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Biomimetic chromatophores for camouflage and soft active surfaces

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Abstract
Chromatophores are the pigment-containing cells in the skins of animals such as fish and cephalopods which have chromomorphic (colour-changing) and controllable goniochromic (iridescent-changing) properties. These animals control the optical properties of their skins for camouflage and, it is speculated, for communication. The ability to replicate these properties in soft artificial skin structures opens up new possibilities for active camouflage, thermal regulation and active photovoltaics. This paper presents the design and implementation of soft and compliant artificial chromatophores based on the cutaneous chromatophores in fish and cephalopods. We demonstrate artificial chromatophores that are actuated by electroactive polymer artificial muscles, mimicking the radially orientated muscles found in natural chromatophores. It is shown how bio-inspired chromomorphism may be achieved using both areal expansion of dielectric elastomer structures and by the hydrostatic translocation of pigmented fluid into an artificial dermal melanophore.

(Some figures may appear in colour only in the online journal)

1. Introduction

The controlled chromomorphism of the skin is a characteristic employed by several organisms for active camouflage and, as argued by Messenger (2001), for communication. Octopuses for example use the tight neuro-muscular interaction of brain impulses with chromomorphic skin cells to generate extremely sophisticated visual patterns that run along their bodies for the purposes of social interaction. Cephalopods such as the common cuttlefish, *Sepia officinalis*, shown in figure 1 also rely on the effectiveness of their chromomorphic appearance to disrupt or confuse the visual attention of natural predators (Allen *et al* 2009, Hanlon 2007, Cornwell *et al* 1997). There are many different types of biological chromatophores (Mäthger and Hanlon 2007). For example, cephalopod chromatophores contain pigment granules which are spread under local muscular action, while zebrafish chromatophores rely on pigmented fluid which is translocated, or 'pumped', from a sub-dermal reservoir to a display structure near the skin surface. All mechanisms however have evolved to maximize visual impact and hence maximize the potential for evasion, escape or for the attraction of a mate (Mäthger *et al* 2009).

In artificial systems the mimicry of such natural chromomorphism is expected to result in entirely new approaches to (1) camouflage, for example by matching an organism with a background (Tachi 2003); (2) thermal regulation, for example by the controlled exposure of thermal-emitting cells or cooling fluids and (3) active photovoltaics, for example where photo-sensitive elements are exposed when necessary to regions of high photon density. Photovoltaic skins (Chen *et al* 2012) may be enhanced by active chromomorphism and have the potential to significantly impact the exploitation of new solar energy harvesting technologies.

Other technologies exist which may be exploited for active camouflage and chromomorphism, including optoelectronics and mechanochromic materials (Graham-Rowe 2009). The disadvantages of these technologies are that they are often slow, show limited optical effects, or are not compliant. In contrast, the artificial muscle chromatophores presented here are soft, show significant optical effects and can act as scaffolds for other optical, thermal and otherwise reactive materials.

To realize a true artificial chromatophore requires, in the simplest embodiment, the integration of two elements; a soft and compliant structure that is sensitive

Figure 1. The common cuttlefish, *Sepia officinalis*, is able to actively camouflage against the seabed.

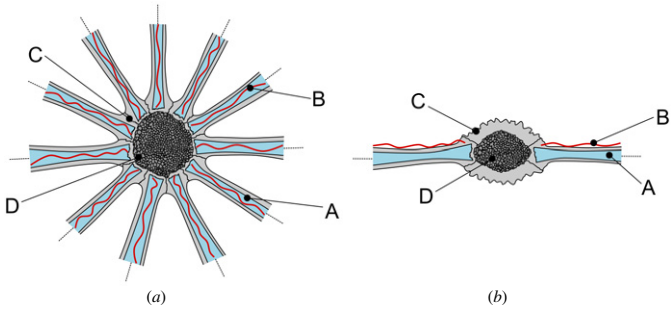


Figure 2. Diagram of horizontal (*a*), and vertical (*b*), sections through a retracted chromatophore organ of the squid, *Loligo opalescens*. Expansion of the chromatophore occurs as follows: motor signals innervate radial muscle fibres (A) to retract via nerve terminals (B), which unfolds the cell membrane (C) and biaxially stretches out the elastic sacculus D, which contains pigment granules.

to strain whereby strain results in some optical effect, and a mechanism for the induction of strain energy into the compliant structure. There are few technologies that can deliver against these requirements, with the most suitable being electroactive polymers (Bar-Cohen *et al* 2007). These materials are inherently soft and compliant, generate the required mechanical strain in response to electrical stimuli and are readily integrated into artificial skin materials. In this paper, we focus on the dielectric elastomer (DE) actuator, a type of planar-actuating electroactive polymer, because of its simple structure, ready fabrication and large strain generation (Pelrine *et al* 2000).

2. Biological chromatophores

2.1. Cephalopod chromatophores

In cephalopods the chromatophore cells consist of a central cytoelastic sacculus which contains pigment granules. This sacculus is surrounded by a series of radial muscles (figure 2) (Cloney and Florey 1968). Typical size of the central sacculus in squids is around 160 μm in diameter when contracted and over 360 μm when expanded. When the chromatophore is activated, nerve signals from the animal's brain travel through nerve fibres to the muscles, which in turn contract. Contraction of the radial muscles results in planar expansion of the central sacculus. It is the expansion of the network of pigmented sacculi, relative to the unpigmented surrounding tissue, which generates the optical effect, as illustrated in figure 3.

