Liquid Crystal Elastomer Based Dexterous Artificial Motor Unit

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Despite the great advancement in designing diverse soft robots, they are not yet as dexterous as animals in many aspects. One challenge is that they still lack the compact design of an artificial motor unit with a great comprehensive performance that can be conveniently fabricated, although many recently developed artificial muscles have shown excellent properties in one or two aspects. Herein, an artificial motor unit is developed based on gold-coated ultrathin liquid crystal elastomer (LCE) film. Subject to a voltage, Joule heating generated by the gold film increases the temperature of the LCE film underneath and causes it to contract. Due to the small thermal inertial and electrically controlling method of the ultrathin LCE structure, its cyclic actuation speed is fast and controllable. It is shown that under electrical stimulation, the actuation strain of the LCE-based motor unit reaches 45%, the strain rate reaches 750%/s, and the output power density is as high as 1360 W kg⁻¹. It is further demonstrated that the LCE-based motor unit behaves like an actuator, a brake, or a nonlinear spring on demand, analogous to most animal muscles. Finally, as a proof-of-concept, multiple highly dexterous artificial neuromuscular systems are demonstrated using the LCE-based motor unit.

1. Introduction

Conventionally, artificial muscle has been often regarded as a synonym for soft actuator, which outputs positive work to move the connected structures. However, abundant evidence from biological studies has recently demonstrated the multifunctionalities of the muscle more than an actuator;[1] sometimes the muscle can function as a brake (actively dissipating energy), or a nonlinear spring (store/release energy).[2–3] The switch between each function is rapid and often controlled by neural signals.[4–5] In animals, the motor neuron is responsible for receiving these control signals, and it will control the muscle fibers innervated by it thus enabling the multifunctionalities of the muscle. The motor neuron and the associated muscle constructs a motor unit[6] which is essential for the dexterous motion of animals.

The recent decade has witnessed rapid progress in creating diverse soft robots.[7–9] Nevertheless, the dexterity of most soft robots still does not match that of the simplest animals in nature. Building an autonomous and dexterous soft robot requires an artificial motor unit with great performance, including a fast actuation response, a large actuation strain/stress, high flexibility, and extraordinary controllability. Despite the great advancement in developing various artificial muscles and control strategies,[10–13] investigations on the compact and comprehensive design of artificial motor units are still limited.

It has been well recognized that the excellent performance of individual elements does not guarantee their compatibility in an integrated system. For instance, the actuation of many artificial muscles previously developed is usually driven by environmental heating,[12,14] light,[15,16] magnetic field,[17,18] or humidity,[19] which makes their control in a robotic system highly challenging. Dielectric elastomer[20,21] actuators and pneumatic artificial muscles[22] have shown great controllability. But they are either driven by high electrical voltages (typically higher than several hundreds of volts) or need extra air supply, which makes their tight integrations at the system level difficult.[20,23,24] Therefore, a compact design of an artificial motor unit using those responsive materials remains challenging.

To construct an artificial motor unit for dexterous soft robots, we need a soft actuating material with a fast response and easily controllable. Recently, liquid crystal elastomer (LCE), which can respond to temperature changes, has been extensively investigated to resemble the contractile behavior of biological muscles.[25–28] Due to the phase transition of liquid crystal mesogens between nematic state and isotropic state, LCE can generate large and reversible actuation with temperature change. However, most of the LCE-based actuators show slow responses.[10,12,25,29] The response time is often around or
even above 1 min, like most thermally driven actuators such as shape memory alloy/polymer-based ones. Azobenzene-coated LCE fiber shows faster responses under stimulations of light, which, however, is hard to be integrated with a compact control system. To address the controllability issue, researchers have tried to embed heating wires inside the LCE to make it electronically actuable. But this strategy increases the overall thickness of the actuator and always leads to a slow response speed. Therefore, there is a clear dilemma between controllability and response speed. To resolve this issue, we adopted a new design, in which we fabricated a wrinkled gold film (thickness of ≈40 nm) on the top of an ultrathin LCE film (thickness of ≈10 µm). The thermal inertia of the LCE decreases when the thickness of the whole structure decreases and therefore dramatically increases its response speed. The wrinkled gold film works as a resistor that can generate Joule heating to stimulate the deformation of the LCE beneath. The whole structure can be further integrated with various electronic control systems. Furthermore, with the integration of different external sensors, we can build different artificial neuromuscular systems, enabling the mimicry of voluntary movements of animals as shown in Figure 1.

