Soft Robotics

# A Biomimetic Soft Lens Controlled by Electrooculographic Signal

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Thanks to many unique features, soft robots or soft machines have been recently explored intensively to work collaboratively with human beings. Most of the previously developed soft robots are either controlled manually or by prewritten programs. In the current work, a novel human-machine interface is developed to use electrooculographic signals generated by eye movements to control the motions and the change of focal length of a biomimetic soft lens. The motion and deformation of the soft lens are achieved by the actuation of different areas of dielectric elastomer films, mimicking the working mechanisms of the eyes of human and most mammals. The system developed in the current study has the potential to be used in visual prostheses, adjustable glasses, and remotely operated robotics in the future.

# 1. Introduction

Collaboration and interaction between human beings and machines or robots have been recently studied extensively and intensively.<sup>[1–4]</sup> To enable such collaboration or interaction, various human–machine interfaces (HMIs) have been correspondingly designed.<sup>[5–22]</sup> For example, HMIs have been

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developed to use electrophysiological signals, including electroencephalographic, electromyographic, and electrooculographic (EOG) signals, to control the motion of wheelchairs<sup>[5–7]</sup> and diverse functions of exoskeletons.<sup>[8–12]</sup> Those HMIs have not only enabled the disabled to restore their mobility and dexterity but also enhanced the capability of healthy people.<sup>[22]</sup>

In most of the previous work, HMIs were constructed between human beings and conventional hard machines. In recent years, a variety of soft robots and soft machines have been designed and constructed, and many advantageous features have been explored and dem-

onstrated, such as great deformability, excellent biocompatibility, and high tolerance of defects. For instance, soft grippers have been built to grasp fragile objects such as raw eggs and fresh fruits,<sup>[23–25]</sup> which has been known to be very challenging for conventional stiff grippers. Soft robots which can greatly deform themselves to pass through small openings have also been built.<sup>[26,27]</sup> Soft lens,<sup>[28–31]</sup> made from different stimuli-responsive materials, have demonstrated superior performance, compared to conventional glass lens. To enable versatile interactions between human and those soft robots or soft machines, corresponding HMIs are imperative. Because the actuation mechanisms for soft robots/machines are typically different from conventional hard robots, specific compatibilities between the HMIs and those newly developed actuation mechanisms are required.

In this study, we developed an HMI between human eyes and a soft biomimetic lens, which was mainly composed of electroactive polymer films. The change of the focal length and the motion of the soft lens closely resembled those of human eyes, which were achieved by the electrical potential-induced actuation of dielectric elastomer (DE) films. An electroactive DE film is composed of a soft dielectric layer sandwiched between two compliant electrodes. When an electrical potential is applied between the two electrodes, the soft layer can instantly expand its area and reduce its thickness through the action of Maxswell stresses.<sup>[32–34]</sup> The biomimetic lens built by us contained multiple separated DE films (**Figure 1**), actuation of which were controlled by EOG signals. EOG signals reflect the change of electrical potential difference between the cornea and the ocular fundus of eyes, which is closely associated with the eye movements.<sup>[35]</sup>

Although in the previous studies, EOG signals have been successfully exploited for the control of the multiple degrees

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**Figure 1.** Design and fabrication of a biomimetic soft lens. a) The schematic of a human eye. The extraocular muscles control the motions of eyeball. The lateral rectus and media rectus form an agonist–antagonist pair to realize the horizontal rotation of the eyeball. The focal length of the crystalline lens can be changed by the contraction of the annular ciliary muscle. b) The design of the biomimetic soft lens. Two prestretched DE films and the lens formed a double-cone configuration. Each of the two DE films had four separate active areas. An annular carbon grease electrode was coated on top of the surface the lens and the salty water served as the other electrode. c) When an electrical potential was applied onto a pair of DE films on one side (as marked by red), a planar movement of the lens could be induced by the expansion of the DE film. d) The expansion of the annular DE film in the lens could reduce the curvature of the film on both sides and thus increased the focal length of the lens. e) The photos of the system. The scale bars are 1 cm.

of freedom motions of wheelchair and robots,<sup>[7,18–21]</sup> the current work is the first proof-of-concept design of using EOG signals to control soft machines. Thanks to the fast response of the DEs,<sup>[36]</sup> the motion and deformation of the soft lens could be easily synchronized with the movements of the eyes. The system developed in the current study has the potential to be used in visual prostheses, adjustable glasses, and remotely operated robotics in the future.