The relative areal expansion of a pigmented region can be seen most clearly in figure 4 (adapted from Suzuki *et al* (2011)), which shows the skin of a squid in the two states of minimal (figure 4(*a*)) and maximal (figure 4(*b*)) chromatophore activation. The black chromatophore sacculi in the unactivated cells in figure 4(*a*) represent 10.9% of the surface area. This increases to 48.5% under activation. Taking the ten largest distinct chromatophores from the smaller region marked with a dashed line in figure 4, we measure the average relative area expansion of 420%. These impressive figures confirm how compliant the chromatophores and the surrounding skin structures are.

The frequency of activation of cephalopod chromatophores has been measured above 4 Hz (Suzuki *et al* 2011). This relatively high frequency comes about through the tight interaction of neuro-signals and a relatively large number of rapidly-acting muscle cells. Additionally, the relatively simple actuation mechanism of a radially expanding sacculus with minimal fluidic effects contributes to this high speed of activation.

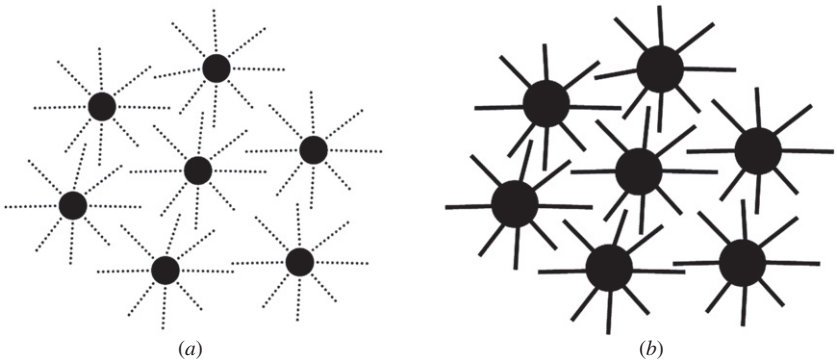
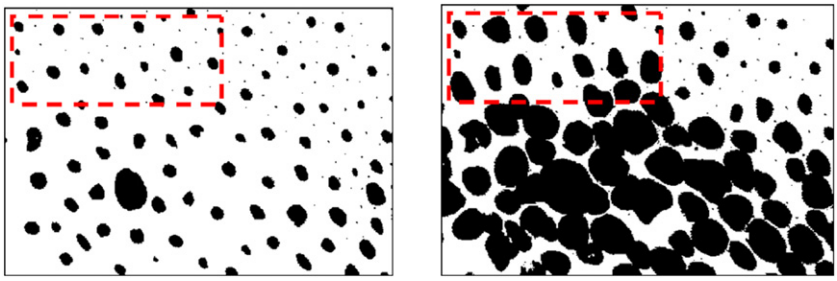


Figure 3. Network configuration of squid chromatophores showing contracted (*a*) and expanded (*b*) states. Dotted lines represent relaxed muscles, and solid lines represent actuated muscles. Note that muscles are shown visible here for illustration but are transparent in the biological organism.



(*a*) (*b*)

Figure 4. Squid chromatophores in states of rest (*a*) and expansion (*b*). Dashed rectangles show the region from which ten distinct chromatophores were analysed. Images adapted from Suzuki *et al* (2011).

(*a*) (*b*)

Figure 5. Inactive (*a*) and active (*b*) states of a zebrafish melanophore. Image adapted with permission from Logan *et al* (2006). (Inactive state approx. 0.5 μm in diameter.)

Other optically effective skin cells in cephalopods include leucophores, cells which reflect ambient light, and iridiphores, cells which iridesce and reflect light (Shashar and Hanlon 1997, Sutherland *et al* 2008). In their most complex embodiment these different cells are formed into a dermal chromatophore unit (DCU) which can display a wide variety of optical effects (Bagnara *et al* 1968). In this paper we focus on monochromatic chromatophores, although the actuation principles later presented are suitable for other opto-morphic cells such as iridiphores and leucophores.

2.2. Zebrafish chromatophores

In contrast to the radially expanding chromatophores in cephalopods, the teleost fish such as the zebrafish employ a different mechanism for chromomorphic effects. The melanophore (black colour changing) cells in the skin of zebrafish contain a small reservoir of black-pigmented fluid (Logan *et al* 2006). Upon activation intracellular muscular contractions cause the pigmented fluid to translocate towards the skin surface and to spread out. This results in an increase in the size of the dark spot and a significant optical effect. Figure 5 shows two states of a zebrafish melanophore (adapted from Logan *et al* (2006)). The initial size of the inactive pigmented spot is approximately 0.5 μm. Upon activation the pigmented region increases to a spot 1640% larger in area. Although zebrafish melanophores are much smaller than chromatophores in cephalopods, the relative areal expansion is much larger. Clearly there are benefits in investigating and mimicking both of these mechanisms when developing artificial chromatophores.

In contrast to the fast neuro-driven chromatophores in cephalopods, the melanophores in zebrafish are predominantly driven by hormonal changes. This means that not only are the patterns generally less precise than for cephalopods but also the speed of activation is slower, taking up to a minute to activate to 50% full size. Fluidic effects in translocating melanophores may also contribute to the slower speed of activation.

