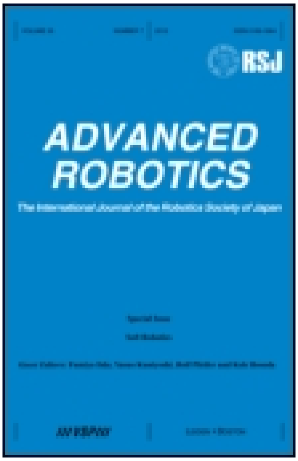

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Active Connection Mechanism for Soft Modular Robots

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Full paper

Active Connection Mechanism for Soft Modular Robots

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Abstract

To date, most modular robotic systems lack flexibility when increasing the number of modules due to their hard building blocks and rigid connection mechanisms. In order to improve adaptation to environmental changes, softness at the module level might be beneficial. However, coping with softness requires a fundamental rethinking of the way modules are built. A major challenge is to develop a connection mechanism that does not limit the softness of the modules, does not require precise alignment and allows for easy detachment. In this paper, we propose a soft active connection mechanism based on electroadhesion. The mechanism uses electrostatic forces to connect modules. The method is easy to implement and can be integrated in a wide range of soft module types. Based on our experimental results, we conclude that the mechanism is suitable as a connection principle for lightweight modules when efficiency over a wide range of softness, tolerance to alignment and easy detachment are desired. The main contributions of this paper are (i) the qualitative comparison of different connector principles for soft modular robots, (ii) the integration of electroadhesion, featuring a novel electrode pattern design, into soft modules and (iii) the demonstration and characterization of the performance of functional soft module mockups including the connection mechanism.

Keywords

Soft robotics, modular robotics, connectivity, electroadhesion

1. Introduction

Modular robots can change morphology to adapt to changing tasks and environments by rearranging the connectivity of their own modules. These systems are expected to attain complex functionalities such as self-assembly, self-repair or self-replication. In contrast to fixed-morphology robots, modular robots have the potential to be functionally more flexible, robust and cheap [1–3]. However, many engineering and scientific challenges prevent the full realization of these potentials.

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Over the last two decades, several sophisticated module designs have been proposed and most of them featured hard mechanical building blocks with a highly rigid connection mechanism [4]. Although this design guarantees controllability and stability, it minimizes mechanical flexibility [4–6]. This lack of flexibility prevents such systems from achieving efficiency and robustness in the case of environmental changes [7] (e.g., when going through a confined space).

One solution to overcome the issue of rigidity in large-numbered modular systems is to use modules that could become mechanically soft when desired. However, when in a soft state, such systems would require a reversible inter-module connector that does not impair the softness of the modules (i.e., the mechanism should become part of the soft membrane of the modules). Ideally, the mechanism could be integrated without changing rigidity and thickness of the membrane. Also, the performance of the connection mechanism should not be critically affected by the intrinsic properties of the module, which might vary due to environmental or functional changes. For instance, the robot modules could need to change their shape to fit into a small cavity and keep their interconnections active. Thus, the mechanism should be robust against changes of the module softness and shape. In addition, to avoid complex shape control of the soft modules for precise alignment of the connection areas for attachment, the mechanism should withstand misalignment of the connection areas.

To date, no soft active connection mechanism exists to the best of our knowledge. In the case of hard modules, four different connection principles have been applied: magnetic, mechanical, vacuum and electrostatic adhesion. All these principles could potentially be used in modular robots of different characteristics, but most of them present serious limitations to be part of a soft connector.

Magnets enable easy attachment and strong connections. However, they have several drawbacks: all sorts of magnets would be difficult to integrate into a soft membrane without adding high rigidity. Furthermore, permanent magnets would need an actuation mechanism for detachment that would add extra weight and power consumption to the module; meanwhile, electromagnets consume high amounts of power for continuous operation [8–10].