# 2. Results

## 2.1. Design and Performance of the Soft Tunable Lens

Inspired by the motion and the tuning of focal length of the eyeball of human beings and mammals, we designed a novel soft and tunable lens using DE films as shown in Figure 1. The central part of the device was a soft lens, which was composed of two DE films (VHB tape from 3M Company) and encapsulated salty water. The salty water was used as a transparent fluidic medium, resembling crystalline lens of eyes, and also as one electrode for the DE film. The top DE film was also coated with annular carbon grease as the other electrode as shown in Figure 1b. The actuation of the annular area of the DE film was used to mimic the contraction of ciliary muscle of eyes. Because the volume of the encapsulated salty water was always conserved, the electrical potential-induced expansion of the coated annular area of the DE film would lead to the decrease of the curvature of central area of both sides of the lens (Figure S2 Supporting Information) and thus increased its focal length. We made the radiuses of cavities of the lens frame on the two sides to be different<sup>[28]</sup>



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to achieve large change of focal length as shown in Figure 1b. When a voltage of 5 kV was applied onto the top DE film of the lens and salty water, the relative change of the focal length of the lens could reach 32.6% (Figure S2, Supporting Information), which was comparable to that of human eyes.<sup>[29]</sup>

The center lens was further connected to two DE films with eight separate areas coated with carbon grease on both sides, which could be used to control the motion of the lens, emulating the function of extraocular muscles as shown in Figure 1a. Each of the eight coated areas could be actuated independently to obtain different motions of the lens as shown in Figure 1c (planar movement), Figure S3 (rotation) and Movie S1 in the Supporting Information. In details, the electrical potential-induced compressive Maxwell stresses could cause the expansion of the activated areas, accompanied by the release of the prestretch in the inactivated areas. As a consequence, the activated and inactivated areas formed an agonist–antagonist pair.

The variations of the images with the electrical potentialinduced movements of the lens are demonstrated in **Figure 2** and Movie S2 in the Supporting Information. It is noted that with the electrical potential-induced rotation of the soft lens, the change of the visual field was not as wide as that of human eyes, because in the current setup (Figure S4, Supporting Information), the position of the camera was fixed in front of the lens, while the retina of human eye can rotate together with the eyeball. Therefore, in the following demonstrations (including Movie S2, Supporting Information), we only used



Figure 2. Controlled image change of the soft lens. a) Rest state. (b) shows the image after the focal length change. (c)–(f) show the images after the motion of the lens to four directions, respectively. In the figure, the red color means an electrical potential was applied, while the gray color means electrical potential was not applied.

planar movements of soft lens to demonstrate the change of the visual field. The distance between the object (the letters) and the center of the lens was shorter than the focal length of the lens. Therefore, the images in Figure 2 and Movie S2 in the Supporting Information, as well as the following demonstrations, were all virtual images.

#### 2.2. Real-Time EOG Signal-Controlled Lens

The setup of the entire system is illustrated in **Figure 3**. The monitoring electrodes were placed in a conventional five-electrode configuration<sup>[21,37–39]</sup> around two eyes to acquire the EOG signals generated by the eye movements from the L-R channel and U-D channel as shown in Figure 3a. We used the Arduino microcontroller for signal processing. To eliminate the noises in EOG signals, we smoothed the raw EOG signals by using moving average filter (more details can be found in the Supporting Information). **Figure 4**a shows the performance of the EOG signal-controlled soft tunable lens. The four moving directions of the eyes could control the planar movements of the tunable lens and double blink of the eyes could trigger the focal length change of the lens.