3. Electro-active polymers as muscles for artificial chromatophores

3.1. Principle of operation

Mimicking the considerable planar expansion and fast response time exhibited by cephalopod chromatophores in a compliant membrane form poses a significant challenge. Conventional electro-mechanical actuation technologies such as electric motors or solenoids are unsuitable due to their rigid components. Similarly, a conventional hydraulic system would depend on numerous localized active valves (with associated actuators) and a bulky, centralized compression device. Pertinent alternatives to these actuation technologies are shape-changing materials, such as piezoelectric ceramics, shape memory alloys and the emerging class of electro-active polymers. In particular, dielectric elastomers (DEs), a type of electro-active polymer, have demonstrated actuation strains comparable to biological muscle with fast response times (Pelrine *et al* 2000) and hence are considered here for the development of biomimetic chromatophores. Additionally, DEs have been shown to work effectively in hydrostatic applications (Carpi and Smela 2009), indicating their suitability for fluid translocating applications such as artificial melanophores.

DEs are essentially elastic parallel-plate capacitors, which consist of one or more elastomeric dielectric film coated with compliant electrodes (figure 6). DEs exhibit planar expansion and transverse compression when a large transverse voltage field ($\sim$100 MV m^{-1}) is applied. An important aspect of this shape changing mechanism is that P, the induced Maxwell stress acting on the dielectric, is dependent on the transverse

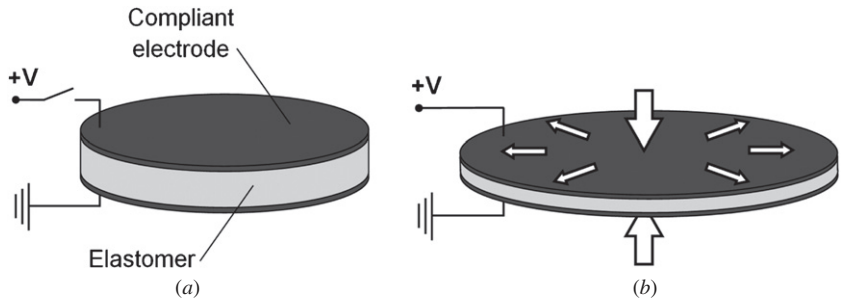


Figure 6. Principle of operation of a DE membrane actuator. Application of a voltage field (*b*) induces transverse compression and planar expansion.

voltage field, E, squared as shown by the following equation (Pelrine *et al* 2000):

$$P = \varepsilon_0 \varepsilon_r E^2, \quad (1)$$

where ε_0 is the permittivity of free space (approx. 8.85×10^{-12} F m^{-1}) and ε_r is the relative permittivity of the dielectric (typically around 4). Therefore, in order to maximize performance from a given input voltage, it is necessary to minimize the DE film thickness. Pre-stretching DE membranes is a widely adopted method for minimizing the film thickness, with the additional benefits of increasing the strain energy density and the dielectric breakdown field strength, E_{max}, of the elastomer (Kofod *et al* 2003). Another important consideration is the selection of the DE material, which should have relatively low stiffness and maximized values of ε_r and E_{max}.

The actuation output of DE actuators can be exploited in a variety of configurations such as stacks, spring rolls, bowties, diaphragms and cones (Bar-Cohen 2004, Carpi and Smela 2009). Unlike almost all previous studies of DEs, here we are concerned with visual effect, rather than the applied force or energy transferred to a load. Therefore, only radial or areal expansion of the artificial chromatophores needs to be considered, along with the associated changes in opacity or other optical effects.

In this study, two principal DE configurations are considered: (i) planar membrane DEs for direct radial expansion or contraction, thus mimicking cephalopod chromatophores, and (ii) diaphragm DEs for fluid translocation thus mimicking the physiological colour change in zebrafish melanophores. Both configurations exhibit the high degree of compliance and flexibility that are required for integration into a functional artificial skin.

3.2. Materials and methods

Here we present a series of planar actuators that exhibit optical effects similar to those in cephalopod chromatophores. In all instances a 500 μm thick 3 M 4905 polyacrylate film is used as the dielectric membrane and several different electrode materials are used including carbon grease and saline solution. To ensure effective actuation all membranes were biaxially prestrained either by hand (for non-uniform prestrain) or by using the uniform radially expanding mechanisms outlined in Conn and Rossiter (2011). All actuators were driven from either a dedicated high-voltage actuator test unit developed by the Bioengineering Institute, Auckland University or by an EMCO high voltage power supply connected to a Hioki potentiostat, itself driven by a National Instruments PCI-6229 data acquisition device. Optical effects were monitored using the high-resolution capture modes of a Canon G9 camera.

