Development of Piston Type Shape Memory Alloy Actuated Pump for Drug Delivery

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ABSTRACT
The supply of drugs is of great importance for healing the disease. The blood sugar level of diabetic personal is required to be repeatedly observed, in accordance with level of sugar insulin be injected to wipe out surplus glucose. Treatment with injections is linked with soreness, contamination, injurious to body ornaments, training of a person to inject required level of drug is not possible. Miniature-pump are finding their rising application in the field of biomedical in particular drug delivery system based on various proposed techniques. Every actuation system for micro pump has their own advantages and disadvantages in terms of voltage applied and rate of flow of drug and algorithm effectiveness and complexity for controlled drug supply. SMA based actuator find their novelty as they required less voltage and provide better flow rate. This research proposes SMA wire actuator based pump for drug delivery system, a novel syringe shaped pump is developed with integration of SMA wires in loop configuration at edges of the syringe. The presented system will be able to discharge prefilled water upon actuation of SMA wire actuators with relatively simple mechanism and can be employed for delivering numerous type of drugs into human body.

General Terms
Soft memory alloy based soft gripper.

Keywords
Shape Memory Alloy (SMA), Piezoelectric (PZT), Drug Delivery Device (DDD), Dielectric Elastomer Actuator (DEA)

1. INTRODUCTION
When it comes to determining the therapeutic impact of a drug, the delivery process is just as crucial as the drug's actual activity. The proper amount of a medicine must reach the right spot at the right time to have the best therapeutic impact. Oral pills and injections are perhaps the most frequent methods of medicine administration nowadays. Pre-determined and calculated amounts, mobility, set dosing times, and the overall non-invasive nature of administration are all advantages of oral tablets. They are, however, constrained by their inability to carry bigger therapeutic molecules like proteins. Injections, on the other hand, can transport macromolecules but are limited in their application due to their intrusive character.Drug delivery research has centered on not just enhancing oral and injectable systems, but also on exploring new routes of administration such as pulmonary, transdermal, ophthalmic, and nasal. Each route has its own set of benefits and drawbacks, as illustrated in Table 1[1].

Table 1: Routes of administration

Route of administration	Advantages	Disadvantages
Injection	• Rapid onset • Up to 100% bioavailability • Controlled depot release • Suitable for most therapeutic molecules	• Difficult for patient to self-administer • Patients' fear of needles leads to noncompliance • Higher instance if infection
Oral	• Patient compliant and most convenient	• Poor bioavailability • Generally non targeted • Not viable for larger therapeutics • Potentially inconsistent due to the presence of food
Inhalation	• Direct target to the lungs • Fast absorption	• Inconsistence delivery stemming from variation in patient-to-patient technique
Transdermal	• Less side-effects due to direct delivery to the skin • Bypasses first-pass degradation	• Patients can potentially use incorrect dose • Absorption dependent on skin condition and location

Over the last few decades, advances in micro-electro-mechanical systems (MEMS) technology have aided in the rapid creation of a diverse spectrum of microfluidic devices with a variety of functions[2-7]. Micropumps, which supply the energy required to push fluid through microfluidic systems, are one of the most essential and widely utilized devices among the numerous devices that have been developed. In biomedical, biological, and environmental applications, micropumps are critical for managing the tiny quantities of sample and reagent necessary [8].Drug delivery and biological assays [8], microfluidic analytics [9], cell culture [10], and other applications [11] have all been established using micro pumps. A detailed study of MEMS-based micro pumps for drug delivery and biological applications was published by Nisar et al. [12]. The operating concept of a variety of micropumps, both mechanical and non-mechanical, is investigated. These micropumps make it possible to correctly move fluidic drugs from a source to a target area, even in micro volume quantities. The type of micropump can be chosen based on the application requirements [13]. Micropumps are often made on biocompatible substrates such as silicon, glass, or polymer polymethylmethacrylate(PMMA), polydimethylsiloxane (PDMS), or SU-8 photo resist) utilizing micro-electro-mechanical systems (MEMS) techniques [14, 15].