Active mechanical latching approaches [11–15] typically guarantee high connection strengths, but are not suitable for a soft connector because they require hard materials for setting up the connection as well as high alignment precision for attachment. Passive mechanical latching (e.g., Velcro) strategies could solve this problem. However, it would still need a detachment mechanism, which would add complexity to the system.

Connections based on a vacuum [16] enable strong connections and controlled detachment. However, they typically depend on precise alignment of the connection areas for attachment and require an integrated pump actuation system.

Karagozler *et al.* [17] proposed a connection mechanism based on electrostatic adhesion. The mechanism enables reliable connection strengths, power and communication transfer. However, its structure is not suitable for soft modules.

In this paper, we explore electroadhesion as a connection principle for soft modular robots. We address how electroadhesive pads can be integrated into completely soft modules, and we characterize and demonstrate the usability of the connection principle when integrated in such a system. We start by describing the operating principle of electroadhesive pads and the principles that we apply for the conceptual design of the electrodes. Then, we give details about the experimental methods (i.e., the implementation of the mechanism on a validation platform composed of soft spherical modules and the experimental setup for measurements of the connection strength). We perform three experiments in order to assess how the size of the pad, the module softness and the tolerance to alignment errors affect the connection strength. Finally, we demonstrate detachment of two modules by remote control.

2. Design

2.1. Working Principle

Electroadhesion makes use of electrostatic forces that are created between electroadhesive pads and a (dielectric or conductive) substrate material (Fig. 1). The pads consist of a dielectric polymer bearing conductive electrodes on its surface. Electrostatic adhesion is created due to alternate charges on the electrodes that set up opposite charges on the substrate. The dielectric material of the pads and air gaps between pads and substrate prevent dielectric breakdown [18].

The general relation describing the principle can be obtained from the formula that yields the electrostatic force between the two parallel plates of a capacitor:

$$F = \frac{A\varepsilon_0 V^2}{2(2d/\varepsilon_r)}, \quad (1)$$

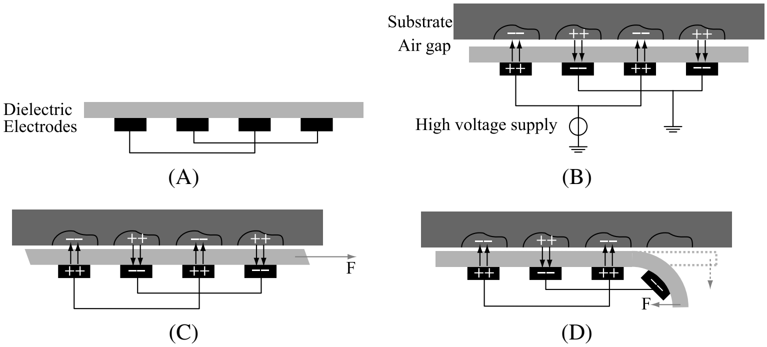


Figure 1. Working principle of electroadhesion. (A) Basic structure of an electroadhesive pad with dielectric in light grey and electrodes in black. (B) Two independent electrodes are connected to a high voltage supply and set up opposite charges on the substrate. (C) The holding force in the shear direction results from the integration of the electrostatic force between all the electrodes and the substrate. (D) Sections of the electrodes can be separated with just a small normal force component (peeling effect).

where A is the surface area of the electrodes, V is the applied voltage, d is the thickness of the dielectric, and ε_0 and ε_r are the relative permittivity of vacuum and the dielectric, respectively. Hence, higher forces can be obtained by increasing the surface area of the electrodes, the operating voltage or reducing the thickness of the dielectric [19].

In order to produce high electrostatic forces, the electroadhesive pads are typically connected to a high voltage supply (1–5 kV). Although high voltage is needed to induce charges on the electrodes, the currents are very small (below 1 μA) and consequently the required power is very low. Thus, small and lightweight voltage converters can be used [20]. In addition, high mechanical compliance of the electrodes is crucial to obtain and maintain close contact with the substrate, because the force decreases with the square of the distance (Coulomb's law) [18].