4. Planar membranes mimicking cephalopod chromatophores

4.1. Single-spot positive chromatophore

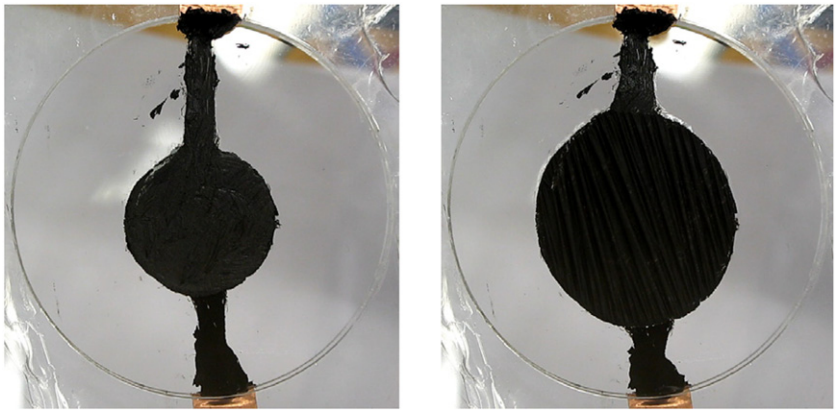
A single spot DE actuator was fabricated by hand-patterning circular electrodes of 19 mm diameter on the top and bottom of a DE membrane, biaxially prestrained and fixed over an orifice of 60 mm diameter as shown in figure 7. This circular electrode spot mimics a pigmented chromatophore sacculus. The electrodes were connected via copper connectors to the high voltage supply. Figure 7 shows the two states (on/off) of the single spot actuator. We term this a 'positive' chromatophore because actuation results in an increase of the area of the central sacculus, very much like the biological chromatophore. This is in contrast with the negative chromatophore described later where the sacculus contracts.

Figure 8 shows the change in the area of the central pigmented sacculus in response to increasing voltage for three different prestrain configurations. Here we see that increasing prestrain results in greater actuation, and hence greater chromatic modulation, in agreement with well-known properties of these acrylate membranes (Kofod 2001). Maximal area expansion is approximately 235%, somewhat less than the 420% of the cephalopod chromatophore.

Note how the non-uniform prestrain in figure 7(*b*) (350% vertically 100% horizontally) leads to the development of vertically aligned buckling at high actuation voltages and the leveling off of the voltage response is shown in figure 8.

4.2. Multi-spot positive chromatophores

In nature, chromatophores are typically found in groups which form an interconnected muscular structure. To demonstrate this in an artificial chromatophore network we fabricated a series of multi-spot positive chromatophores, an example of which is shown in figure 9. Here carbon grease was used for both the upper and lower electrodes. Figure 9 shows the two states (on/off) of the membrane. For a greater number



(*a*) (*b*)

Figure 7. Single artificial chromatophore in 'off' (*a*) and 'on' states (*b*).

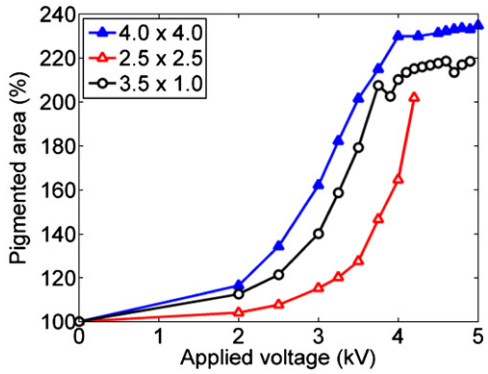
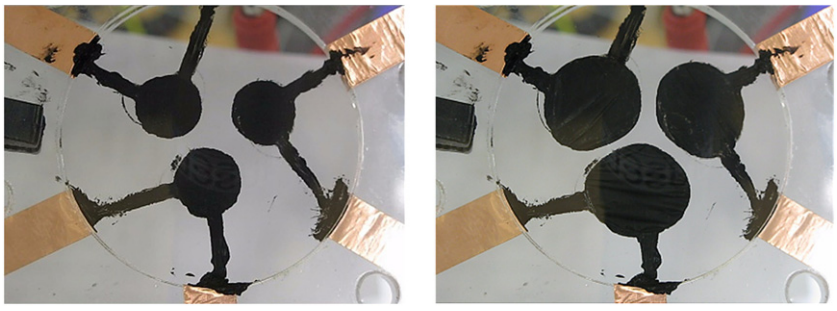


Figure 8. Areal expansion for three different biaxial pre-stretch ratios. The vertical axis shows the pigmented area as a percentage of the initial pigmented area.

of chromatophores extending across a larger area we would repeat the triangular pattern shown here. When considering this multi-spot structure we need to only measure changes in optical properties within the area encompassed by the triangle whose vertices lie at the centres of the three spots, as shown in figure 10(*a*). The optical effect of varying spot separation was investigated, where the size of the spots was kept constant at 10 mm diameter and the spot separation varied. Figure 10(*b*) shows the change in active region density against voltage, where the active region density is the area of black electrode region within the triangle with respect to the total area of the triangle. For all three spot separations (15, 17, 20 mm), the active (black) area increases by more than 25% of the total area, resulting in a significant optical effect.

4.3. Single-spot negative chromatophore

In the previous cases the mimicry of the muscular action of cephalopod chromatophores was achieved through the direct activation, and hence expansion, of the central sacculus. This actuation mechanism relies on the ability of the prestrained passive material surrounding the sacculus to take up the induced strain. This also means that, of the whole surface, only a smaller proportion can be used for actuation since we would desire the central spot to be as small as possible when inactive. It may be more effective, on the other hand, to invert this structure so that the central spot is passive and the surrounding area is made active. This is readily achieved in a DE actuator by applying electrodes to only the area surrounding a central clear spot, as shown in figure 11. The artificial chromatophore in figure 11 has a passive central region with an inactive diameter of 19 mm and an electrode annulus with an outer diameter of 60 mm. Here we see the two states (on/off) of the 'negative' artificial chromatophore. Figure 12 shows the areal contraction of the centre clear spot down to 35% of its initial size. This is equivalent to an areal expansion of the actuated spot (figure 11(*b*)) into its unactuated state (figure 11(*a*)) of 286%. This negative chromatophore shows a greater



(*a*) (*b*)

Figure 9. Example of triple disc artificial chromatophore network showing 'off' (*a*) and 'on' (*b*) states.

