Micropumps for Microfluidic Devices and BioMEMS

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Abstract. The development of micropumps are reviewed and their applications are summarized. The micropumps are categorized into indirectly-driven and directly-driven micropumps according to the ways of driven origination from working principles. The actuation principles are introduced in detail including electrostatic, piezoelectric, thermopneumatic actuation, etc. Moreover, the performance influencing parameters on the property and the applications of various micropumps for medical therapy are described such as reciprocating, peristaltic, rotary, electrohydrodynamic, micropumps, etc. The challenge of micropumps is also discussed.

Keywords: Micropump; Microfluidics; BioMEMS.

1. Introduction
MEMS-based medical applications either improve performances of traditional medical devices in existence or produce new medical means and microsystems. Obviously, the latter is more attractive. As to date, bound of BioMEMS technologies are studied, however, only a few medical devices come into commercialization. Some principle mechanisms and microfabrication techniques need to further study. There are tremendous demands for pumping drugs in the transdermal DD system. The conventional macroscale pump is not suitable for microfluidic devices and BioMEMS. Obviously, the sizes of pumps cannot be used in microsystems. Only the pumps in micrometer scales are employed in MEMS. Moreover, the working voltage and power consumption also limited the applications of macroscale pumps even though having great progress and advancement. In order to match with the microfluidic devices and BioMEMS, the pumps in microscale, MEMS or micromachining-based micropumps, should be utilized to most extent. Actually, the research on micropump has been carried out at the beginning of MEMS emergence [1-3]. Micropump is very important and the main part of microfluidic devices and BioMEMS. There are most noticeable properties of micropumps compared to pumps in macro size. Besides sizes, the among and range of pumping rates can be small [4][5], they can meet the requirement of microfluidic devices. Moreover, power consumption is very low for application [6,7]. And, the working voltage and pumping pressure of micropump can be less than the ones of the pump in macroscale [8]. In addition, fabrication compatibility with other parts of the system is also flexible.

2. Actuating Principles
Different applications have their specific necessities and requirement. Therefore, the significance is different from various systems for which the micropumps are employed. Consequently, remarkable different types of micropumps are studied and developed to meet specific various requirements. Generally speaking, micropumps are divided into main types, namely indirectly driven micropumps, and directly-driven micropumps according to the ways of driven origination from working principles.
The indirectly-driven micropumps mean that the fluid delivered is directly driven by the force or pressure generated from external energy, such as reciprocating, peristaltic, rotary, and bubble-driven micropumps. As for the directly-driven micropumps, the fluid delivered is directly driven by the force or pressure resulted from external energy, such as electrohydrodynamic, magnetohydrodynamic, electroosmotic, electrowetting, and surface wave-induced micropumps. But then, in many literatures, micropumps are classified into mechanical and non-mechanical [9]. The indirectly-driven micropumps are classified into reciprocating, peristaltic, rotary, and bubble-driven micropumps in accordance with their actuation principles as the development of micropumps currently. A reciprocating micropump is the most popular. It is comprised of the check valves and a reciprocating membrane. Besides, a peristaltic micropump is another common micropump. It works through the periodical movement of multiple membranes orderly. The others are utilized infrequently including a rotary and bubble-driven micropump.

The driving principles are important for micropump. There are many kinds of actuation mechanisms corresponding to various micropumps. It is necessary to acquaint with driving principles in order to understand micropumps. The common actuating principles are as follows.

2.1. Electrostatic Actuation
Electrostatic actuation is a common way in actuation principles. In that case, there are two parallel plates that are applied to AC voltage respectively, like a capacitor. Usually, one can move, the other is fixed. Figure 1 illustrates the graphic of the micropump actuated by electrostatic force [10]. The electrostatic force exerts between electrodes, because of no static current flows between two plates. It results in the deformation of the moving plate into the upper direction, which will cause the chamber to enlarge. Therefore, the import valve will open and the fluid enters from the import. Then, the applied voltage is off or decreases, the deformation of the moving plate (membrane) is reinstated by the elastic force of the membrane. The chamber will be compressed. The import valve will close and the export valve will open. Finally, flowing the fluid will flow away via the outlet.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** A graphic view of the working principle for electrostatic actuation.