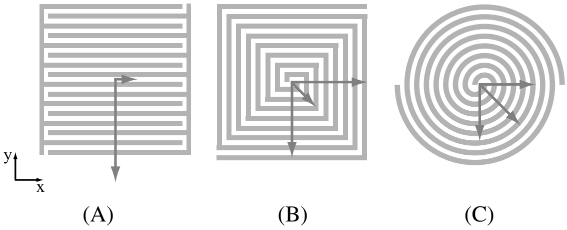
To detach an electroadhesive connection, when voltage is still applied, a high shear force or a significantly lower normal force is required (Fig. 1). Thus, electroadhesive pads suffer from the peeling effect, which means that portions of the electrodes can be separated with little force [17]. By turning off the operating voltage, the electrostatic forces typically drop. However, when using a DC voltage source a residual force remains. This effect can be compensated for by using an AC voltage source, operated at low frequency [19].

When designing electroadhesive pads, the most important parameters affecting the performance are the (i) operating voltage, (ii) properties of the pad (dielectric) and (iii) properties of the electrodes [18]. For further details concerning the design of the pads (e.g., material choices or dimensioning) the interested reader is referred to Refs [18, 21].

2.2. Pad Design

In this subsection, we describe the conceptual design of the geometry of the electrodes for the integration into soft modules. In addition to the two electrode designs (A) and (B), which have been presented and analyzed before [19], we propose a novel solution (C) consisting of a round spiral pattern design (Fig. 2).

Design (A) consists of two interlaced electrodes. The main advantage is given by its very high shear attractive force in the direction perpendicular of the electrodes.



(A) (B) (C)

Figure 2. Three different electrode pattern designs, including a qualitative estimation of the attractive force vectors for different directions. We propose a novel solution (C) that is advantageous for soft modules because of its homogeneity and isotropy.

However, it has a very weak attractive force in the parallel direction. The second electrode pattern (B) is a spiral rectangular design. This solution has the advantage that the shear attractive force is relatively high in both the x- and y-direction. However, it still has a relatively weak force component in the diagonal directions.

To address these limitations, we suggest here a novel spiral round design (C). Compared to the previous patterns, it has the weakest adhesion force in shear; however, it is equal for all directions. The benefit of this homogeneity and isotropy in the context of modular robots is that the alignment of the connection mechanism is independent of its orientation. We therefore suggest to implement pattern (C) into soft modules.

3. Experimental Method

In order to validate the connection mechanism in hardware, we developed mockups of soft spherical modules and integrated electroadhesive pads into them. Additionally, we built an experimental setup to characterize the connection strength of the mechanism.

3.1. Soft Modules

We developed mockups of soft modules to test various aspects of the connection mechanism. *A priori*, we assume the scalability of the electroadhesive mechanism and we build the modules at the macroscale to simplify the prototype fabrication [17]. In order to obtain lightweight and soft modules, we designed spherical modules with a thin outer skin membrane encapsulating a gas (Fig. 3). The prototype modules have a size of 18 cm in diameter when inflated. In order to vary the softness of the modules, we simply change their gas inflation. The membrane of the modules is composed of two circular 10-μm-thick polyvinylchloride (PVC) foils. For simple, fast and safe fabrication of the pads using a paint brush, we dimensioned the electrode and gap width to be 2 mm. The two electrodes are made of Conductive Graphite E33. A 10-μm layer is deposited on the PVC foil. A thin copper cable is taped to one end of each of the electrodes. The foil with the electrodes

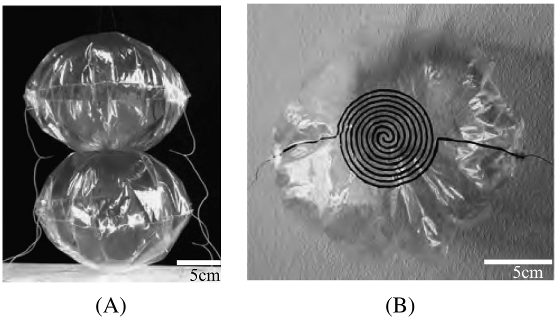


Figure 3. Fabricated prototype. (A) Two modules connected together. (B) The module has a diameter of 18 cm and weighs 1.5 g, the pad has a radius of 3.9 cm, and the electrode and gap width are 2 mm.

is then sealed by heat to the other foil, keeping the electrodes at the inner side. The complete module, without cables, has a weight of 1.5 g.