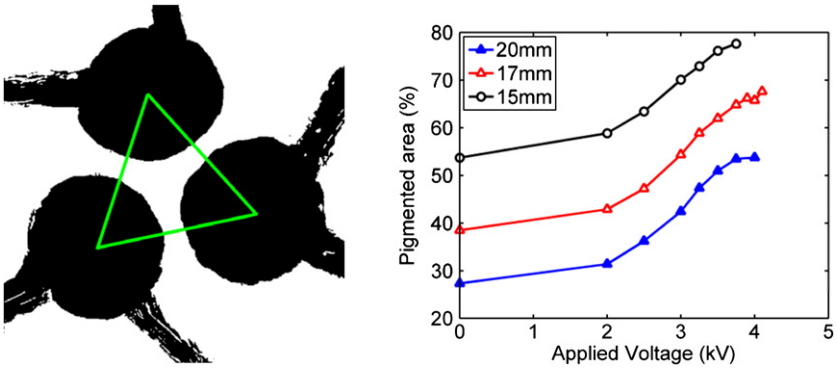


Figure 10. Expansion results for the artificial chromatophore network. (*a*) The triangular area under consideration and (*b*) percentage of triangular area covered by the black pigment, for the inter-spot separations of 15, 17 and 20 mm.

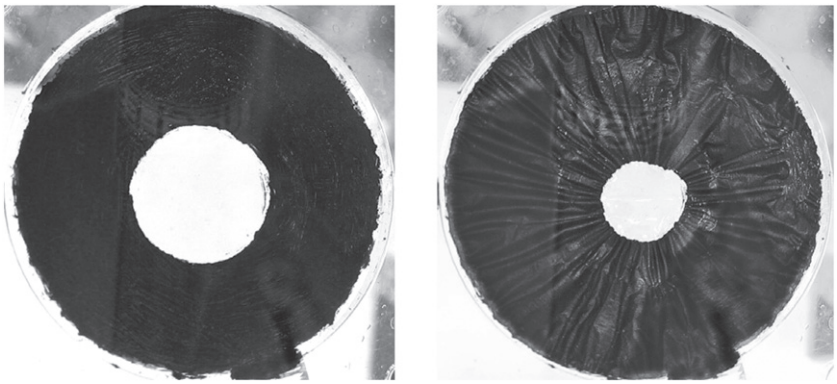


Figure 11. Contracting spot 'negative' artificial chromatophore showing 'off' (*a*) and 'on' (*b*) states. Note radial wrinkling in the electrode region in (*b*).

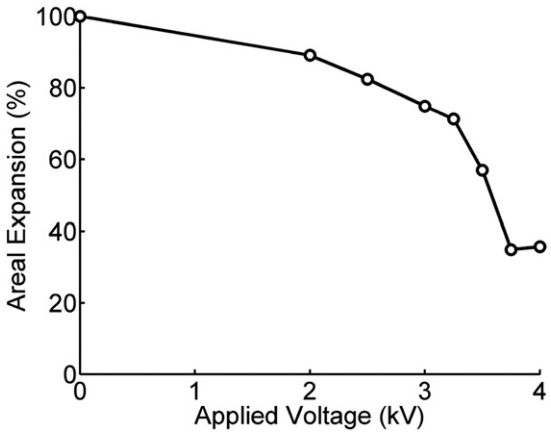


Figure 12. Areal contraction of the central clear spot in the contractile actuator, showing size of the central sacculus region as percentage of unactivated size.

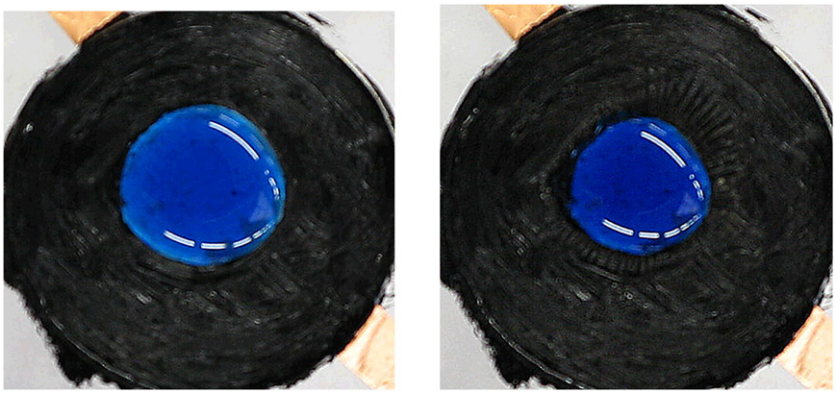
conformational change than the 235% change measured for the positive chromatophore previously demonstrated.

Note that in figure 11(*b*) the actuated black region shows significant radial buckling. This buckling behavior provides an additional optical effect which could greatly increase the application of these artificial chromatophores. For example, if the surface of the electrode regions are coated with iridescent paint the reflectivity of the surface will change as it buckles. This would give rise to a combined artificial chromatophore/iridophore. The buckling is also illustrated by the leveling off of the response, as shown in figure 12, above 3.75 kV.

