuator [11] driven by heat. Also, a soft linear actuator utilizing an ultrasonic motor has been developed [12]. These actuators can generate force using flexible materials.

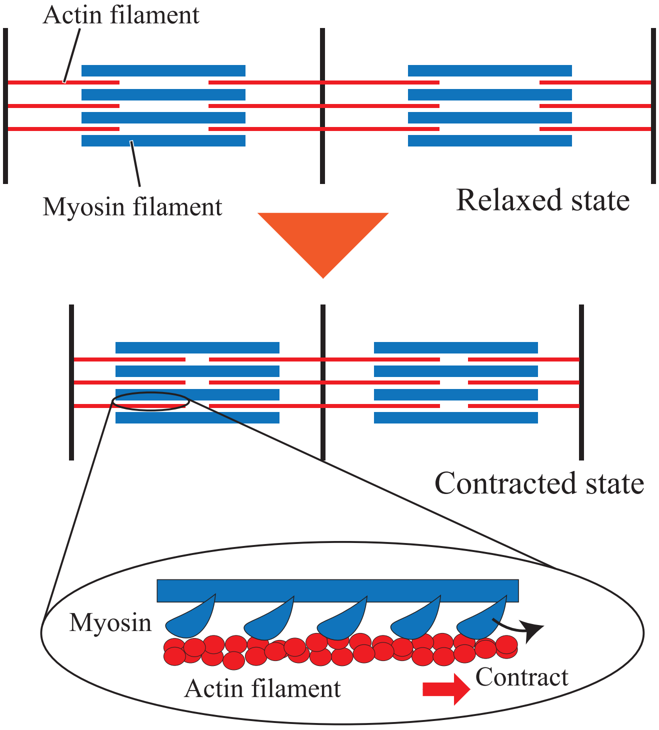

Fig. 1. Contraction mechanism using slippage by actin filaments and myosin filaments in biological muscles.

However, the realization of actuators that combine high-force and high-work capabilities has not yet been successful. This is making it difficult to realize practical soft robots for care-giving and medical applications. SMA or fluidic elastomer actuators can generate large forces relative to their weight. However, there is a limit to their contraction ratio. As for actuators capable of producing large displacements [13], [14], their forces is not as high as aforementioned actuators. The realization of actuators that can achieve both high force

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and large displacement remains a challenge for soft actuators.

Actuators utilizing the driving principles of biological muscles are expected to be developed to achieve large displacement and work [15], [16]. In [15], research on ratchet-type actuators is being conducted for actuators that simultaneously achieve high work and high output. Biological muscles contract through the sliding of actin filaments and myosin filaments, as shown in Fig. 1 [17]. By using this principle, it is believed that actuators capable of large displacements can be realized. It can be said that these biological muscles do not contract the substance itself, but rather achieve contraction through changes in the relative positions between two filaments (actin filaments and myosin filaments) and through a Ratchet transport mechanism. As shown in Fig. 1, myosin pulls the actin filament into the filament, and the relative position of the two filaments changes. Through this idea, a balloon-type transport mechanism using DEA has been proposed for the development of voltage-driven actuators [16].

The authors aim to develop artificial muscles that are thin, planar, capable of producing large displacements, and can be integrated. By integrating thin, planar artificial muscles, it is possible to develop artificial muscles that combine both high force and large displacement. Therefore, in this research, we propose a thin soft linear actuator using conductive threads arranged in parallel. This actuator could transport an object on threads linearly. The simple configuration of parallel threads makes it easy to integrate. By realizing this transport mechanism, it becomes possible to contract like the sliding of actin and myosin, leading to the development of the artificial muscle that the authors aim for. In this paper, we describe the principle of a soft linear actuator, which is based on ratchet transport mechanism using conductive threads. Then, the principle is verified through experiments using testing prototype.

The remainder of this paper are structured as follows: Section II describes the mechanism of the proposed transport system. Section III explains the design of a prototype to realize this transport mechanism, and Section IV describes the operational experiments. Finally, we present our conclusions.

II. TRANSPORT MECHANISM USING CONDUCTIVE THREADS

In this research, we propose a transport mechanism using conductive threads. The threads used in this study have a high resistance value of several tens of MΩ per cm, depending on the tension, but can store electric charge when voltage is applied. It is believed that an electrostatic drive transport mechanism is possible by using electrostatic force. This section explains the transport mechanism.