3.2. Experimental Setup

In accordance with the established requirements for the connection mechanism, we aim at evaluating how (i) pad size, (ii) module softness and (iii) pad alignment affect connection strength (i.e., the detachment force). Ideally, small pad sizes would enable high connection strengths and neither the module softness nor the pad alignment would influence the detachment force.

We vary the pad size by increasing the pad radius from 1.5 to 6.3 cm, while keeping the electrode and gap width at 2 mm for every pad size. Since the module has a radius of 9 cm, the smallest pad size takes up approximately 1% of the hemipshere of the module and 25% for the biggest one. We change the gas inflation in order to vary the softness of the modules. We assume the softness to be the inverse of stiffness (i.e., the ratio of strain to the applied stress (average force per unit area of a surface)). The unit of softness is kPa^{-1}. This definition is commonly used to describe the softness of biological cells [22–24]. To test misalignment, we vary the pad alignment from 0 to 100% overlap.

In order to measure the detachment force, we use the setup shown in Fig. 4. We first bring two modules together and align the electroadhesive pads to ensure an optimal connection. Both pads are connected to the high voltage converter and activated. Then, we incrementally add water drops of 0.05 g using a syringe into a cup attached to one of the modules while the other one is fixed until the two modules detach. The detachment force is equal to:

$$F = m_{\text{water}} g \cdot \mathrm{e}^{-\gamma \cdot \mu}, \tag{2}$$

where γ is the angle of deflection of the wire connecting the module and the cup (180°), and μ is the coefficient of friction between the wire and the round deflection elements. For all measurements, we keep the voltage constant at 3000 VDC, which

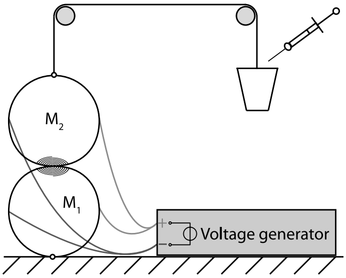


Figure 4. Experimental setup: module M1 is fixed to the ground, while module M2 is connected to a cup through a wire. The pads on both modules are activated. By incrementally adding water drops (with a weight of 0.05 g), we measure the total force in the normal direction of the pads that the mechanism can hold until torn off.

is lower than the maximum voltage before dielectric breakdown occurs and, thus, guarantees safe operation.

4. Results

4.1. Pad Size

In the first set of experiments, we aim at estimating the effect of the pad size on the connection strength. We measure the detachment forces for five different pad radii: 1.5, 2.7, 3.9, 5.1 and 6.3 cm. The electrode and gap width is 2 mm for every pad size and the softness of the modules is kept constant at 50 kPa^{-1}. The mean detachment force per pad area and its standard deviation over five measurements per pad radius are plotted in Fig. 5.

We can observe that the detachment force per pad area decreases with the pad radius. However, the decrease is not linear. The average detachment force per pad area for the smallest pad radius of 1.5 cm is 6.5 mN/cm^2, for a radius of 2.7 cm it is 4.2 mN/cm^2, while for the largest pad radius of 6.3 cm it is 1.1 mN/cm^2. This suggests, in general, that the pad size is a major indication for the detachment force, but implies that for soft modules other factors play a role as well. As we observed during the experiments, detachment happens through fast peeling (less than 100 ms). Peeling normally strongly depends on the peel angle and the width of peel [25]. Considering that, in the case of soft modules, both peel angle and peel width change for every pad size, we believe that a combination of these factors leads to this nonlinear increase of the detachment force with the pad size.

