Microhand for biological applications

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A microhand, approximately 1 mm in fist diameter, has been developed with microelectromechanical systems technology to mimic the human hand in microscale. The hand has multiple microfingers, composed of silicon phalanges and polymer-balloon joints. By pneumatically inflating and deflating the balloon joints, the microfingers perform the motions of flexion and extension. This device possesses attractive characteristics: (i) gentle but strong holding, (ii) out-of-plane enclosure, (iii) active grasping, (iv) being inert to surroundings, and (v) reliable monolithic construction. It operates in both air and aqueous environments, as well as demonstrates grasping, stretching, and detaching of soft objects in submillimeter scale for biological applications. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2362602]

Micromanipulators, miniature devices capable of handling tiny objects, are useful in biomedical applications, as many biological entities exhibit dimensions on the micrometer scale. The applications of such devices include cell handling for research purposes, sample preparations for inspection, and microsurgical operations in clinical use. Some of these devices have been developed using traditional manufacturing methods, while others were produced with exploratory micro- and nanotechnologies.[1–8]

While manufacturing capabilities for miniature tools continue to advance, the state-of-the-art micromanipulation devices are mostly limited to the simple function of tweezers and actuated by such forces as electrostatic,[3] electromagnetic,[4] thermal expansions,[5] electrochemical,[6] and shape memory alloy.[7] These actuation principles, however, pose a formidable challenge when manipulating small biological targets in an aqueous medium. Electrostatic actuation becomes ineffective in ion-rich fluids due to the cancellation of surface charges. Thermal actuation is impractical because the high surface-to-volume ratio inherent in miniaturization causes excessive heat loss in liquid. Therefore, an inert actuation scheme—one that does not affect and is not affected by the surroundings—has drawn much attention in recent years.[8,9]

The majority of design geometries employed by today's micromanipulation tools mimic grippers, forceps, and tweezers. These devices use the simplest construction: two moving cantilevers. Tools with such a design can only grab, clamp, or squeeze objects with relatively simple symmetric geometry and have limitations in handling soft and delicate objects such as cells. While a tool with great flexibility and precision is a dexterous hand,[10,11] microscale versions of such a complicated device could not be made with conventional micromachining technology, with which assembling of parts is not practical. Thus, our device is confined to monolithic construction being reliable against leakage and to batch production by utilizing common microelectromechanical system fabrication methods only for future adoption.

The basic motions of the human hand include flexion and extension. To reproduce these motions, one would need a finger mechanism that generates similar out-of-plane movement. Miniature devices with such out-of-plane capabilities have been made, but many of them, including the conducting-polymer actuator,[2] pneumatic-balloon actuator,[12] polyimide-joint actuator,[13] and surface-tension assembled device,[14] are limited by certain factors. These include their need for specific operating conditions,[2] manual assembly,[12] or low yield in fabrication.[13–16] To achieve broader microscale applications in air and aqueous medium, a pneumatically actuated microhand as a safer and more stable platform is proposed, as conceptually depicted in Fig. 1(a).

The microhand consists of four fingers in a cross pattern that have multiple phalanges (i.e., finger segments) connected by joints. Our mechanism to produce flexion and extension involves using the balloons, located between the phalanges, to imitate muscles in controlling the joints, as illustrated by a simplified experiment in Fig. 1(b).[17] When the balloons are inflated, the distance between two attachment points shortens and the angle of the joint decreases, flexing the fingers. Conversely, when the balloons are deflated, the distance lengthens and the angle increases, extending the fingers. As a result, the balloon functions as an active joint for an out-of-plane motion, transforming the actuation signal of pressure into the grasping force of the device.

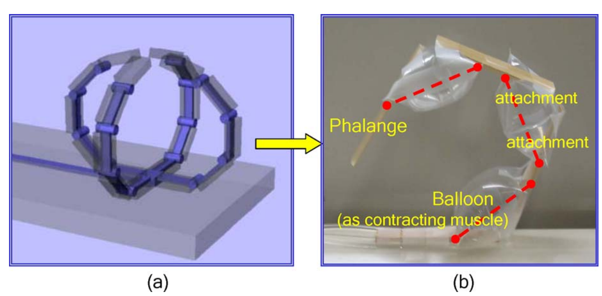

FIG. 1. Schematic drawing of a microhand device with four fingers articulated by balloon joints, mimicking the flexion and extension capabilities of the human hand in microscale. (b) The actuation mechanism is illustrated in a simplified centimeter-scale experiment, in which the inflating of the balloons (plastic bags) shortens the distance between the attachment points, drawing up the Plexiglas phalanges.