Generally, when a potential difference is given between two objects, positive and negative charges accumulate on the objects, and a force is generated in the direction that attracts the two objects due to the electric field generated between them. Consider the case where voltage is applied between two threads as shown in Fig. 2, and a charge of $+\lambda$ per unit length is stored on the positive pole side and a charge of $-\lambda$ per unit length on the negative pole side. In this case, the electric field E_A created by the thread on the positive pole side and the electric field E_B created by the thread on the negative pole side can be expressed using the length r from each center of the thread as

Fig. 2. Two conductive threads with an applied potential difference

$$E_A = \frac{\lambda}{2\pi\varepsilon_0 r},\ E_B = -\frac{\lambda}{2\pi\varepsilon_0 r}. \tag{1}$$

Here, ε_0 is permittivity. Therefore, the magnitude of the electric field at a distance r from the positive pole thread and $d-r$ from the negative pole thread is

$$E = \frac{\lambda}{2\pi\varepsilon_0}\left(\frac{1}{r}+\frac{1}{d-r}\right). \tag{2}$$

Therefore, the potential difference between the two threads is

$$V = -\int_a^{d-a} E dr = \frac{\lambda}{\pi\varepsilon_0}\ln\frac{d-a}{a}. \tag{3}$$

a is the radius of thread. From the above, the magnitude of the stored electric charge is

$$\lambda = \pi\varepsilon_0 V \frac{1}{\ln\frac{d-a}{a}}. \tag{4}$$

The electrostatic force per unit length experienced by the thread is as follows:

$$F = \lambda E_A = \frac{V}{2d}\frac{1}{\ln\frac{d-a}{a}} \tag{5}$$

Moreover, by applying tension to the threads, they gain elasticity, and when a uniformly distributed load is applied to a thread fixed at both ends, the thread bends and vibrates. Therefore, when a potential difference is created between two threads, it is possible to make the threads vibrate due to electrostatic force.

Here, consider the case where multiple threads are arranged in parallel. In the figures in this paper, objects displayed in red indicate a state where high voltage is applied and positive charge is accumulated, while objects displayed in blue indicate a state where they are connected to the GND side and negative charge is accumulated. As shown in Fig. 3(a), when voltage is applied, considering a single thread, it receives equal electrostatic forces from left and right, and these external forces balance each other. This is because the applied potential is alternately changed, and the resultant electrostatic force has no anisotropy. On the other hand, as shown in Fig. 3(b), by applying voltage to the threads, directionality occurs in the resultant electrostatic force, causing the threads to bend and displace as the

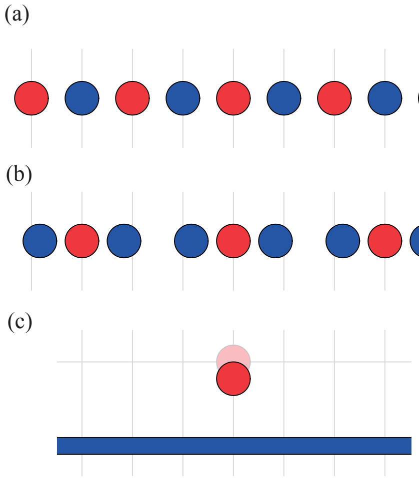

Fig. 3. (a) How the thread is displaced when one of two consecutive threads is charged with a positive charge and the remaining thread is charged with a negative charge. (b) How the thread is displaced when one of three consecutive threads is charged with a positive charge and the remaining thread is charged with a negative charge. (c) How the thread and metal plate thread are displaced.

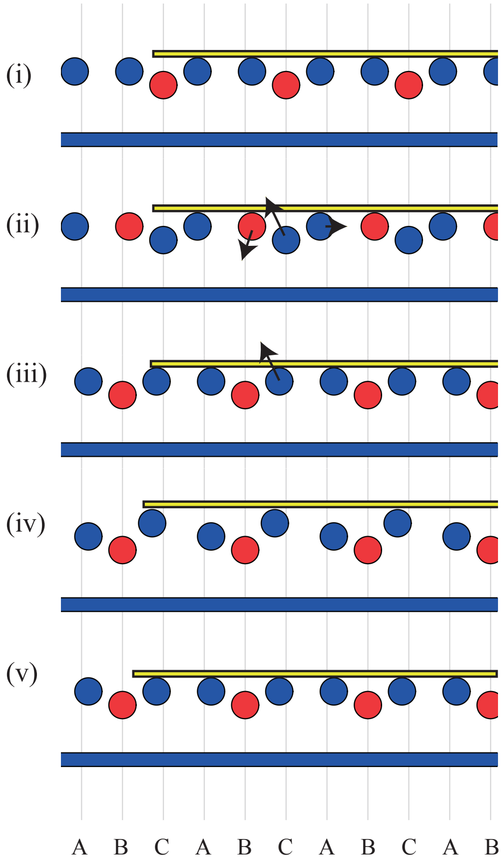

Fig. 4. Mechanism for transporting an object by applying a voltage to cause the conductive thread to rotate.

negatively charged threads are attracted to the positively charged threads.