In a biological motor unit, the motor neurons receive signals either from the central nervous system or the sensory receptors and then control the motion of the associated muscle fibers based on the received signals (Figure 1a). In the artificial neuromuscular system developed in the current study (Figure 1b), the thin gold-film-coated LCE film with a connected MOSFET (metal–oxide–semiconductor field-effect transistor) forms a motor unit. The voltage pulses generated by an electronic controller are similar to the action potentials received by the motor neuron. The MOSFET is the power amplifier and signal receiver, in which its gate receives the voltage pulses as control signals, analogous to a synapse. By tuning the frequency and the time width of the voltage pulses, different dynamic behaviors of an artificial motor unit can be achieved, which enables the controlling strategies such as rate coding as employed by animals.

Besides the control strategies, the real-time performance of the muscle is essential to many applications. Similar to the in vivo strain profile of an animal muscle as shown in Figure 1c, the artificial motor unit can generate large deformation with an actuation strain of ≈25% within 0.08 s under applied stress of 1.5 MPa (Figure 1d). The LCE-based motor unit can output mechanical work with a power density of 1360 W kg⁻¹, which is several times the power density of mammalian skeletal muscle (20–300 W kg⁻¹) and even insect flight muscles (400–800 W kg⁻¹). Overall, the similarities between the

Figure 1. Biomimetic design of an LCE-based artificial motor unit. a) Schematics of neuromuscular systems of an animal: after receiving a signal from the sensory receptor, a central nervous system generates a signal to control the motion of muscle (created with BioRender.com). b) Biomimetic design of an LCE-based artificial neuromuscular system. The electrical potential (V_p) is the control signal and MOSFET amplifies the input power by connecting the LCE actuator with a DC source (V_s). c) Schematics of pigeon humerotriceps and its time-dependent strain profile during flying (reproduced from reference[5]). d) Cyclic oscillation of the LCE-based motor unit with a frequency of 6 Hz, which can lift a weight of 2500 times of its own weight within 0.08 s and recover within another 0.08 s, outputting a mechanical power density of 1360 W kg⁻¹ close to or even outperforming flight muscles of animals.
artificial neuromuscular system developed here and that of animals include their actuation dynamics, versatile control strategies, and the compact integration of neurons and muscles. We hope that the artificial neuromuscular system developed in this article can inspire and enable the design of novel dexterous soft robots of various forms. Moreover, it may provide an experimental platform for biologists to investigate the physics of the various activities of animals.

2. Results and Discussion

2.1. Fabrication of the LCE-Based Motor Unit

We invented a compression-assisted molding method to fabricate the ultrathin LCE film (Figures S1 and S2, Supporting Information). With the obtained polydomain LCE films, we further cut them into desired shapes through laser cutting (Figure S3, Supporting Information). We obtained monodomain LCE films by applying stretch and simultaneously shining a UV light (wavelength: 365 nm) onto the samples. The thickness of the final monodomain LCE was \( \approx 10 \mu m \). The alignment of mesogens in the monodomain sample was verified using a polarized light field (Figure S4, Supporting Information). The glass transition temperature of the LCE is \( \approx 4^\circ C \) based on the differential scanning calorimetry (DSC) analysis results (Figure S5). To enhance the actuation stress of the LCE under high temperatures, we increase the crosslink density. However, the phase transition temperature is not detectable due to the high crosslinking density of the LCE used in the current study, which is consistent with previous reports.\[38\] We further showed that the LCE film owns a high tensile strength of 150 MPa at room temperature (Figure S6, Supporting Information) and above 10 MPa at 100 °C (Figure S7, Supporting Information). The actuation performance of the LCE can also be obtained from the mechanical tensile test under different temperatures (Figure S8, Supporting Information).