As indicated in Fig 1, micropumps can be classed as mechanical or non-mechanical. Moving mechanical elements, such as pumping diaphragms and check valves, are found in mechanical micropumps. Non-mechanical micropumps, on the other hand, lack mechanical moving parts and instead rely on hydrodynamic, electroosmosis, or electrowetting phenomena to control fluid flow. A pumping chamber with a diaphragm (pumping membrane) and two passive check valves characterises traditional PZT micropumps [16-26]. A resonantly-driven micropump consisting of a folded PZT vibrator, two PDMS check valves, and two compressible spaces near the check valves was shown by the Feng group [16,17]. Many numerical analyses into various elements of PZT micropumps have recently been published, including the deflection or vibration of the diaphragm [18, 19] and the flow state [20].Table 2 summarizes a number of additional recent studies on PZT micropumps [21-26].

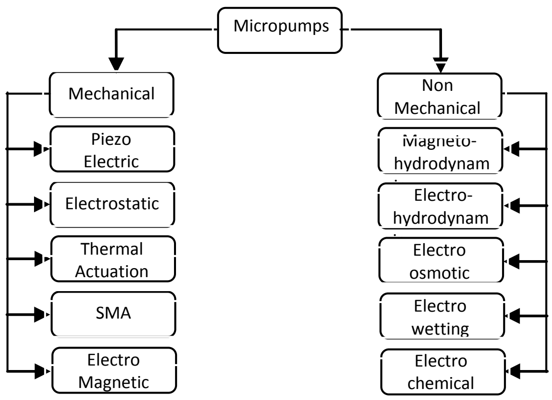

Fig 1: Types of Micropumps

Table 2: Piezoelectric micropumps

Ref	Voltage (V)	Frequency (Hz)	Flow rate	Pumping medium
[21]	260	265	186.8ml/min	Gas
[22]	24	1	3.5µL/min	Water
[23]	±70	70	9.1mL/min	Water
[24]	60	5.8k	32cm/min	Gas
[25]	200	18.4	0.24mL/min	Water
[26]	60	320	218.7mL/min	Air

To produce displacement or exert a force, electrostatic actuation relies on the columbic attraction of two oppositely charged substances [27]. The working concept of dielectric elastomer actuator (DEA) micropumps is similar to that of electrostatically actuated micropumps. A sinusoidal voltage is supplied between a flexible membrane and a lower fixed substrate in particular, resulting in alternating fluid flow into and out of the pumping chamber. In recent years, new concepts for electrostatic and electroactive polymer composite micropumpstabulated in table 3 have been proposed in the literature [28, 29].

Table 3: Electrostatic micropumps

Ref	Voltage (V)	Frequency (Hz)	Flow rate	Pumping medium
[28]	10	0.083	186.8ml/min	Gas
[29]	800	25	3.5µL/min	Water

Thermopneumatic [30-32], and shape memory alloy [33-35] mechanisms are commonly used in thermally actuated micropumps. Thermopneumatic actuators are made up of a heater, a diaphragm, and a chamber, and they work by changing the volume of the chamber or the phase of the fluid contained within it. Chee et al. [31, 32] constructed a thermopneumaticmicropump powered by a planar LC resonator and activated by a wireless microheater. Form memory alloy (SMA) and bimetallic micropumps, respectively, are based on the shape memory effect of specific alloys and the difference in thermal expansion coefficients of different materials. Both actuation systems provide a huge force but demand a lot of power (usually >100 mW).Fong et al. [33, 34] created an active, implantable drug delivery device (DDD) with a SMA, microfluidic pump and Parylene C check valves. Table 4summarizes a number of additional thermal actuation micropumps that have been proposed in recent studies.