Figure 4b shows the waveforms of the EOG signals corresponding to different eye movements, obtained from L-R channel and U-D channel, respectively. When the eyes moved from the primary position to any direction (right, left, up, or down) and then moved back, a peak with a valley followed successively (or a valley with a peak followed successively) could be found in the EOG signal from both channels. In general, when the eyes moved toward the positive monitoring electrode, a peak could be found in the signal, while a valley could be found in the signal when the eyes moved away from the positive electrode. Taking the signal from the R-L channel generated by the left movement of the eves as an example (Figure 4b), the first valley corresponded to the leftward movement of the eyes. The plateau indicated that the eyes stayed at the gaze direction and the following peak indicated that the eyes moved back to the primary position. In addition, comparing the EOG signals from the two channels (L-R channel and U-D channel), we could find that the EOG signals had opposite phases for horizontal movements (left or right) but the same phase for vertical movements (up or down) and blink or double blink. We used such features to distinguish horizontal movements and vertical movements of eyes. In addition, the amplitudes of EOG signals were larger in R-L channel for the horizontal movements of the eyes, while the amplitudes were larger in U-D channel for vertical movements of the eyes. Therefore, as shown in the flowcharts (Figures S6 and S7, Supporting Information), we always used the signals from R-L channel to determine left or right movement, and the signals from U-D channel to determine upward or downward movement, blink and double blink.

Similar to previously reported signal recognizing mechanism,<sup>[20,21,38,39]</sup> based on the above features of the EOG signals, we could process the EOG signals in real time through the microcontroller to determine the eye movements. By comparing the magnitude of the EOG signals with a predefined threshold values (represented by the dash lines in Figure 4b), we could determine whether a peak or a valley appeared. The



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**Figure 3.** Schematic and photograph of the system setup. a) The monitoring electrodes were placed around the eyes in five-electrode configuration. The EOG signal was acquired and amplified by the AD8232 module and then processed by the Arduino microcontroller. The output signals from the microcontroller were used to control the state of the relays and thus the actuation of the DE films of the lens. b) The photo of the system where the two cables were connected to the monitoring electrodes.

threshold values needed to be calibrated after the monitoring electrodes were placed. We could distinguish the horizontal motion and vertical motion of the eyes by comparing the signs of the first derivative of EOG signals from both L-R channel and U-D channel, once the magnitude of the signal passed the threshold value of peak or valley. If the signs were opposite, the eye movement was recognized as horizontal. Otherwise, the eye movement was recognized as vertical. We then could use the sequence of the appearance of the peak and the valley in L-R channel to further determine whether the eyes moved toward left or right, and in U-D channel to determine whether the eyes moved upward, downward, or blinked. Numerically, the first derivative of the EOG signal f(t) was approximated by the first-order difference  $[f(t) - f(t - \Delta t)]/\Delta t$ , where  $\Delta t$  was the sampling period of the microcontroller ( $\Delta t = \approx 35$  ms for the current experiments). It can be seen from Figure 4b, the profiles of the EOG signals from U-D channel were similar for the upward movement of eyes, blink and double blink. If there was no need to trigger the focal length change of the lens, the blink was the only disturbance for the signal recognition of the eye movements. Since the amplitude of the valley of the EOG signals for blink was usually smaller than that for eye movement, we could eliminate the noisy signal from blink by carefully defining the threshold value of valley determination in the U-D channel. The flowchart of the recognition algorithm in this case is illustrated in Figure S6 in the Supporting Information.

To avoid the influence of the electromagnetic interference, in the experiments, we turned off the high voltage amplifier for 20 ms before and after the high voltage relays were switched on. Consequently, a time delay of around 40 ms was introduced into the system. As demonstrated in Movie S3 in the Supporting Information, the lens could respond to the eye movements almost instantaneously. The time delay of 40 ms could be further eliminated by using multiple high voltage amplifiers to control the DE films separately instead of using high voltage relays, which would, however, greatly increase the complexity and cost of the system. It is further noted that we required that the time interval between two adjacent actions of eyes was longer than 500 ms. Such that, an EOG signal from one action could reach the stable value before the arrival of the signal from the next action of eyes. The time interval for the current system was comparable to that of other EOG signal-controlled systems reported previously. <sup>[21,38,39]</sup>

In the system, we intended to further use double blink to actively tune the focal length of the soft lens, where a longer time delay was needed. To achieve that, we needed to extract more features of the EOG signals to distinguish the upward movement of eyes, blink and double blink. As can be seen from Figure 4b, double blink could generate a local peak in the EOG signal (from U-D channel). Such local peak was regarded as an indicator for double blink in our signal processing procedure. To further distinguish upward movement of the eyes and the blink, we compared the duration time ( $\Delta T$ ) when the amplitude of signal from the U-D channel was below the threshold value defined for determining valley. In most cases, we could find that such duration time was longer for upward movement of the eyes, namely,  $\Delta T_{\rm u} > \Delta T_{\rm b}$  as shown in Figure 4b. In practice, once the duration time for the signal from the U-D channel staying below the threshold value was longer than 500 ms, the corresponding eye movement was recognized as an upward