To make the LCE film electronically actuatable, we fabricated a wrinkled structure of gold on the surface of the LCE film, as shown in Figure 2a. We first pre-stretched the LCE film and then sputtered one layer of gold (≈40 nm, Figure S9, Supporting Information) on top of the LCE. The surface of the gold film on top of the LCE after sputtering was flat initially without releasing the pre-stretch (Figure S10, Supporting Information).

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Fabrication of LCE-based motor unit with a wrinkled gold film coating. a) Schematics showing three main fabrication steps. b,c) Images of the LCE-based motor unit in its free-standing state and stretched state. d) Optical microscopic images of the surface of the gold film under different stretches. When the applied stretch is small, surface wrinkles remain; when the applied stretch is large, the surface flattens. e) Electrical resistance of gold film under different stretches. When the applied stretch is less than 1.35, the electrical resistance remains unchanged as the stretch increases, corresponding to the process of wrinkle flattening and indicating a safe operation window of the applied stretch.
Once the pre-stretch of the LCE film was released, the gold film coating formed a wrinkled configuration (Figure S11, Supporting Information) which enabled its large stretchability, and the LCE film recovered to its original length with residual strain of less than 1%. After that, we installed the soft electrodes to connect the wrinkled gold film to external circuits as shown in Figure 2a.

Figure 2b and Figure 2c show the images of the fabricated LCE-based motor unit before and after stretching, in which $L_0$ denotes the original length of the LCE-based motor unit without bearing any load and heating, and $L$ is its length after stretching. The microscopic images in Figure 2d show the flattening of the wrinkled gold film as the stretch increases. To examine the stretchability of the LCE-based motor unit, we stretched it up to 1.4 times its initial length and then gradually released the stretch, during which we measured the electrical resistance of the LCE-based motor unit as shown in Figure 2e. The electrical resistance remained constant if the stretch was less than 1.35 ($L/L_0 < 1.35$), corresponding to the flattening process of the wrinkled configuration. If the stretch was beyond 1.35 and smaller than 1.4, the electrical resistance linearly increased with the applied stretch, which was caused by the increase of the strain in the gold film. It is also noted that the electrical resistance of the gold film fully recovered to its original value once the applied stretch was reduced below 1.35, indicating that the gold film can be stretched by 1.4 times without damage.

2.2. Dynamic Behaviors of the LCE-Based Motor Unit

2.2.1. Muscle-Like Performance with Capability of Outputting High Power Density

With the ultrathin LCE film, we showed that the LCE-based motor unit can respond to an electrical stimulus within 1 s under quasi-static stimulating cases (Figures S12–S15, Supporting Information), which is faster than most conventional LCE-based actuators. While more interestingly, if the energy input is further concentrated within several milliseconds (smaller than the time set by the mass inertia), the dynamics of the motor unit changes dramatically. A representative dynamic behavior of the LCE-based motor unit with a hanging weight under the stimulation of periodic voltage pulses is shown in Figure 3a (see Movie S1, Supporting Information for the real-time behavior). When the motor unit was subjected to an applied stress of 1.7 MPa, it was able to generate an actuation strain over 45% within 0.1 s, and a maximal velocity during the contraction or recovery can reach 0.3 m s$^{-1}$ with a peak acceleration of $\approx$10 m s$^{-2}$ (Figure S16, Supporting Information). In the experiment, we applied a voltage of 30 V with a pulse width of 5 ms and a frequency of 2 Hz onto the actuator. The pulse width is much shorter than the time scale determined by the mass inertia of the motor unit (100–200 ms). With the periodic voltage stimulation at 2 Hz, the motor unit oscillated cyclically at a higher frequency of 6 Hz, which was mainly determined by its resonant frequency (verified through Fourier analysis, Figure S17, Supporting Information). Such frequency mismatch is reminiscent of the dynamic behavior of asynchronous muscles widely existing in insect flight muscles (IFMs). Though the working mechanisms are not identical,[39] our work may provide an insight for understanding the dynamic behaviors of asynchronous muscles.