Furthermore, as shown in Fig. 3(c), when a metal plate is placed under the threads and positive charge is applied to the threads and negative charge to the metal plate, the threads are attracted to the metal plate as shown in Fig. 3(c). As described above, the potential difference between threads can generate horizontal movement, while the potential difference between threads and the metal plate can generate vertical movement. By utilizing these two-directional vibrations of the threads, we can achieve the transport of objects on the threads.

The transport mechanism is shown in Fig. 4. It shows a cross-section of parallel threads with a metal plate placed underneath. First, in Fig. 4(i), only thread C is positively charged, while threads A, B, and the metal plate are negatively charged. Threads A and B are attracted to thread C, and thread C is displaced downward. From this state, when the applied voltage is changed as shown in Fig. 4(ii), it transitions to the state shown in Fig. 4(iii). Then, the thread that was attracted to the lower plate in Fig. 4(i) releases its elastic energy, and as shown in Fig. 4(iv), it vibrates left upward, propelling the object upward. Finally, it returns to the state shown in Fig. 4(v), thus enabling transport using a progressive wave generated by the vibration of conductive threads.

III. DEVICE AND DRIVE CIRCUIT FOR TRANSPORT USING CONDUCTIVE THREADS

This section explains the device used for verifying the transport mechanism shown in Section II.

A. *Device design*

The necessary functions for the device include: (i) the threads are arranged parallel to each other with equal spacing, (ii) the tension in the threads is equal, and (iii) the threads do not contact each other to prevent short circuits when different voltages are applied to adjacent threads. To achieve this, we manufactured fixing components that can arrange the threads parallel and equidistant by placing two plates with equally spaced holes in parallel and passing the threads through them. The spacing between the threads, that is, the distance between the holes in the thread fixing component, was set to 2.5 mm.

As shown in Fig. 5(a), each thread is passed through two holes in the fixing component. This allows the threads to be arranged in parallel. Then, as shown in Fig. 5, the threads are hung over plastic rods, and weights are attached to their ends to maintain constant tension. Furthermore, they are brought into contact with metal rods. By contacting the metal rods, the threads become equipotential with the rods. This allows the same voltage to be applied to multiple threads at once. Moreover, as shown in Fig. 5, every third thread is made to contact the same metal rod. Based on the above, we have manufactured a device that meets the three required functions.

B. *Circuit used to drive the threads*

To control the voltage applied to the threads, we used the circuit shown in Fig. 6. To realize the transport mechanism, it

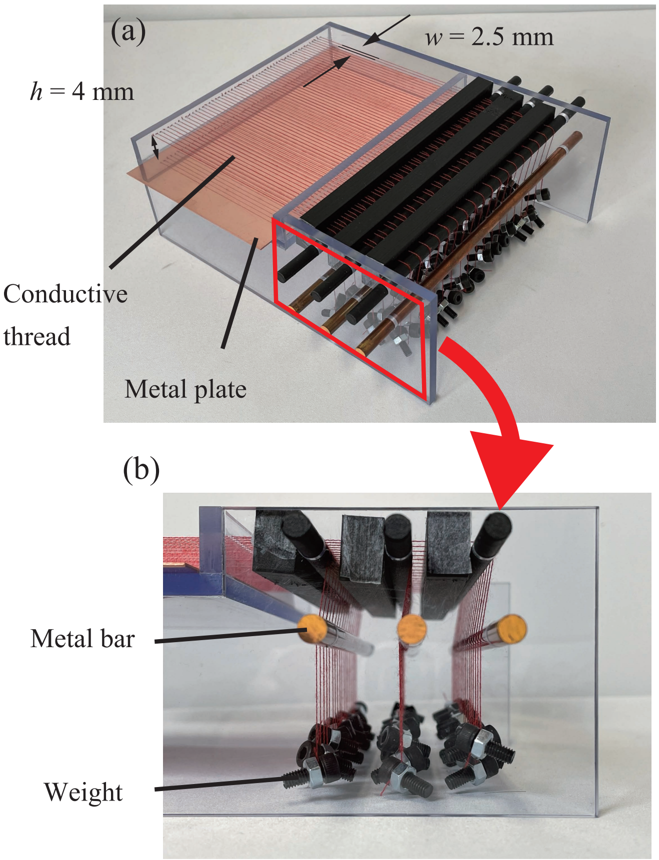

Fig. 5. Overall view of a device for transport by conductive threads.