It is also possible to replace the opaque carbon grease in this example with a transparent electrode (as demonstrated in later sections) and to colour the central sacculus region. This would more closely resemble a natural chromatophore, while retaining the characteristic of contraction upon actuation.

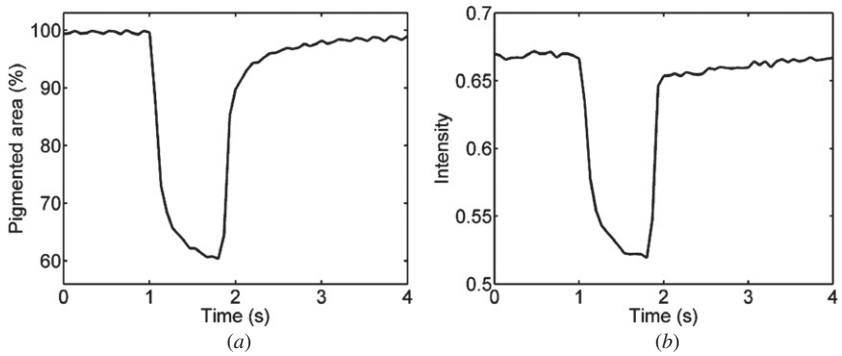
4.4. Pigment-based variable opacity in artificial chromatophores

The tests above show the potential of dielectric elastomer actuators to generate sufficient strain to significantly expand or contract a clear or opaque central sacculus. In these cases optical effects rely only on size change and not on any optical changes in materials themselves. In contrast, if we contract or stretch a pigment-containing fluid or gel which is not completely clear or opaque (i.e. it is semi-opaque) we can achieve a change in the optical reflectivity or transmissivity of the pigmented region. For example if we contract a pigmented gel it will increase in thickness and colour density, yielding a darker colouration (likewise stretching will result in a lighter colour).



(*a*) (*b*)

Figure 13. Contractile membrane actuator with the coloured gel central spot showing 'off' (*a*) and 'on' (*b*) states and the decrease in colour intensity with contraction.



(*a*) (*b*)

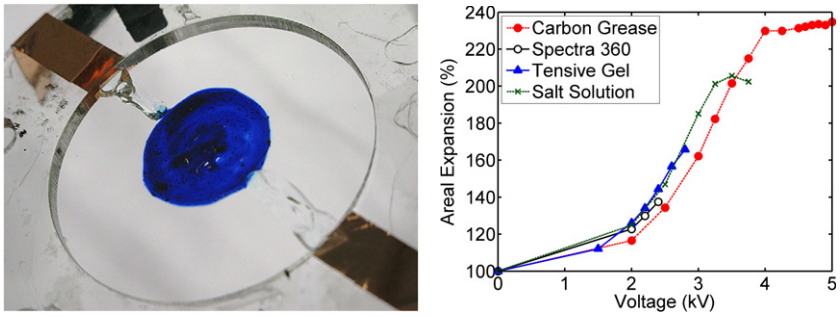
Figure 14. Mean pigmented area (*a*) and mean intensity (*b*) of the central blue sacculus region showing highly correlated response. Intensity of 0 is pure black and 1 is pure bright blue.

To illustrate this effect a disk actuator similar to figure 11(*a*) was fabricated and a layer of soft gelatin gel, approximately 3 mm thick, was deposited on the central non-electroded region. During preparation the gelatin was mixed with a small amount of methylene blue to give it a mid-blue colour. Figure 13(*a*) shows the fabricated actuator with blue gelatin circle at rest and figure 13(*b*) shows the darker colouration (reduction in light intensity) of the contracted circle when 3.5 kV is applied to the actuator. Figure 14(*a*) shows the area change with time as the actuator is subjected to a square pulse of length 1 s. Figure 14(*b*) shows the mean intensity of the central spot only, where light travels through the sacculus from the illuminated white background. Note that changes in mean intensity closely match changes in the area of the central spot, showing how colour intensity is inversely proportional to spot thickness.

4.5. Transparent electrodes

The structures previously explored have been fabricated with black carbon grease, a widely used and effective compliant electrode material. However, in some soft artificial chromatophores it may be desirable for the electrodes to be transparent, and indeed biological muscle fibres are transparent in aquatic chromatophores. Four different transparent and compliant electrode materials were tested in the expanding spot configuration shown in figure 7. Three transparent electrode materials were compared: Spectra 360 gel (Parker Laboratories), Tensive gel (Parker Laboratories) and salt solution, along with opaque carbon grease (MG Chemicals). Both Spectra 360 and Tensive gels are intended for medical applications.