To quantitatively understand the dynamic performance of the motor unit, we first used 1 Hz 30 V voltage pulses with different pulse widths (1 ms–5 ms) to perform the tests and the LCE-based motor unit was subjected to different applied stresses (0.75 MPa–1.75 MPa). We plot the maximum actuation strain of the motor unit versus the pulse width in Figure 3b (see Figure S18a, Supporting Information for detailed results of actuation strain versus time). With a longer pulse width, the motor unit generated a larger actuation strain. By taking the derivative of the actuation strain we can further obtain the maximum strain rate (Figure S18b, Supporting Information). Figure 3c shows the result of the peak strain rate versus the applied stress. Under a specific pulse width (i.e., $t_p = 5$ ms), the maximum strain rate of the LCE-based motor unit decreases with increasing the applied stress. Notably, the highest strain rate during either actuation or recovery is $\approx$600%/s (when $t_p = 5$ ms, applied stress = 0.75 MPa). As a comparison, the typical strain rate of human muscles is $\approx$50%/s.[10,12,40] The actuation stress measurements using similar control signals can be found in Figure S19 (Supporting Information).

We next estimated the output of the mechanical power density of the motor unit by computing the work done during the first contraction cycle immediately after the voltage pulse was applied, as shown in Figure 3a (orange region). We varied the frequency of the voltage pulse from 2 Hz to 10 Hz while controlling the input electrical power ($\bar{P}$, see Figure 1b) as a constant (250 mW). We then calculated the output mechanical power density for different stimulation frequencies based on the actuation strain data (Figures S20 and S21, Supporting Information). We plotted the power density with respect to the frequency of voltage pulses under different applied stresses (0.75 MPa–1.75 MPa), as shown in Figure 3d. The output mechanical power density becomes larger as the frequency of the simulation voltage becomes closer to the resonance frequency of the mechanical system. The appearance of the peak of the output power density shifts from 7 Hz to 8 Hz as applied stress decreases from 1.75 MPa to 0.75 MPa. Moreover, when the applied stress is 0.75 MPa, we observed two peaks of the power density, which is possibly due to the system’s nonlinearity. For a nonlinear oscillation, additional peaks often appear at the frequencies different from the resonant frequencies of the system (e.g., sub-harmonic or super-harmonic behaviors).[41]

Meanwhile, we also verified the significance of reducing the thickness of LCE as shown in Figure 3e. With fixing all the other controlling parameters, the mechanical power density (calculated from actuation strain in Figure S22, Supporting Information), increases dramatically as the thickness of the LCE decreases from 50 µm to 10 µm. When the thickness of the LCE film is 10 µm, the motor unit can output the highest power density of 1360 W kg$^{-2}$, which outperforms most of the biological muscles.[30]

We further summarized all the measured performance metrics and plotted the highest value in a radar plot (Figure 3f). As shown in the radar plot, LCE-based motor unit has maximum actuation stress of 3 MPa (Figure 3f), maximum actuation...
strain of over 50% (Figure S23, Supporting Information), maximum energy density of 455 J kg\(^{-1}\) (Figure S24, Supporting Information), maximum power density of 1360 W kg\(^{-1}\) (Figure S25, Supporting Information), maximum strain rate of 750%/s (Figure S16, Supporting Information), and bandwidth of 6 Hz (Figure S26, Supporting Information). Noticeably, the overall performance of the LCE-based motor unit is comparable to or better than that of human muscles. Moreover, its actuation performance is also compared with other previously reported artificial muscles as shown in Table 1.

2.2.2. Electro-Thermo-Mechanical Model of the LCE-Based Motor Unit

To better understand the dynamic behavior of the LCE-based motor unit, we developed an electro-thermo-mechanical model to simulate the system responses under different stimulations. Once the thickness of the LCE film is reduced to 10 µm, its Biot number is much smaller than 1 (≈0.0002), implying that the temperature field inside LCE is nearly homogenous. Therefore, we can easily solve the temperature profile \( T(t) \) of the LCE.