Table 4: Thermo pneumatic and SMA micropumps

Ref	Voltage (V)	Frequency (Hz)	Flow rate	Pumping medium
[30]	10	n/r	12.5nL/min	Water
[35]	n/r	n/r	1.7mm^3/s	Ink-oil

Micropumps with magnetic actuation use either an electromagnetic (EM) or a magnetostrictive mechanism. The diaphragm movement of an EM micropump is caused by the interaction of permanent magnets with a changing magnetic field generated by a current-carrying micro-coil [36, 37]. Bi-directional membrane deflections can be achieved simply by changing the phases of the input current because the magnetic actuation force can be either attractive or repelling.

Chee et al. [36, 37] introduced a micropump with a solenoid plunger, a gourd-shaped chamber, and a flexible PDMS membrane that was EM actuated. When actuated at resonance frequencies of 15 Hz and 20 Hz, the micropump attained maximum flow rates of 1.52 ml/min in the forward direction and 1.48 ml/min in the reverse direction. Micropumps made of PDMS provide a number of advantages. Their manufacturing procedure, on the other hand, is usually quite complicated. Casting and bonding of numerous PDMS layers, for example, is usually necessary. The proposals for EM actuation micropumps proposed in [38-40] are summarized in Table 5.

Table 5: Electromagnetic micropumps

Ref	Voltage (V)	Frequency (Hz)	Flow rate	Pumping medium
[38]	17	10	1.2L/min	Magneto fluid
[39]	5	25.5	135µL/min	
[40]	n/r	100	0.055µL/s	

To operate its diaphragm or valve, a mechanical pump requires a distinct sort of actuation mechanism. Several studies have been conducted in the past offering various systems for regulating and actuating a micro pump for drug delivery. However, a search of the literature reveals that there are few designs of SMA actuated micro-pump.The objective of this research is to develop a piston-type shape memory alloy (SMA) actuated micro pump for biomedical applications, specifically drug delivery systems.

The introduction and associated studies from the literature are discussed in Section I of this paper. The methodology used to implement a novel SMA-based micropumps is covered in Section II. The findings of the experiments are presented in Section III. Furthermore, the conclusions reached as a result of the research findings are discussed in Section IV. In addition, Section V highlighted the research paper's future recommendations.

2. DESIGN &DEVELOPMENT

A SMA-based micropump was created utilizing a 1CC (1 mL) syringe, 0.25 mm diameter SMA wires, two supporting arms for SMA wire integration into the syringe, and a spring to provide the micropump with the requisite biasing force.

The suggested design may be categorized into two wire two loop configuration and single wire four loop configuration based micropumps based on how SMA wire is implanted into the syringe.

2.2 Two Wire Two Loop Configuration

One of the two supporting arms was put over the plunger between the thumb rest point and the finger flange, while the other was positioned over the syringe's barrel.

As shown in Fig 2, two 0.25 mm thick SMA wire actuators were put into the edges of the supporting arms, generating two loops. In addition, for SMA wire actuators, a spring was added between the supporting arm and the finger flange to provide the requisite restoration force. The specifications of SMA wire is tabulated in Table 6.

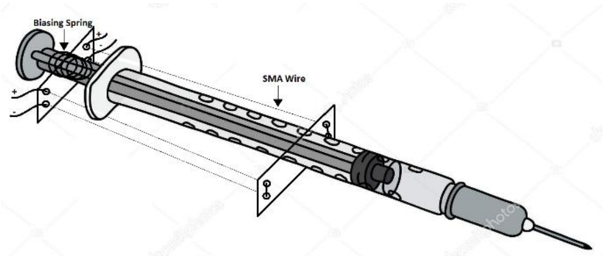

Fig 2: Parallel configuration of SMA wires based micropump

Table 6: Specification of SMA Wire Actuator

Parameters	Value
Diameter	0.25mm
Resistance per meter	18.5Ω
Martensitic start temperature (Ms)	52^{o}C
Martensitic finish temperature (Mf)	^{o}C
Austenite start temperature (As)	^{o}C
Austenite finish temperature (Af)	^{o}C

2.3 Single Wire Four Loop Configuration

The model of single wire four loop configuration pump in shown in Fig 3 where single four times longer SMA actuatorwas configured in four loops between two supporting arms, as opposed to the two wire two loop arrangement.