Figure 15(*a*) shows an example of a positive single spot actuator with transparent gel electrodes and a blue-coloured soft gel sacculus. The transparent electrodes extend from the sacculus to the copper connectors and are just visible in figure 15(*a*). Figure 15(*b*) shows the areal expansion of the central pigmented region with the increasing voltage. For each electrode material the voltage applied to the corresponding actuator was increased until dielectric breakdown occurred. Breakdown electric field strengths were 110, 150, 240 and 375 V μm^{-1} for Spectra 360, Tensive gel, salt solution and carbon grease, respectively. Figure 15(*b*) shows that the performance of the carbon grease actuator (in areal expansion per volt) was lowest amongst all electrode materials, but the breakdown voltage was much higher, more than twice that of Spectra 360. It can be speculated that the low breakdown voltage of the conducting gels and salt solution may be due to solvents or salts in the electrode materials infusing into the VHB elastomer membrane. Alternatively these effects may be due to non-uniform field distributions resulting in localized high voltages, arising themselves from reactive components in the materials or from decomposition under strong electric fields. It should be reiterated that the compositions of the



(*a*) (*b*)

Figure 15. Expanding gel actuator using transparent electrodes (*a*). Area expansion of the central blue sacculus for different electrodes (*b*).

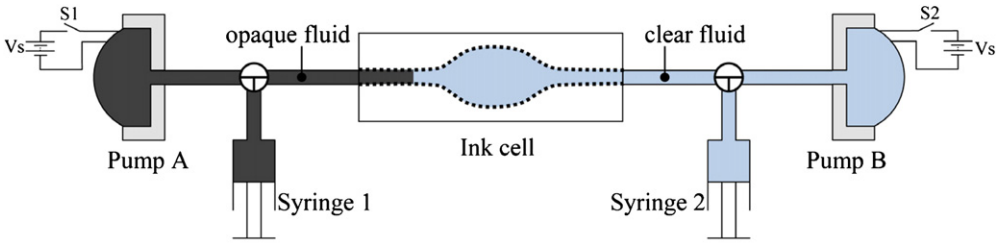
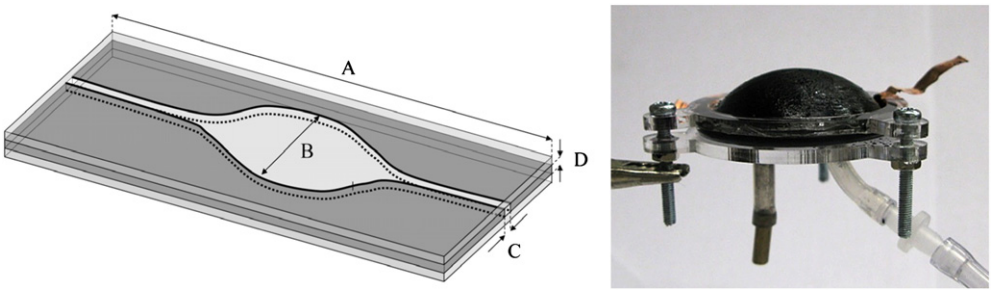


Figure 16. Experimental setup for the artificial melanophore, showing two pumps driving fluid through the ink cell.



(*a*) (*b*)

Figure 17. (*a*) Structure of the ink cell (approx. dimensions: $A = 75$ mm, $B = 13$ mm, $C = 1.6$ mm, $D = 0.2$ mm). (*b*) Diaphragm pump in a pre-tensioned (pressurized) state (membrane diameter = 40 mm).

conducting gels are tailored to low-voltage and/or low-current medical applications. A trade-off therefore exists between the use of transparent electrode materials to fabricate transparent chromatophores which have low actuation strain and the use of opaque electrode materials that generate high strains. Single-walled and multi-walled carbon nanotubes, graphene and ion-implantation have been demonstrated to function as transparent electrodes (Rosset *et al* (2009), Yuan *et al* (2008), Kujawski *et al* (2010)). These may provide the best route to achieving robust transparent electrodes with minimal reduction in breakdown strength, but at the cost of manufacturing complexity or environmental impact and toxicity (for the case of nanotubes.)

5. Fluid translocation mimicking zebrafish melanophores

In the previous sections it was shown that electroactive polymer artificial muscles can mimic the muscular actuation of natural cephalopod chromatophores and generate changes in optical reflectivity and opacity using solid and gel structures. In contrast, other species, such as the zebrafish, achieve chromatic modulation through the local translocation of fluids, such as inks. The ability to pump fluids means that extremely large colour or intensity changes can be achieved relatively rapidly and at a low mechanical cost. To demonstrate the effectiveness of such an approach, and to compare with the artificial cephalopod chromatophores above, an artificial ink-cell melanophore was designed and fabricated using electroactive polymers. The advantage of this method is that the fluid pumping elements can be physically separate from the display cell, the two only being linked hydrostatically, and that the shape of the fluidic ink cell can be customized independent of the pumping elements. Additionally, fluids with a wide variety of functionalies can be used, including those with electrical or thermal conductivity, photo-sensitivity and photo-emissivity.

Figure 16 shows the setup of the artificial ink-cell melanophore. It consists of two DE pumping elements (A and B) which move fluid from one side of an ink cell to the other. The ink cell is shown in figure 17(*a*) and is fabricated

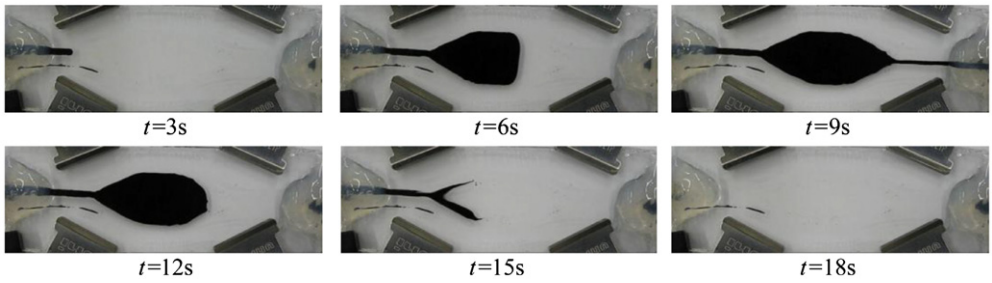


Figure 18. Ink cell chromatophore activated from transparent (t <3 s) to opaque (t = 9 s) to transparent (t > 16 s).