Figure 3. Dynamic behaviors of the LCE-based motor unit. a) Representative dynamic behavior of the LCE-based motor unit under the stimulation of periodic voltage pulses (\( V_p = 30 \) V, \( f = 2 \) Hz, \( t_w = 5 \) ms), when it is subjected to an applied stress of 1.7 MPa. b) Maximum actuation strain versus voltage pulse width (\( t_w = 1 \) ms–5 ms, \( V_p = 30 \) V, \( f = 1 \) Hz) under different applied stresses (0.75 MPa–1.75 MPa). c) Maximum strain rate versus different applied stress (0.75 MPa–1.75 MPa) by taking derivative of previous actuation strain results. d) The peak of power density shifts with varying the applied stress (0.75 MPa–1.75 MPa) during isotonic tests. e) Increase of power density with decreasing the LCE thickness. f) Radar plot showing the similar performance between the LCE-based motor unit and the human muscle in terms of actuation strain, actuation stress, bandwidth, strain rate, power density, and energy density. g) Schematics defining the main variables of the system. h) Experimental measurements of the equilibrium strain \( (\varepsilon^*(T)) \) versus temperature under applied stress of 1.5 MPa and the associated quadratic fitting equation. i) Comparison between experimental result and simulation result of actuation strain versus time in dynamic case (\( V_p = 30 \) V, \( f = 2 \) Hz, \( t_w = 4 \) ms, applied stress = 1.5 MPa).
under a given voltage stimulation by solving the thermal equation involved with Joule heating, heat convection, and radiation. More details of the model can be found in Text S2 (Supporting Information).

To predict the dynamics of the LCE-based motor unit with a hanging weight, we further adopted a mass-spring model (Figure 3g) to relate the mass of the hanging weight, its position, and the temperature in the LCE film based on the following equation:

\[ m \frac{d^2 x}{dt^2} + b \frac{dx}{dt} = k \left( l_0 - x \right) \left( T(t) \right) \]

(1)

where \( x \) is the position of the weight and \( x = 0 \) at the beginning, \( m \) is the mass of the hanging weight, \( b \) is the coefficient of the damping, \( k \) is the spring constant of the LCE motor unit, \( l_0 \) is the initial length of the LCE-based motor unit with a hanging weight before any stimulation, \( l^0 \) is the equilibrium length of the LCE-based motor, which is a function of the temperature of the LCE, \( T(t) \).

Recall the equations of the natural frequency of a mass-spring system \( \omega_n = \sqrt{\frac{k}{m}} \), the definition of damping ratio \( \zeta = \frac{b}{2m\omega_n} \), the definition of actuation strain \( \varepsilon(t) = x(t)/l_0 \) and the definition of temperature-dependent equilibrium strain \( \varepsilon^*(t) = (l_0 - l^0)/l_0 \). Equation (1) can be rewritten as:

\[ \frac{d^2 e}{dt^2} + 2\zeta\omega_n \frac{de}{dt} + \omega_n^2 e = \alpha^*e \left( T(t) \right) \]

(2)

The term on the right-hand side of Equation (2) provides the driving force for the oscillation of the motor unit, which is originated from the dependence of the equilibrium strain on the temperature changes: \( \varepsilon^*(T(t)) \). Such dependence can be measured experimentally as shown in Figure 3h and Figure S27 (Supporting Information). The dependence can be further given by a quadratic fitting for later simulation. We can then use the electro-thermo-mechanical model developed above to predict the time-varying strain of the LCE-based motor unit for dynamic oscillation (Figure 3i, \( V_p = 30 \text{ V} \), \( f = 2 \text{ Hz} \), \( t_w = 4 \text{ ms} \)). More simulation results under different voltage profiles can be found in Figures S28 and S29 (Supporting Information). The prediction agrees well with the experimental data which confirms the validity of our thermo-mechanical dynamic model.

### 2.3. Work Loop of the Artificial Motor Unit

As we introduced previously, biological muscles have multifunctionalities more than an actuator: they can also behave like a brake or a spring[2,6] simply controlled by the neuron signals. As shown in Figure 4a, the different functions can be classified through the work loop technique[44] from the energy perspective: whether the muscle does positive work or negative work and how much the work done is. In the tests, the periodic voltage stimulation shares the same frequency as the controlled cyclic motion, while the phase (%) defined in Figure 4a indicates the phase difference between the two periodic events. We controlled the cyclic deformation of the LCE-based motor unit with the strain varying between 0% and 6% at a frequency of 0.25 Hz while stimulating it with voltage pulses (\( V_p = 30 \text{ V} \), \( t_w = 4 \text{ ms} \)) of the same frequency (0.25 Hz) but varying the phase from 0% to 90%. Both real-time strain and stress data were collected simultaneously to generate work loop plots (stress versus strain) as shown in Figure 4a, detailed process can be found in Figure S30 (Supporting Information).