2.2. Piezoelectric Actuation
The working principle of piezoelectric actuation accomplishes actuation using the piezoelectric effect. When an electric field applies to the disc of piezoelectric material, it will lead to the deformation (shrinking or expanding) of the piezoelectric disk resulted from the mechanical strain. Therefore, this shape change will implement pumping. However, this structural deformation is difficult to acquire enough displacement for the pumping work. It is necessary to enlarge displacement. The methods usually are depicted in Figure 2.

Figure 2 (a) plots the common means by connecting piezoelectric layers with a membrane. When the piezoelectric layers are compressed (or swelled) in a special direction, the membrane will force the membrane upward or downward movements. The second means is to employ an actuator with a piezoelectric cantilever. In this case, just one end of the cantilever is connected to the membrane (Figure 2 (b)) [11]. Besides, we can stack some piezoelectric disks to enlarge the vertical displacement, as depicted in Figure 2 (c).
Figure 2. Various working principles for piezoelectric actuation. Although piezoelectric actuation can consume less energy, their working voltage is very large, larger than 100 V in most applications. This high working voltage limits application of piezoelectrically-actuated micropumps. Moreover, it is difficult to mass production using the piezoelectric actuation principle. Besides, the manufacturing cost is high, and reliability is also concerns.

2.3. Thermopneumatic Actuation
Thermopneumatic actuation, which uses volume expansion of heated fluid, is also a common means applied to micropump. The heated fluid providing the driving power is not the actuated fluid. Commonly, this actuation principle can produce a large deflection of the membrane, resulting in a large power. The heated fluid for actuating source may be either liquid or gas which should be separated from the chief pumping cavity, as shown in Figure 3 [12]. A large periodic deformation at a relatively low working voltage is an advantage when Thermopneumatic actuation compares with the electrostatic and piezoelectric actuation. Moreover, thermopneumatic micropumps may be easily built by micromachining. However, high power consumption resulted from the heating fluid is required. In addition, the slow thermal response is also an intrinsic feature. Besides, the heated fluid needs cooling down.

2.4. Electromagnetic Actuation [13]
Electromagnet actuation, which is produced by employing NiFe and copper, is seldom used in micropump. As shown in Figure 4, the alloy layer is built on a silicon film which is deformed by magnetic force while the current is exerted. Although having a low working voltage, however, the electromagnetic actuation requires large power consumption. Moreover, electromagnetic components are difficult to achieve employing typical MEMS processes. Except for actuation principles above, there are still other actuation principles adopted including pneumatic [14], electrowetting, shape memory alloy, electrohydrodynamic, actuation. Compared to afore actuation principle, there are few applications in practice.

Figure 3. Various working principles of thermopneumatic actuation.

Figure 4. Schematic view of electromagnetic actuation.
3. Indirectly-driven Micropumps

3.1. Reciprocating Micropumps
Probably, the favorite mode of micropump is a reciprocating micropump [15]. The membrane able to reciprocate and check valves are required in reciprocating micropump.

The reciprocating micropumps implement pumping by using a reciprocating member with the check valves. It is the same as the working principle of a human heart pushing blood into blood vessels, as depicted in Figure 5. In general, the reciprocating pump comprised of four components: a reciprocating membrane which can thrust or draw the fluid in a cavity by reciprocation; check valves that only allow a directional movement of driving fluid; import and export openings from which the driving fluid can flow in and out, and the driving fluid is kept in the cavity during the driving cycles. When the membrane bends to enlarge the cavity space (Figure 5(a)), the left valve is unlocked and the right valve is locked, forcing the driving fluid into the cavity via import opening. Then again, as the membrane bends to shrink the cavity space (Figure 5(b)), the left valve is locked and the right valve is unlocked by the flow pressure. Therefore, the fluid in the driving cavity is moving out via export opening. A net flow of driving fluid depends on the deformation of the reciprocating membrane. Consequently, the characteristics of reciprocating micropumps intensely rely on the membrane movement, valve mode, materials, and the shape of micropump.

![Figure 5](image_url)

**Figure 5.** The operating mechanism of reciprocating micropumps.

3.2. Peristaltic Micropumps
The first peristaltic micropump was proposed in 1990. The actuation principle is that a few of continuous actuating cavities accomplish pumping through pressing fluid to produce peristaltic motion. Every cavity is forced by a piezoelectric material and the fluidic flow drifts from one direction to another direction through the reciprocating movement of each membrane. There are at least three pump chambers to achieve directional fluid pumping. As for actuation principles, peristaltic micropumps can adopt a few actuation principles such as piezoelectric, thermopneumatic, pneumatic, and electrostatic actuation.