Also, the results show that the efficiency of the mechanism decreases with an increase of the pad size. Therefore, in order to achieve high connection strengths when implementing electroadhesion into soft modules, not the pad size, but rather

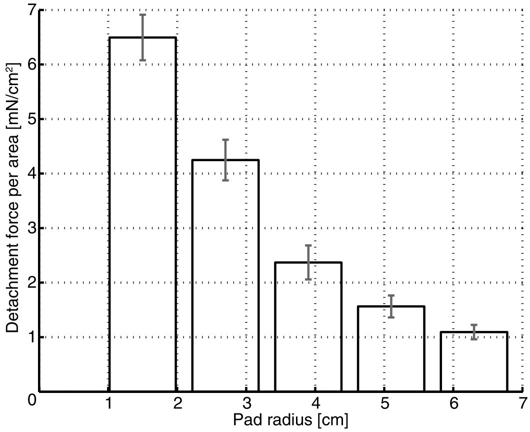


Figure 5. Mean and standard deviation of detachment force per pad area for five pad radii. The electrode and gap width is 2 mm for every pad size, and the softness is 50 kPa^{-1}.

parameters such as the operating voltage or the electrode and gap width should be adjusted.

In our setup, the smallest pad led to a mean detachment force of 46 mN. This force would be sufficient to hold together two modules of a weight of 4 g. Although the connection could be further strengthened and optimized, we expect that, even in that case, the mechanism will be only suitable for lightweight modules. Consequently, it becomes challenging to integrate power and control electronics while staying at low weight, and for the design of the connection pads one will need to consider carefully the characteristics of the module mass.

4.2. Module Softness

In order to test the influence of the module softness on the connection strength, we take the modules with a pad radius of 2.7 cm and measure the detachment force for four different softness settings: 10, 50, 90 and 130 kPa^{-1}. For every softness setting, we perform five sequential measurements. The mean and the standard deviation of the detachment force are plotted in Fig. 6.

It can be seen that the detachment force slightly decreases when the module softness is increased. This effect may be caused by the increase of the peel angle for modules with increased softness, as illustrated in Fig. 7. In our configuration, the pulling force F_1 is applied at the end of one of the two connected modules. This force F_1 is axis-symmetrically transmitted along the membrane of the module to the edge of the pads (F_2). Depending on the softness of the modules, the force F_2 has a different orientation to the contact area. This is due to the fact that the softness is mainly a consequence of the internal gas pressure of the module. For lower gas pressure (i.e., higher softness) the module will be more compliant and the peel angle β_{peel} between the contact area and F_2 increases. The increase of β_{peel} results in a lower detachment force F_2 due to a higher normal component $F_{2\text{normal}}$.

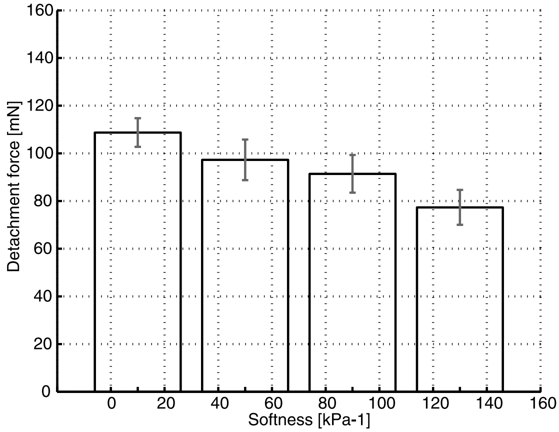


Figure 6. Mean and standard deviation of detachment force for four different module softness settings. Pad radius: 2.7 cm.