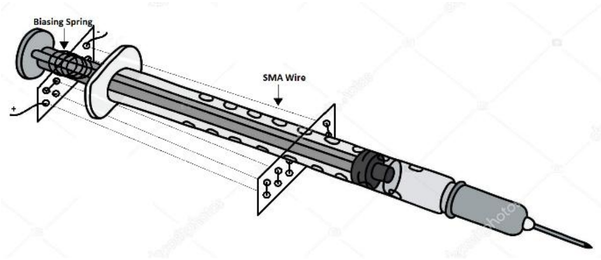

Fig 3: Series configuration of SMA wires based micropump

Fig 4: Two wire two loop configuration pump before actuation

Fig 5: Two wire two loop configuration pump after actuation

Fig 6: Single wire four loop configuration pump before actuation

Fig 7: Single wire four loop configuration pump after actuation

3. RESULTS & DISCUSSION

The characterization of SMA actuators is critical for the development of SMA actuated systems since the SMA wire's behavior is very nonlinear and has hysteresis among its martensitic and austenite phases, and the bending deformation is dependent on the heating and cooling duration.

The actuation characteristics of an actuator are crucial since they aid in the development of a better system.The micropumps as shown in Fig 4 and 5, with two wire two loop and in Fig 6 and 7, with single wire four loop configurations of SMA wire actuators were subjected to supply current with resolution of 200mA from 0 to 1A, and the resulting deformation or water outflow were assessed against numerousexperiments, as shown in Table 7.

Table 7. Experimental Design

Experiment #	SMA Wire Configuration	Actuation Time (Sec)	Supply Current (mA)
1	Two Wire Two loop	1	200 400 600 800 1000
2	Two Wire Two loop	2	200 400 600 800 1000
3	Single Wire Four Loop	1	200 400 600 800 1000
4	Single Wire Four Loop	2	200 400 600 800 1000

In experiment 1, a two wire two loop configuration pump, as shown in Fig 8, is initially subjected to a supply current of 200mA to 1A with a resolution of 200mA at the positive and negative ends of each loop of SMA wire actuators for one second.

Fig 8 shows the amount of water outflow measured with a calibrated scale over the barrel of a syringe against the actuating current. For applied currents of 200mA to 600mA, experimental examination revealed that SMA wire actuators did not change their states because no deformation is recorded and the plunger of the syringe retains its position at the start point.A 5µL and 10µL water outflow was measured against an applied current of 800mA and 1A, respectively.

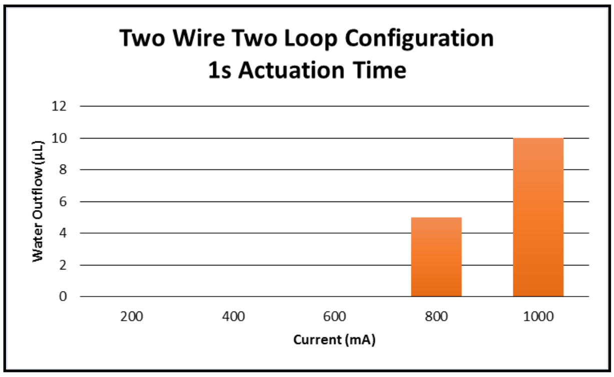

Fig 8.Two wire two loop SMA wire configuration pump at 1s actuation time

Secondly, for a period of 2 sec, the same sequence of current was applied to a two wire two loop configuration pump, and outflows of 15µL and 20µL were observed against applied currents of 800mA and 1A, respectively, as shown in Fig 9, whereas no displacement of the syringe plunger was recorded, resulting in 0µL of water outflow for currents less than 800mA.