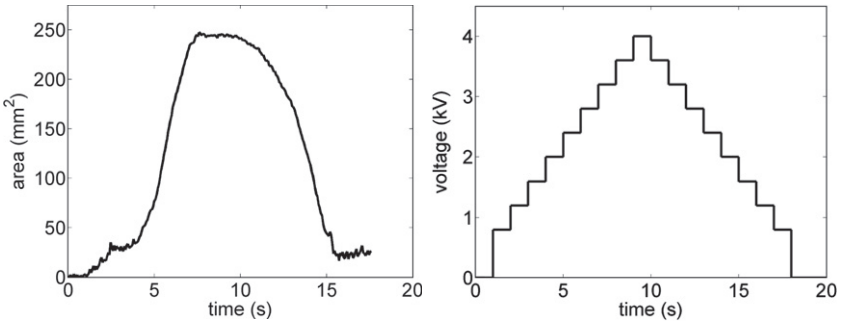


Figure 19. Dynamic response of the ink cell chromatophore in terms of the opaque area (*a*) and DEA pump driving voltage (*b*).

from two glass microscope slides which sandwich a silicone layer into which a chamber is moulded. The chamber is 75 mm long, 13 mm at its widest point and is 200 μm thick, giving a total volume of 0.048 ml. The working fluid consists of approximately equal volumes of two immiscible liquids of approximately equal viscosity. In these tests, a clear organic solvent (white spirit) and an opaque water-based ink (black inkjet ink mixed with water in a ratio 1:10) were used. Since the two liquids are immiscible the phase interface between the two liquids also corresponds to a discrete change in opacity. By hydraulic pumping of the fluid the opacity of the ink cell can be reversibly switched from completely transparent to completely opaque. Because the organic solvent preferentially adheres to the inner surfaces of the silicone tubes and the ink cell, a solvent boundary layer is maintained. As a result, ink can be pumped into and out of the ink cell without it adhering to the cell wall and leaving traces of opaque material behind. The two syringes in figure 16 are used to introduce a hydraulic pre-load on the DEA membranes in the two pumps, causing them to bulge out and to act as local stores of elastic energy, as shown in figure 17(*b*). At rest the pressures from both pumping membranes balance and the fluid is stationary. When one of the pumps is actuated its membrane relaxes and the membrane in the other pump contracts in order to balance the pressures. This causes a movement of the fluid towards the actuated pump, a movement of the liquid–liquid interface through the ink cell and a resulting sharp change in opacity.

The dielectric membranes in the pumps were formed from VHB4095 and were biaxially prestrained 200%. Carbon grease electrodes were applied to both sides of the membranes. The ink cell was monitored during experiments using a video camera and the recordings were analysed to determine the area of the opaque region. The pump B was actuated with a triangular step function as shown in figure 19(*b*) with the maximum voltage of 4 kV. In these experiments, it was found that, after actuation, relaxation of the membrane in pump B was sufficient to drive fluid back through the ink cell and actuation of antagonistic pump A was not required at these relatively low fluid velocities. Figure 18 shows six frames, at 3 s intervals, showing the clear cell at the start, the stages of influx and reflux, and the clear cell at the end. Note that at t = 9 s the cell is completely filled with black ink, corresponding to a 100% change in opacity. The area covered by the ink in each frame was calculated and is shown in figure 19(*a*), with a maximum pigmented area of approximately 247 mm^2.

Although the rigid glass cell of this demonstrator is different from the elastic chamber of the biological chromatophore, it does show how the simple fluidic chromatophores can be extremely effective. It is also easy to see how the ink chamber and pumps can be fabricated from the same flexible material, such as transparent silicone PDMS, resulting in a compact and integrated artificial chromatophore. By using a prestrained passive membrane in place of one of the pumps, the chromatophore can be further simplified whilst preserving the full opacity range, although this will be at the expense of a lower maximum actuation frequency.

6. Conclusion

In this paper we have demonstrated how soft compliant artificial muscle structures can be used to mimic the underlying actuation mechanisms of chromatophores. A series of artificial chromatophores were fabricated which all show significant optical modulation in response to electrical stimuli. The contrasting mechanisms of sacculus expansion employed by cephalopod chromatophores and fluid pumping

as seen in zebrafish melanophores are shown. The artificial expanding (positive) and contracting (negative) cephalopod chromatophores show area changes in the region of 200%–300% and are limited by the interaction of active material and surrounding passive materials. The fluid-based artificial melanophore, on the other hand, is not limited in this way and can generate extreme opacity changes at the expense of slower operation and added complexity.

The artificial chromatophores presented here have the potential to be applied to a wide range of applications including active camouflage, controllable heatsinks and active photovoltaics in compliant skins. Future work will investigate the use of natural and artificial chromatophores in order to generate camouflage patterns and their miniaturization and efficient fabrication.

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