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**Figure 4.** Performance of the whole system. a) The lens could be switched between near vision mode and distance vision mode due to the focal length change that was triggered by double blink. Within each vision mode, the lens could move following the direction of the eye motion. b) Waveforms of the smoothed EOG signals of the concerned eye movements from the L-R channel and U-D channel.

motion; otherwise, the eye movement was recognized as a blink. Because of the recognizing mechanism described above, to make use of double blink for changing focal length, a time delay around 500 ms was introduced into the system. The delay between the eye movement and the response of the system was also introduced in the previous work on EOG controlled virtual keyboard or wheelchair.<sup>[21,40]</sup> The flowchart of the recognition algorithm is illustrated in Figure S7 in the Supporting Information.

The motion and the tuning of focal length of the lens controlled by EOG signal is demonstrated in Movie S4 in the Supporting Information. The lens first followed the motions of the eyes to four different directions. The double blink triggered the increase of the focal length of the lens for distance vision. The lens with changed focal length could also follow the motion of eyes. Finally, the focal length could be changed back to its initial value after another double link. It can be seen from Movie S4 in the Supporting Information, the time delay



between the motion of the eyes and the actuation of the lens was insignificant.

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Similar to most biological signals, real EOG signals can be different from expectations and errors in movement recognition are inevitable. These errors can lead to unexpected response of the system. The results of the error rate for the recognition of eve movements are listed in Table S1 in the Supporting Information. The accuracy of our algorithm was satisfactory and close to that of the previous studies on EOG signal-controlled systems.<sup>[21,38]</sup> In our demonstrations, the error occurred when a complete eye movement was incorrectly recognized or simply ignored. When the eve movement was ignored, the system did not respond. We could simply repeat the eye movement to trigger the desired motion of the lens. For the incorrect recognition, there were several possibilities: If the first peak or valley in the signal was not recognized for the movements of the eyeballs, the second peak or valley was instead regarded as the first peak or valley. As a result, the lens moved to the opposite direction of the eye movement and stayed there. If the first peak or valley was recognized but the second peak or valley was not, there was no trigger for the lens to move back to the primary position. In the both cases described above, to let the lens move back to the primary position, we could simply move the eyes to the same direction as the lens. Movie S5 in the Supporting Information demonstrates the recovery of the lens from unexpected response by eye movements for such cases. Eye movements may also be sometimes incorrectly recognized as double blink, leading to unexpected change of focal length of the lens. In this case, we could simply blink twice to change back the focal length of the lens.

Finally, it is noted that in the previous demonstrations, we only used horizontal and vertical movements of eyes to control the motions of the soft lens. In the current device, the waveforms of the EOG signals generated by diagonal eye movements were similar to those generated by either horizontal or vertical eye movements. Consequently, diagonal eye movements would still be recognized as either horizontal or vertical eye movements. Although we can further improve the algorithm<sup>[38,39]</sup> to also use diagonal eye movements to trigger diagonal motion of the lens, it may reduce the accuracy of eye movement recognition as reported previously.<sup>[38]</sup>

## 3. Conclusion

In this study, we have developed an interface between the human eyes and a soft tunable lens. The EOG signals generated by the eye movements were used to control the movements and the change of focal length of the soft lens. The planar movements or rotations of the lens could be achieved by the actuation of different DE films. The motions and deformation of the soft lens mimicked that of human eyes. Because of the use of soft materials, the relative change of focal length of the lens could be as large as 32% through deformation. Due to the fast response of DE, the movements of the eyes and the soft lens could be easily synchronized. The system developed in our study has the potential to be used in visual prostheses, adjustable glasses, and remotely operated robotics in the future. In addition, because of the biomimetic features of the system, it can also be used as physical model for visualizing physiological principles, which is important in biology and medicine. According to our knowledge, a soft tunable lens, whose position and focus length can be separately controlled by soft active material, has never been designed and constructed before.