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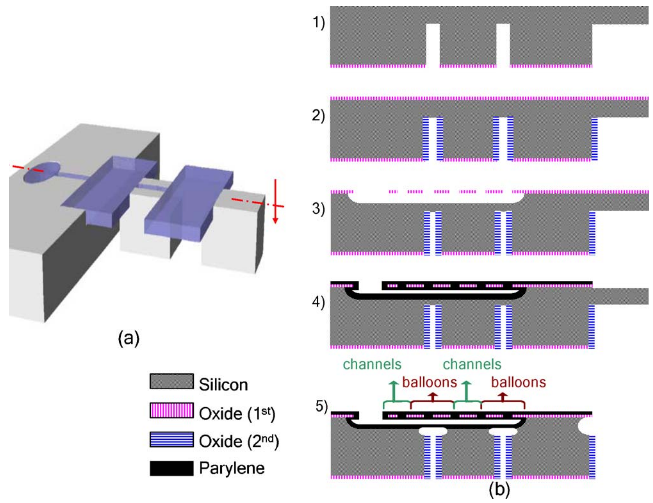

FIG. 2. Microhand fabrication process. (a) shows a three-dimensional schematic of one finger. For simplicity, only two phalanges and two balloon joints are shown. (b) illustrates the process flow in the cross section of (a).

The grasping force and flexion motion of the microhand are functions of actuation pressure.[17] A higher actuation pressure produces more bending motion and a greater closing force onto objects. In addition, when forces are exerted to the fingers, the fingers can be stiffened by pressurizing the balloon joints. We call this controllable flexion, i.e., stronger grasping by higher actuation pressure, "active grasping," as opposed to the usual "passive grasping" in which the mechanism for device closure is the spring-back force of the stressed microstructures.[3,7,8] Active grasping allows us to design powerful application-specific tools to manipulate micro objects.

The fabrication process is summarized in Fig. 2.[18] In the first lithography and deep reactive ion etching, a 150 μm thick silicon wafer with a 1000 Å silicon dioxide layer (oxide) is etched 110 μm deep from the backside to define the phalanges. A 300 Å thermal oxide layer is then grown and reactive ion etching (RIE) is used to remove the oxide layer from the bottom of the back side trenches between the phalanges. The remaining oxide on the trenches will protect the phalanges in the final XeF_2 release step. The second lithography defines the cavity area (balloon mold) and the oxide grid membrane. The front side oxide layer is patterned using RIE to create the 4×4 μm^2 grid holes that will allow XeF_2 to diffuse through and isotropically etch the underlying silicon, forming 30 μm deep cavities for the balloons and channels. A 5 μm thick Parylene layer (from Specialty Coating Systems, Indianapolis, IN) is then conformally deposited to form the balloon and seal the grids. The third lithography and oxygen plasma defines the balloon areas. XeF_2 finally removes the remaining silicon in the trenches, resulting in the microhand device with Parylene balloons connecting the silicon phalanges.

The fabrication process, optimized to require only three lithography steps, possesses the following advantages: First, the process involves only dry etching, avoiding the problem of stiction frequently encountered during microfabrication that involves wet etching. Second, Parylene is conformally deposited on the inner walls of the cavities and eventually seals the oxide grid to monolithically form the balloons, providing uniformity, durability, and strength. Third, whole silicon blocks serve as the phalanges, providing structural robustness.

Each microhand device consists of four fingers in the current design. Each finger has six silicon phalanges with dimensions of 144 (length) $\times$ 70 (width) $\times$ 150 (thickness) μm^3 joined by $146\times418\times30$ μm^3 Parylene balloons. The device on the chip is mated with a separately machined