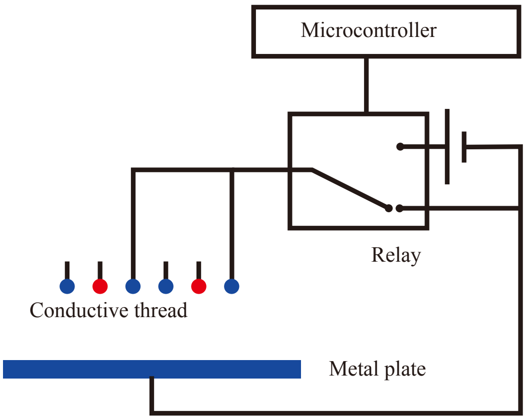

Fig. 6. Circuit to control the voltage applied to the threads.

is necessary to apply the same voltage to every third thread, and voltage is applied to the three metal rods shown in Fig. 5(b). By using one high-voltage relay for each metal rod, it is possible to switch the voltage applied to multiple threads at once. The on-off state of the relays can be controlled by a microcontroller. Using this circuit, we can control the threads and conduct experiments to transport objects as shown in Fig. 4.

TABLE I

VALUES OF EACH PARAMETER USED IN THE TRANSPORT EXPERIMENT WITH CONDUCTIVE THREADS

Parameter		Value
Voltage	V	7 kV
Distance between threads	w	2.5 mm
Distance between thread and plate	h	4 mm
Weight mass	m	4 g
Time interval for voltage switching	Δt	0.2 s

IV. TRANSPORT EXPERIMENT

A. *Parameters for the experiment*

We conducted transport experiments using the experimental device described in Section III. The parameters used in this experiment are shown in Table I. What is important in this transport is that the threads displace both horizontally and vertically. Therefore, the gap between threads and the plate should be adjusted so that the threads displace in both horizontal and vertical directions. Considering these factors, we appropriately determined each dimension.

In this study, to demonstrate the possibility of transport using threads, we used objects suitable for transport. The transported objects in the proposed thread-based transport method should ideally have properties such as a firm plane surface, being lightweight, and having insulating properties. Therefore, we used cover glasses used in microscopes as the transported objects. The cover glasses used were 18×18×0.3 mm and weighed 0.13 g.

B. *Experimental results*

Figure 7(a) shows the transport process when high voltage is applied to the threads in the order of A, B, and C for the three sets of threads A, B, and C shown in Fig. 7. Figure 7(b) shows the transport process when high voltage is applied in the order of C, B, and A. As shown in Fig. 7, it was confirmed that by reversing the direction of the input voltage wave, the transported object moves in the opposite direction.

Figure 7(c) shows the trajectory of the center coordinates of the cover glass in Fig. 7(a), while Fig. 7(d) shows the trajectory of the center coordinates of the cover glass in Fig. 7(b). These trajectories were obtained through motion tracking using Adobe After Effects on the recorded video. The video, originally captured at 29.97 fps, was accelerated to 29.97 fps at 100 times the original speed, and the coordinates were plotted for each frame. Consequently, two consecutive points represent the position of the cover glass at 3.3 s intervals. As the conveying principle utilizes string vibration, it was confirmed that the cover glass moved not only in the horizontal direction but also slightly in the vertical direction. Within the measurement, the average speed in Fig. 7(a) was 2.1 mm/min, while in Fig. 7(b) it was 2.2 mm/min.

Additionally, since the object made slight up and down movements during transport, it was confirmed that the vibration of the threads was responsible for the object's transport, as shown in Fig. 7.