Because the device shown in the current work is a proof-ofconcept design, its performance can be further improved from many aspects. First, in the current work, we used the commercially available monitoring electrodes attached to the skin, which were neither very flexible nor stretchable. It has been shown in previous studies, flexible and stretchable electrodes work much better for biosignal capture and processing.[41-43] Second, in the current device, we did not realize the control of continuous motion of the lens. To continuously tune the position or the focal length of the lens, we can probably use high voltage amplifiers, instead of high voltage relays, together with advanced biosignal processing algorithm to control the actuation of each individual DE films. Third, as shown in the demonstration, the correction of the unexpected motions of the lens was not automatic, and the interference of human was required. Better signal capturing and processing techniques may be needed to further reduce the possibility of unexpected motion of the lens and enable automatic correction. Forth, the spherical shape of the lens and the uniform refractive index of the fluid resulted in optical aberration, as shown in Figures 2 and 4a. The optical aberration in human eyes is minimized by using crystalline lens of inhomogeneous refractive index.<sup>[44]</sup> To reduce the optical aberration of the lens constructed in the current work, we can replace the salty water, encapsulated by two DE films, by hydrogels with predesigned distribution of refractive index. Lastly, in real applications, the bulky and rigid frame as shown in Figure 1 can be redesigned to increase its compatibility with other devices.

# 4. Experimental Section

Fabrication of the Lens: The entire fabrication process of the soft biomimetic lens is illustrated in Figure S1 in the Supporting Information. Two VHB 4910 films (3M Company) were first equi-biaxially prestretched with the stretch ratio of 2.5 and then adhered to two polymethyl methacrylate (PMMA) frames (3 mm thickness) named as Frame 1 and Frame 2, respectively. An annular stiff polyethylene terephthalate (PET) sheet (0.5 mm thickness) was adhered to the center of each prestretched VHB film to enhance the adhesion between the VHB film and the lens frame. The center part of the VHB film attached to Frame 1 was cut off. With the help of masks, carbon grease (846, MG Chemicals) with certain shapes was coated on both sides of VHB films as the electrode in both Frame 1 and Frame 2. The frame for the central lens was fabricated by gluing three PMMA annular frames (1 mm thickness) together with a cavity being introduced. A circular VHB 4905 film (3M Company) was adhered to bottom of the PMMA frame and an annular VHB 4905 film was adhered to the top of the PMMA frame. The lens was attached to the center of the VHB films of Frames 1 and 2. With the help of the spacers, the two frames were separated with certain distance, and a double-cone shaped structure was obtained as shown in Figure S1 in the Supporting Information. Salty water was then injected into the cavity of the lens through silicone tubing. The electrodes of all the VHB films were connected to high voltage power source through metallic wires.

EOG Signal Acquirement, Amplification, and Processing: Five commercial monitoring electrodes (2560 Red Dot Monitoring Electrodes, 3M Company) were used. The placement of the electrodes



around the eyes is shown in Figure 3a. Signed informed consent was obtained from the participant for participation in the study and for the use of identifiable images. The AD8232 module (Cjmcu-8232, Smakn) was used for the acquirement and amplification of the EOG signal and was connected to the monitoring electrodes through two cables (SHIELD-EKG-EMG-PRO cable, Olimex LTD), each with three snap connectors. One of the cables was used to record the signals from the R-L channel and the other cable was used to record the signals from U-D channel. The reference electrode was shared by the two channels. The EOG signal obtained directly from the monitoring electrodes has the magnitude in the range of 10–3500  $\mu$ V.<sup>[37]</sup> After the amplification by the AD8232 module, the magnitude of EOG signals was in the order of 1 V, which would be easier for processing in the microcontroller. After signal processing, the outputs from the microcontroller, i.e., Arduino board, were used to control the high voltage reed relays (DAT70510, Cynergy3 Components Ltd) to further determine the actuation of the DE films of the lens.

High Voltage Supply and Reed Relays: High voltage DC–DC converter (Q60-5, XP-EMCO) was used for high voltage amplification. Five high voltage reed relays were used to separately control the voltage applied to the DE films. To achieve that, one pin of the relay was connected to the high voltage output and another pin was electrically connected to one electrode coated on DE films or the salty water. A resistor (200 MΩ) was connected in parallel with the DE film for electric discharge when the relay was switched off in the experiments. The on and off of the relays was controlled by the output signals from the microcontroller after power amplification.

# **Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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# **Conflict of Interest**

The authors declare no conflict of interest.

# Keywords

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