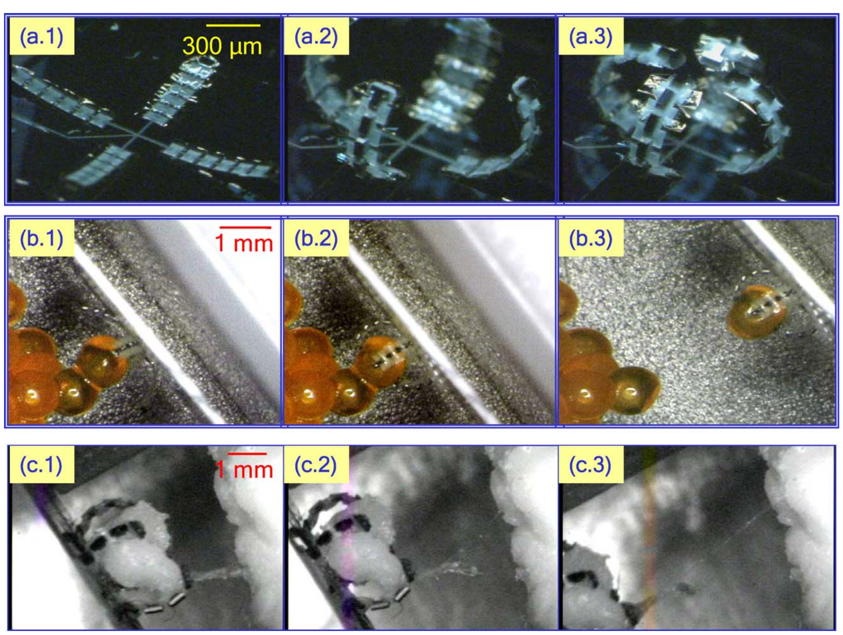

FIG. 3. Sequenced pictures show the full flexion and extension of the microhand as well as its operation on microbiological objects. (a) The microhand is flexed at 0, 160, and 240 kPa. (b) The microhand grabs a capelin egg ($\sim$1 mm in diameter) and detaches it from its mass. The detachment force is at least 0.23 mN. The microhand (b.1) approaches the target, (b.2) encloses to gently hold a target, and (b.3) detaches a single target and moves away. (c) The microhand manipulates the fatty tissue from the mucosal layer of the swine stomach fixed on a slide. The microhand holds the fatty tissue and pulls it away. A strand of elastic fibers binding the fatty tissue is exposed during this action. The long and thin fibers, forming intercellular matrices within the fatty tissue, hold the cells together. Further retraction of the microhand breaks the connective fibers apart. A larger microhand ($\sim$2 mm fist) was used for this task. The microhand (c.1) grasps fatty tissue, (c.2) moves away and pulls the connective fiber, and (c.3) breaks the fiber apart.

Plexiglas piece, containing air ducts and connection adaptors, which interface between the microdevice and the compressed nitrogen cylinder. The balloons are all pneumatically connected and controlled by the same pressure regulator.

The capabilities of the microhand are illustrated in the following experiments. The experiments were performed and recorded with a three-dimensional video microscope (HiScope from Hirox-USA Inc., River Edge, NJ), and still images were captured from the frames of these videos. The first experiment demonstrates the flexion and extension, mimicking the motion of human hands. The microhand can completely open and close between actuation pressures of 0 and 240 kPa, as shown in Fig. 3(a). When actuated, all the fingers flex and the microhand produces a closed fist 1.2 mm in diameter. The microhand has also been repeatedly actuated at higher pressure of 800 kPa without failure, showing the durability of the balloons. Although the device was actuated in liquids as well, the operation in air is shown for better image quality.

The second experiment in Fig. 3(b) evinces the capability of the microhand manipulating delicate biological objects. An experiment was conducted to illustrate how the microhand can physically enclose and separate a single capelin roe ($\sim$1 mm in diameter) from a sticky matrix holding the egg mass. The microhand, constructed as flexible because of the balloon joints, can gently hold a delicate egg without damaging it. Yet, the microhand is strong enough to detach the egg against adhesion that is very strong in this scale.

Additional experiments were conducted to study the feasibility for more applications. Figure 3(c) demonstrates the microhand holding a fatty (adipose) connective tissue and pulling apart its connective (elastic) fibers. The fatty tissue found in the mucous membrane lining of a swine stomach was chosen, as it represents one type of loose connective tissue that is composed of cells (e.g., adipocyte) and intercellular materials (matrix). The microhand shows enough stiffness to grab the fatty tissue and, when moved away from the tissue bulk, can pull apart the connective fiber that binds the fatty tissue together. Although not shown here, the microhand also successfully manipulated more objects, for example, grabbing, stretching, and retracting a nerve bundle (spinal cord).

In summary, the functionalities of the microhand in (i) performing flexion/extension motion, (ii) grabbing and detaching biological objects, in both millimeter and submillimeter sizes, from a mass, and (iii) pulling apart the connective fiber have been successfully performed. The device is useful in many more general biological object manipulations due to the following traits. The device can operate in most relevant environments, including air, salt solutions, silicon oil, and cell culture medium. The multiple-finger configuration is convenient when handling irregularly shaped objects. Its force capability by active flexion and its gentle grasp by flexible joints are advantageous for handling fragile microscopic biological objects.

The microhand represents an important advance toward employing microrobots in biomedical research. Possible applications include manipulating animal embryos in liquid medium for embryology study and retracting nerve bundles/cells in neurological surgery. The device can serve as the platform for manipulating objects for tissue-level biopsy and for cell electrophysiology study. The microhand can also serve as a medical tool, integrated with catheters or endoscopic instruments, for biopsy application and microsurgery.

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