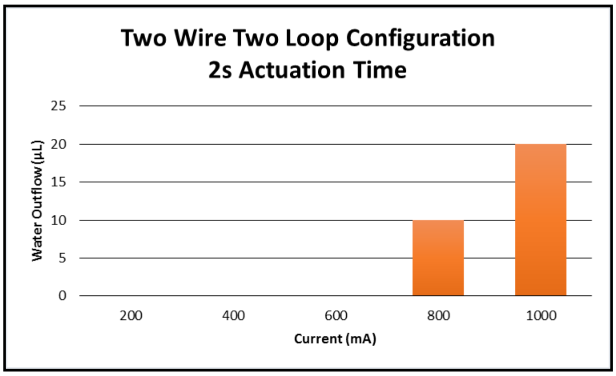

Fig 9.Two wire two loop SMA wire configuration pump at 1s actuation time

Fig 10 shows the experimental results obtained by applying the same currents as in Fig 8 and 9 to a four wire single loop configuration pump over a period of 1s, resulting in an increased level of water outflow over a calibrated scale on a syringe barrel at currents of 800mA and 1A.

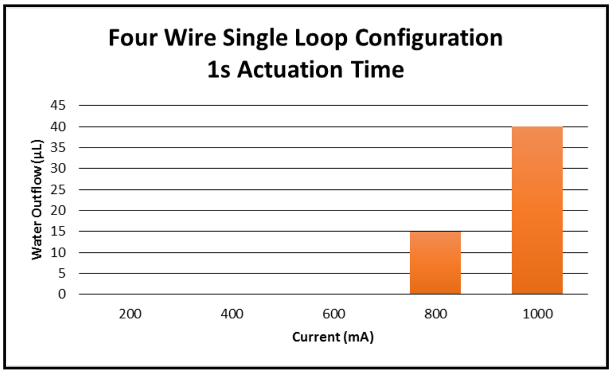

Fig 10.Two wire two loop SMA wire configuration pump at 1s actuation time

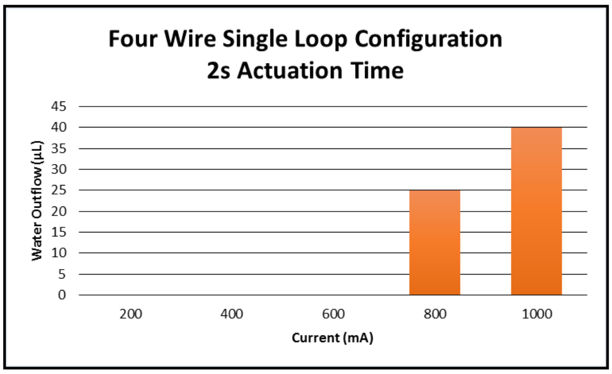

Fig11.Two wire two loop SMA wire configuration pump at 1s actuation time

The highest deformation of SMA wire actuators was found when the same array of current was applied for 2s actuation time on a four wire single loop configuration pump.In contrast to the 1s actuation time instance in Fig 11, water outflow increases by 10µL at 800mA while remaining unchanged at 1A.

4. CONCLUSION

A novel practical model for SMA wire actuated micro pump was proposed in this study. For the actuation periods of 1s and 2s, two designs with different configurations of SMA wires were investigated. In comparison to displacement of plunger produced at the same actuation current on two wire and two loop and four loop single wire pump, the results reveal that parallel design of SMA wires creates less deformation. It has been determined that as the number of loops increases, the deformation increases, resulting in a bigger water discharge. Implementation of proposed model have justified its practical application in pumps employed for injection of controlled drugs in body of humans.

5. FUTURE RECOMMENDATIONS

Only water was pre-filled in the syringe with in suggested study, but fluids of various densities might be examined.

Instead of prefilled water, an intake part for injecting material into the syringe can be provided and operated by a SMA wire actuation mechanism.

In the current design for monitoring rate of water outflow from syringe, the timing circuit can be developed taking into consideration the restoring time of SMA wire as limiting factor for repetitive actuation of SMA wire actuator.

6. ACKNOWLEDGMENTS

I, Muhammad Sajid Khan, am grateful to Mehran University of Engineering and Technology Jamshoro for providing complete lab facilities as well as guidance from renowned faculty members during my research.

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