3.3. Rotary Micropumps
Rotary pumps are the common pumps in macroscale applications. The main components include rotor, stator, and coils. These parts are easy to acquire. With the great progress of the micromachining process, many researchers explored the application of rotary micropumps [16]. The parts of the motor can be built through electroplating. A rotary micropump was presented with two toothed wheels which one is an actuating wheel and the other is an actuated wheel. The driving wheel revolved around an external magnetic stirrer. However, it is not easy to acquire rotary micropumps fabricated employing micromachining. In addition, because of existing of wearing and friction, the life is a concern.

4. Indirectly-driven Micropumps

4.1. Electrohydrodynamic Micropumps
Although employing electrostatic force like electrostatic actuation, Electrohydrodynamic (EHD) micropumps pump fluid through electrostatic force directly exerting on the charges in the dielectric flow [17]. There are three kinds of EHD micropumps including injection, induction, and polarization
pump. The electric charges are produced by inpouring from electrodes in the injection pump, while the induction pump depends on the production of charges in the actuating fluid using different principles. As for the polarization pump, the Kelvin polarization force is used to drive fluid.

4.2. Electroosmotic Micropumps Practicalness
Electroosmotic manipulation is often applied in sample analysis such as -TAS employment counting electrophoretic separation, electrochromatography, and electrospray. The working mechanism of electroosmotic micropumps is depended on the electrostatic force exerting on charges in the flow [18]. Unlike electrohydrodynamic micropumps, in electroosmotic micropumps, electroosmotic fluid is led by electric layers that are generated at the interface.

5. Discussion
Although all the advancements in basics and material innovation, the conventional pump technologies in macroscale also have restrictions in mini size, energy utilization, and working voltage in most MEMS. The technologies of micropump must have been further enhanced because of the great progress of bioMEMS [19-21].
The main characteristics of micropumps are defined by their sizes, working voltage, range of actuating velocity, energy utilization, manufacturability, and compatibility, actuating pressure with other parts of the bioMEMS. The micropumps can be used in many fields such as micro total analysis systems (μ-TAS) and lab-on-a-chip. They can accomplish many tasks involving analysis, mixing, and discharging of reagents reaction, or drug delivery through transferring sample reagents. The many different types of micropumps have been developing to meet specific system requirements.
Accurate control of fluidic velocity and amount is significant to enhance the reliability of analytical results, especially for a few amount of pumping fluid. Energy utilization and working voltage are not focused on a macroscale pump. However, it is very important such a low working voltage and low power consumption for micropumps. For example, micropumps can be used for environmental pollution monitoring. Low energy utilization and reliability with long-term are momentous for work in a long term. Besides, micropumps can be applied in a microdevice that can sample biological fluids from the body and dispense drugs into human tissues. The device must withstand high and fluctuating blood pressure.
Even in the space area, there are remarkable applications. For example, micropumps can be employed as a thruster in microscale to create propulsion for short control of global positioning in spacecraft or satellite. Micropumps with piezoelectric mechanisms need moderately high-working-voltage. The high fluidic velocity and amount are the main issues in the delivery of drugs. There is still a need to further exploration, for example, integration of various categories of micropumps to meet the requirement in multi-functions though most advance has great progress in the research for micropump. The micropumps driven by smart material actuators have been studied substantially, such as unidirectional shape memory alloy, ferroelectric polymer, dielectric elastomer, ionic polymer-metal composite actuating. The working voltages of those pumps are low, therefore, the driving principles are suitable to the micropumps. The micropumps at a mode of driven indirectly is not easy to fabricate, while the micropumps at a mode of driven directly can be easy to acquire due to no mechanical movable parts. In addition, the reliability of micropumps is the main issue to define whether to be able to commercialize. In addition, the integration of micropumps in a microfluidic device or system is still a vital issue. It intrinsically limits the kind of driving fluids and needs a high working voltage. Therefore, new actuation mechanisms and materials should further study.