We show four typical work loops (phase = 0%, 30%, 60%, and 90%) in Figure 4b (more results in Figure S31, Supporting Information). The direction of the work loop tells whether the LCE-based motor unit produces negative work (absorb energy) or positive work (output energy), which can be tuned by the phase when the stimulation signal is sent. During the tests, the LCE-based motor unit can behave differently as a brake (phase = 0% and 90%), as a spring (phase = 30%), or as an actuator/motor (phase = 60%), which is similar to the performance of animal muscles.[2]

To understand this energetic process quantitatively, we further calculated its output work density within one cycle based on the work loop plots with stimulation signals at different phases (Figure S31, Supporting Information). We integrated the area inside the work loop to obtain the positive work (counterclockwise loop) and negative work (clockwise loop) done by the LCE-based motor unit within one cycle of movement as shown in Figure 4c. By adding up the two works, we obtained the net output work of the LCE-based motor unit in one cycle of movement for different phase values. We then can classify the behaviors of the LCE-based motor unit based on the energetic process: brake-like behavior (net negative work); actuator-like behavior (net positive work); and spring-like behavior (nearly zero output work) as shown in Figure 4c.

### Table 1. The comparison of the performance of the LCE-based motor unit in the current work with the previously reported electrically controlled artificial muscles.

<table>
<thead>
<tr>
<th>Artificial muscles</th>
<th>Actuation strain [%]</th>
<th>Strain rate [%/s]</th>
<th>Work density [kJ/m³]</th>
<th>Power density [W/kg]</th>
<th>Driving voltage [V]</th>
<th>References</th>
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<tr>
<td>This work</td>
<td>50</td>
<td>750</td>
<td>480</td>
<td>1360</td>
<td>5–30</td>
<td>[15,25]</td>
</tr>
<tr>
<td>Previous LCEs</td>
<td>40</td>
<td>&lt; 2</td>
<td>150</td>
<td>&lt; 1</td>
<td>3–5</td>
<td>[12,23,42]</td>
</tr>
<tr>
<td>DE</td>
<td>380</td>
<td>450</td>
<td>&lt; 3500</td>
<td>3600</td>
<td>&gt; 100</td>
<td>[42–43]</td>
</tr>
<tr>
<td>IPMC</td>
<td>40</td>
<td>3.3</td>
<td>5.5</td>
<td>2.56</td>
<td>&lt; 10</td>
<td>[12,42]</td>
</tr>
<tr>
<td>SMA</td>
<td>10</td>
<td>&lt; 300</td>
<td>&lt; 10000</td>
<td>50 000</td>
<td>≥ 4</td>
<td>[12,42]</td>
</tr>
<tr>
<td>TFA</td>
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<td>50</td>
<td>5.3</td>
<td>5300</td>
<td>10–100</td>
<td>[12,14,42]</td>
</tr>
</tbody>
</table>
2.4. Dexterous Artificial Neuromuscular System

With the unique combination of fast response and easy controllability for our LCE-based motor unit, various control strategies (Figures S32–S33, Supporting Information) can be realized. Therefore, we can further integrate it with various sensory components and control systems to build artificial neuromuscular systems.

First, we demonstrated an autonomous object capturing system, inspired by the ruler drop test (Figure 5a) for examining the reaction time of a person. We used an optical sensor to mimic the visual systems (eyes) of humans and used the artificial LCE-based motor unit to replicate the performance of real motor units as shown in Figure 5b. Once a falling ball blocked the light from the LED, a triggering signal was generated by the optical sensor and sent to the micro-controller, and then the micro-controller generated a stimulation voltage pulse and triggered the MOSFET to provide the LCE with thermal energy to contract and catch the falling ball (see Figure 5c and Movie S2, Supporting Information). The whole process resembles the brain controlling the finger movements to catch the ruler through visual feedback in a reaction time test. It is noted that the reaction time of our artificial neuromuscular system (0.1 s) is comparable to the average reaction time of a human being (0.2 s), indicating the high dexterity of the artificial LCE-based motor unit.