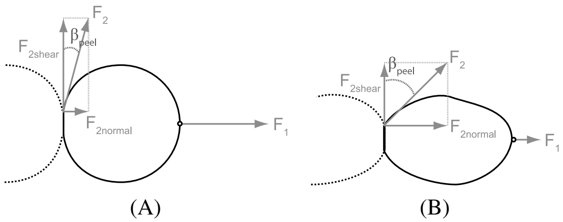


Figure 7. Mechanical model of the change of the peel angle β_{peel} for a connection between two modules with (A) low and (B) high softness. F_1 is the pulling force and F_2 is the translated force acting at the edge of the pads. The increase of the module softness leads to an increase of the peel angle, which results in a lower detachment force.

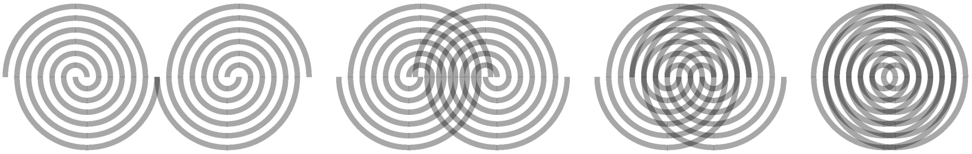


Figure 8. Four different pad alignment settings. From left to right the overlapping area corresponds to 0 (0%), 9.2 (40%), 16.0 (70%) and 22.9 cm^2 (100%).

The variation of the softness from 10 to 130 kPa^{-1} resulted in a difference of 30% for the detachment force. These results suggest that, in general, softer modules within a specific softness regime lead to a slightly lower detachment force. Thus, when designing electroadhesive pads for soft modules, one should dimension them for the softest module state. For instance, in the case of our configuration, the mechanism would be sufficiently strong to connect two modules having each a weight of 7 g, assuming the softest module state does not exceed 130 kPa^{-1}.

4.3. Misalignment

The purpose of this set of experiments is to estimate how misalignment affects the detachment force. We take the modules with a pad radius of 2.7 cm and set the module softness to 50 kPa^{-1}. We then align the two connection areas in four different ways (Fig. 8) such that the overlapping area varies from no overlap to 100% overlap.

For every configuration, we perform five sequential measurements. The mean and the standard deviation of the detachment force are plotted in Fig. 9. We can observe that the more the pads overlap, the higher the detachment force is. It is worth noting that there is an attracting force even if the modules do not align at all. This is because a single pad can polarize the substrate of the other module (PVC) and, thus, still generate some adhesion.

The results show that the mechanism is sensitive but highly tolerant to misalignment. The detachment force decreases not more than 40% when the pad areas do not match by 70%. However, the fact that the pads stick to the unprepared membrane should be taken into account when designing the modules. For example, to

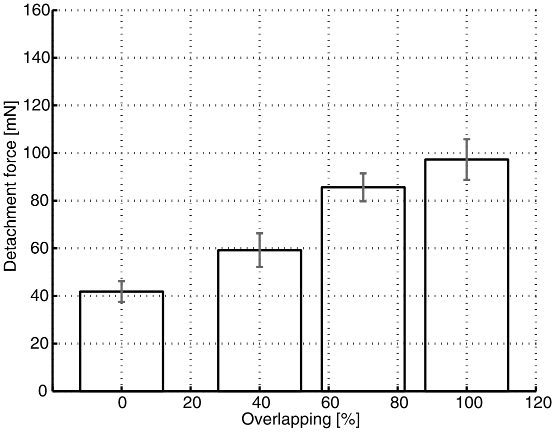


Figure 9. Mean and standard deviation of detachment force for four different alignment settings from 0 to 100% (Fig. 8). Pad radius: 2.7 cm; softness: 50 kPa^{-1}.