6. Conclusions
A micropump is an important component in BioMEMS and microfluidics because it can control and transport a tiny volume of fluid. The micropumps actuated directly and indirectly can work in different working principles to meet many requirements. Miniaturization, monolithic integration, and applications of high-resolution dosing are still the aims pursued.
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References
[1] E.A. Sideris, H.C.deLange. Pumps operated by solid-state electromechanical smart material actuators - A review. Sensors and Actuators A: Physical, 2020, 307, 111915
[2] S. Sengupta, D. Patra, I. Ortiz-Rivera et al. Self-powered enzyme micropumps. Nature Chemistry, 2014, 6(5): 415-422.
[3] P. A. Gould, L. T. Hoang, J. R. Scherrer et al. PERISTALTIC MICROPUMP AND RELATED SYSTEMS AND METHODS, United States Patent Application, 20180209552, 2018.
[4] K. Uesugi, K. Nishiyama, K. Hirai et al. Survival Rate of Cells Sent by a Low Mechanical Load Tube Pump: The "Ring Pump". Micromachines, 2020, 11(4):447.
[5] H. Jarrett, M. Wade, J. Kraai et al. Self-powered microfluidic pump using evaporation from diatom biosilica thin films. Microfluidics and Nanofluidics, 2020, 24(5).
[6] H. Hamed, A. Bagheri and R. Ansari. "An Analytical Investigation for Vibration Characteristics of a Beam-Type Liquid Micro-Pump." International Journal of Applied Mechanics (2020).
[7] W. Xiong and J. Wang. Minimizing power consumption of an experimental hvac system based on parallel grid searching. Energies, 2020, 13(8), 2083.
[8] A. H. Shiravi, M. Firoozzadeh, Experimental study on carbon nanofluid pressure drop and pumping power, Adv. Nanochemistry, 2020, 2
[9] A. A. Aziz et al. "Fabrication of micropump for microfluidics application." Applied Physics of Condensed Matter 2019.
[10] U. Sebastian, G. Matthieu, L. Sergiu et al. Electrostatically Driven In-Plane Silicon Micropump for Modular Configuration. Micromachines, 2018, 9(4):190.
[11] Q. Bao, J. Zhang, M. Tang et al. A Novel PZT Pump with Built-in Compliant Structures. Sensors, 2019, 19(6).
[12] O.C. Jeong, and S.S. Yang, Fabrication and Test of a Thermopneumatic Micropump with a Corrugated p+ Diaphragm, Sen. Actuators A-Phys., 2000;83: pp.249–255.
[13] S. Santra, P., Holloway and C.D. Batich, Fabrication and Testing of a Magnetically Actuated Micropump, Sen. Actuators B-Chem., 2002;87: pp.358–364.
[14] M. Nafea, J. Baliah, S. Ali. Modeling and simulation of a wirelessly-powered thermopneumatic micropump for drug delivery applications. International Journal on Electrical Engineering and Informatics, 2019, 7(2): 182-189.
[15] N.-T. Nguyen, and T.-Q. Truong, A Fully Polymeric Micropump with Piezoelectric Actuator, Sen. Actuators B-Chem., 2004;97; pp.137–143.
[16] W. Na, J. Kim, H. Lee et al. Asymmetric fluttering ferromagnetic bar-driven inertial micropump in microfluidics. Biomicrofluidics, 2018, 12(1): 014115.
[17] L.-J. Yang, J.-M.Wang and Y.-L. Huang, The Micro Ion Drag Pump Using Indium-tin-oxide (ITO) Electrodes to Resist Aging, Sen. Actuators A-Phys., 2004, 111: pp.118–122.
[18] C.-H. Chen and J. Santiago, A Planar Electroosmotic Micropump, J. Microelectromech. Syst., 2002;11: pp.672–683.
[19] S. Gao, Y. Li and P.Y. Zhang, Analysis and Characterization of Compounded CMUTs for Medical Imaging and Therapy, Journal of Imaging Science and Technology, 2019, 63(3): 30402-1-30402-8(8)
[20] C.Y. Meng, Y.Y. Miao, P.Y. Zhang, Modelling and analysis of drug pathway in tissues with a MEMS-based microneedle array, Basic & Clinical Pharmacology & Toxicology, 2019, v129: 10-11, 2019
[21] S.Gao, Y. Li, P.Y. Zhang, Model of compounded CMUTs for medical imaging and therapy, Basic & Clin. Phar. & toxi., 2017, v121: 10-11