We next integrated the LCE-based motor unit with a position sensor to mimic the control of the forearm through the biceps of a person, as shown in Figure 5d. We installed a hall-effect sensor at the joint position to detect the joint angle of the arm (defined in Figure 5d). An LCE-based motor unit was used to move the arm. As shown in Figure 5e, initially, the joint angle equals 72°. After we suddenly hung a weight of 0.7 g at the end of the lower arm without stimulating the LCE-based motor unit, the arm moved toward the zero joint angle. The arm was then stimulated to move back to the 72° position, demonstrating the ability of the artificial motor unit to mimic the control of the biceps through a hall-effect sensor.
unit, the arm fell down and oscillated for several cycles before reaching the equilibrium position, as shown in Figure 5e (See Movie S3, Supporting Information). We next showed that the LCE-based motor unit behaved like a brake. After a sudden release of a weight of 0.7 g, once the joint angle (detected by the position sensor) passed a pre-set joint angle (trigger angle, set to be 70°), a pre-programmed voltage pulse ($V_p = 20$ V, $t_w = 13.5$ ms) was sent to trigger the contraction of the LCE-based motor unit. As shown by the blue curve in Figure 5e, the amplitude of the arm oscillation decreased and the number of oscillation cycles also reduced before the arm reached the equilibrium, as compared to the experiment without stimulating the LCE (grey dash curve in Figure 5e). We showed that the LCE-based motor unit behaved like a brake in this case which dissipated the mechanical energy of the system and also resembled the eccentric contraction of biological muscles. In contrast, if we set the trigger angle as 65° with the same voltage pulse ($V_p = 20$ V, $t_w = 13.5$ ms), the amplitude of the arm oscillation increased slightly (red curve in Figure 5e). In this case, the LCE-based motor unit behaved like a spring, slightly reducing the system damping. Based on the work loop results shown in Figure 4c, we can readily understand the behaviors of the LCE-based motor unit described above. We regard the ratio between the time when the triggering signal was sent and the time when the
arm reached its highest position as the phase value in Figure 4c. Here, if the trigger angle is 70°, the phase is 17°, and consequently, the LCE behaves like a brake according to Figure 4c, which is consistent with the results shown in Figure 5e. Likewise, if the trigger angle is 65°, the phase is 28°, and consequently, the LCE behaves like a spring according to Figure 4c.

At last, we demonstrated a close-loop proportional–integral–derivative (PID) control (Text S3, Supporting Information) of the joint angle, as shown in Figure 5f. Herein, we showed that the arm could be stabilized around the set point with the joint angle of 100° (see Movie S4, Supporting Information). In the experiment, we dropped a load (0.4 g or 0.7 g) at the end of the arm. It is shown that with these perturbations, the joint angle can be stabilized around the set value through effective PID control within several seconds. The response speed we showed here was significantly faster than the previously reported close-loop control results using LCE-based actuator,[45] which made our motor unit more adaptive to the random disturbances from the environment (Figure S34 and Movie S5, Supporting Information).

3. Conclusions and Perspectives of Future Work

Though various soft actuators, sensors, and the control systems associated with them have been intensively explored by researchers in the past, the compact integration of these elements has been much less studied, which hinders the construction of dexterous soft robots. In this study, we developed a gold-film-coated ultrathin LCE-based motor unit that was electronically controlled. We further demonstrated that the LCE-based motor unit showed a superior actuation performance with the performance indices (actuation strain, actuation stress, power density, and bandwidth) close to or outperforming those of biological muscles. Like biological muscles, by varying the time of sending the stimulating signal, we demonstrated that the LCE-based motor unit could behave as an actuator, a brake, or a spring in a mechanical system. Moreover, the electronic controllability of the LCE-based motor unit makes it compatible with most electronic devices. Integrating the LCE-based motor unit, sensors, and electronic control systems, we can easily build an artificial neuromuscular system, which shows great dexterity in autonomous robotic structures.

Finally, we would like to discuss future research opportunities based on the design presented in the current study.