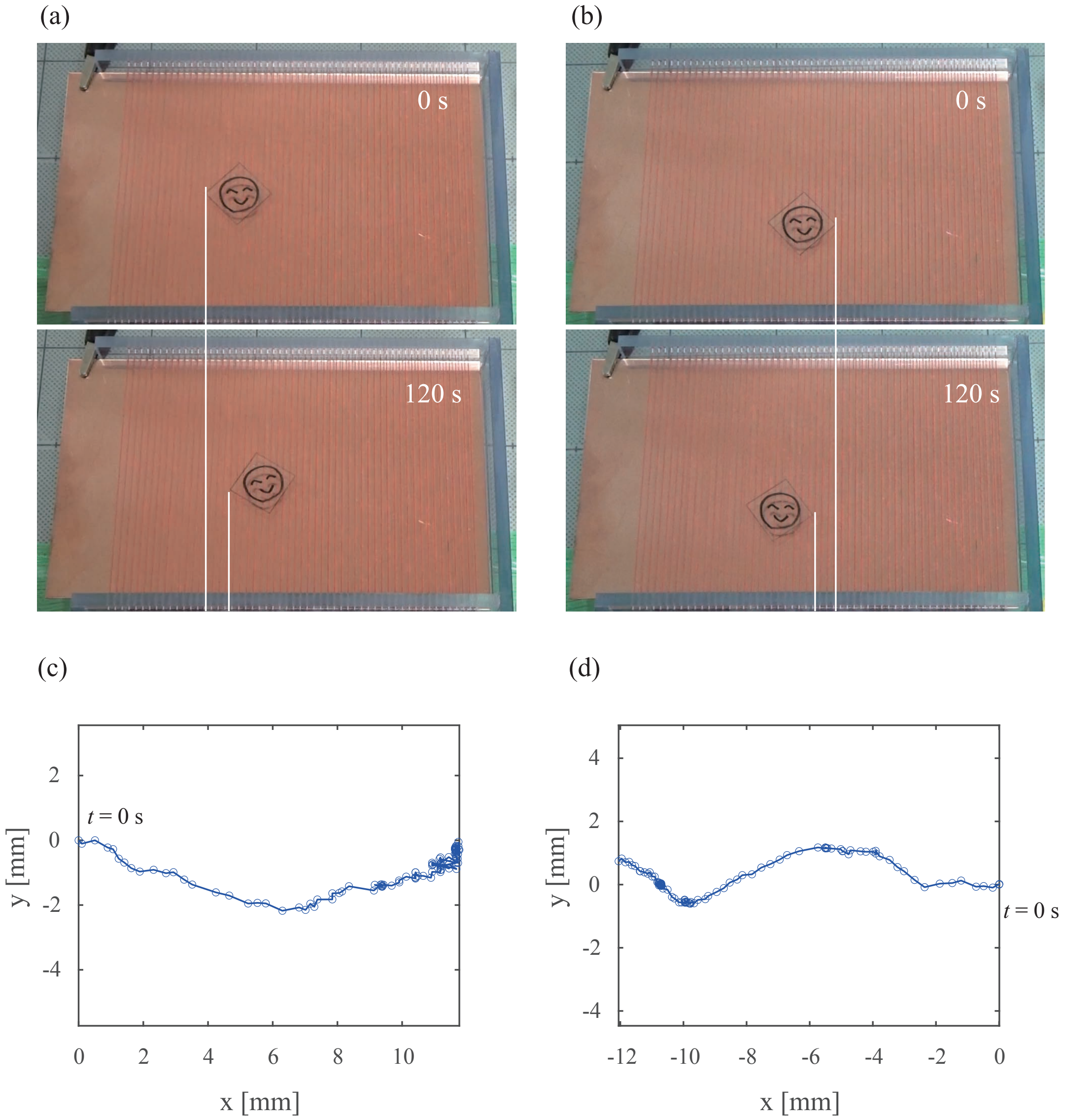

Fig. 7. (a) Transportation when the yarn to which high voltage is applied is varied in the order of A, B, and C. (b) Transportation when the yarn to which high voltage is applied is varied in the order of C, B, and A. (c) Trajectory of conveying object in (a). The x and y coordinates refer to the horizontal and vertical positions, respectively. (d) Trajectory of conveying object in (b).

V. CONCLUSION

In this paper, we proposed a soft linear actuator using conductive thread aimed at realizing artificial muscles capable of high-work and high-force through integration. The principle of this soft actuator uses transport by a thread that vibrates due to electrostatic forces. To verify the conveying principle, transport experiments were conducted using the device. By changing the voltage applied to the threads which are arranged in parallel, we succeeded in transporting cover glasses with speed of approximately 2.1 mm/min for movement in the right direction and 2.2 mm/min for movement in the left direction.

In the future, we aim to develop a transport mechanism capable of faster transport. Furthermore, we aim to realize artificial muscles capable of contraction movements with high-force and high-work.

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