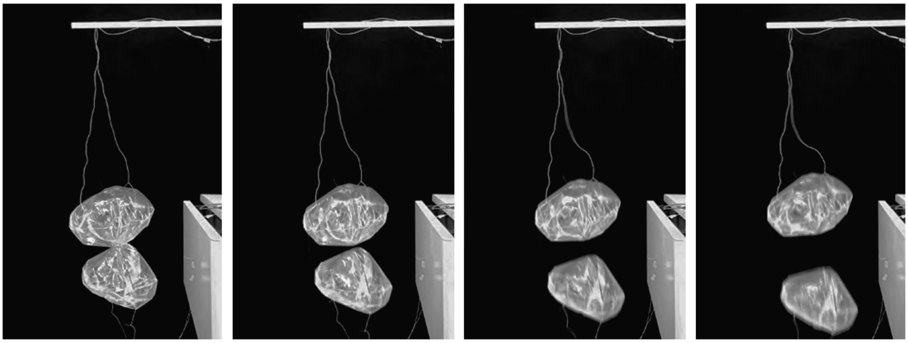


Figure 10. Sequence of a controlled detachment experiment. The upper module is fixed and holds up the lower module. When cutting the voltage, the connection breaks.

avoid adhesion out of connecting sites, areas without the mechanism could be protected, making the surface rougher or brush-like. Another solution would be the use of sensors to detect the kind of surface (module or object) in order to avoid unwanted connections.

4.4. Detachment on Command

As a demonstration to show that the mechanism enables detachment on command, we adapted the experimental setup described in Section 3.2. In this, one module is fixed but freely hanging in air and the other one is left completely free (Fig. 10). Thanks to the connection mechanism the upper module carries the lower module when we bring the two modules together. Then, by cutting the voltage manually at both pads the connection breaks and the lower module is released. We repeated this experiment 5 times with 100% success rate.

This experiment demonstrates the controllability of the connection. Thus, it would be possible (e.g., with a simple control unit that handles the voltage settings) to provide modules with several attachment areas featuring selective attachment.

5. Conclusions

In this work, we presented the development and characterization of an active connection mechanism for soft modular robots based on electroadhesion. In line with the major requirements of the mechanism we tested the influence of the pad size, module softness and pad misalignment on the connection strength. According to the experiments, when electroadhesive pads are integrated into soft modules, the increase of the pad radius leads to a nonlinear decrease of the detachment force per area. We explain this nonlinearity by the fact that both peel angle and peel width vary for every pad size. Further, the results show that the efficiency of the mechanism decreases with an increase of the pad size. Therefore, in order to achieve high connection strengths, not the pad size but rather parameters such as the operating voltage or the electrode and gap width should be adjusted. Further, we found that the variation of the softness from 10 to 130 kPa^{-1} resulted in a difference of 30% for the detachment force. These results suggest that, in general, softer modules within a wide softness regime lead to a slightly lower detachment force. Thus, when designing electroadhesive pads for soft modules, one should dimension them for the softest module state. In addition, we found that the attractive force in the case of misalignment decreases, but not more than 40 for 70% misalignment. This shows that the mechanism is sensitive, but highly tolerant to misalignment. However, the fact that the pads stick to the unprepared membrane should be taken into account when designing the modules. Finally, we have shown that the mechanism enables easy detachment on command.

We conclude that electroadhesion is suitable as a connection principle for soft modules when efficiency over a wide range of softness, tolerance to alignment and easy detachment are of prime importance. In comparison to other principles, electroadhesion is advantageous because it can be embedded into the soft membrane with very little invasion and allows for controlled detachment. The mechanism is suitable for soft lightweight modules and could be useful, for example, for soft stochastic modular robotic systems, a promising approach to reduce module size and scale systems to large numbers [26]. When modules are small in size, they tend to be lightweight as well. The scalability of electroadhesion has been modeled before and it has been shown that the mechanism would perform similarly at the microscale [17]. Downscaling of the mechanism would enable lower operating voltage requirements; however, it would need more elaborated fabrication techniques. Soft miniature modules featuring electroadhesion could then have several attachment areas featuring selective attachment (e.g., with a simple control unit that handles the voltage settings of each area). However, since activated electroadhesive pads have the ability to adhere to a wide range of substrates, modules would require sensing to identify the type of connection (module or other object).

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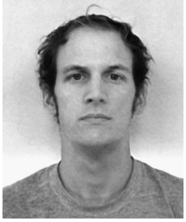

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