(1) Though we only demonstrated a simple motion (contraction) of the LCE-based motor unit in this work, more complex motions can be easily achieved with different arrangements of multiple motor units.

(2) The fast response of the LCE-based motor unit results from the ultrathin LCE structure, sacrificing the magnitude of the actuation force. Increasing the actuation force could be achieved by the assembly of multiple LCE-based motor units, like the structural hierarchy of a biological muscle.

(3) Though we have only demonstrated the artificial neuromuscular system with optical sensors and Hall-effect sensors, they can be easily replaced by different types of sensors for various purposes.

(4) For small structures like microrobots (less than 1 cm), a smart material-based actuation mechanism shows a great advantage over electrical motor-based ones on actuation mechanism. Though the prototype shown in the current study is not small, it is not hard to significantly shrink the physical size of the entire system for a more compact design.[46]

(5) Our results showed that the LCE-based motor unit can stably generate a cyclic strain of 25% for more than 400 cycles without performance degradation, but its actuation performance decreased significantly after 800 cycles of contractions (Figure S35, Supporting Information). The performance decay of the system after hundreds of cycles mainly originates from the fatigue of the gold film sputtered on top of the LCE, which finally leads to the failure of the electrical connection. We believe the durability of the gold film can be improved with further optimization of the fabrication process.

4. Experimental Section

Materials: (1,4-bis-[4-(3-acryloyloxypropoxy) benzoxyloxy]-2-methylbenzene) (RM257) (Wilshire company, 95%), 2,2′-(ethylenedioxy) diethanethiol (EDDET; Sigma-Aldrich; 95%), pentaerythritol tetrais (3-mercaptopropionate) (PETMP, Sigma-Aldrich; 95%), dipropylamine (DPA, Sigma-Aldrich; 98%), (2-hydroxyethoxy)-2-methylpropionophenone (HHMP, Sigma-Aldrich; 98%), and all the solvents were used as received without further purification.

Fabrication of 1st Cross-Linked Ultrathin LCE Film: To get the LCE film, liquid crystal mesogens RM257 (10,000 g, 16.65 mmol) were first added into toluene, and the mixture was heated at 85 °C. The photo-initiator HHMP (0.077 g, 0.3 mmol) was added to the mixture. Then, 1.902 g (9.9 mmol) of spacer EDDET, 1.529 g (2.9 mmol) of cross-linker PETMP, and 0.032 g (0.3 mmol) of catalyst DPA were added into the solution. After stirring and degassing, the compression-assisted molding technique was used to get the 1st cross-linked ultrathin polydomain LCE films as described in the Supporting Information.

Construction of LCE-Based Motor Unit: The dog-bone shape 1st cross-linked polydomain LCE films were fabricated first through laser cutting (Figure S3, Supporting Information). They were then stretched to 2.75 times of their original length to align the mesogens. The stretched LCE thin films were placed under UV light (365 nm) and cured for 1 h to finish the 2nd cross-linking and get the monodomain LCE films. Without releasing the stretch, the UV-cured LCE thin films were then placed inside a DC magnetron sputter deposition system (Denton Discovery 18) for gold sputtering. After sputtering, the fixed stretch was released, and the gold film formed the desired wrinkled structure. The soft electrodes were installed to the LCE/gold film and the LCE/gold film was connected with a MOSFET Module (IRF540) and an LCE-based artificial motor unit was constructed.

Characterization of the LCE-Based Motor Unit: During the later test, DC power source (Dr. Meter PS-305DM) was used to provide the heating power, and a function generator (Keysight, 33500B) to generate periodic voltage pulses as control signals. A self-defined python algorithm (Figure S36, Supporting Information) was used to analyze the actuation strain data from the videos captured by the high speed camera (Edgetron).
Acknowledgements
The authors acknowledge support from the Office of Naval Research through grant no. N00014-17-1-2062 and the US Army Research Office through grant no. W911NF-20-2-0182.

Conflict of Interest
The authors declare no conflict of interest.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords
artificial motor unit, liquid crystal elastomer, soft robot

Received: December 2, 2022
Revised: January 18, 2023
Published online: March 19, 2023