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Friction Enhancement via Micro-Patterned Wet Elastomer Adhesives on Small Intestinal Surfaces

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Abstract. A micro-pillar based silicone rubber adhesive coated with a thin silicone oil layer is investigated in this paper for developing friction-based clamping mechanisms for robotic endoscopic microcapsules. These adhesives are shown to enhance the frictional force between the capsule and the intestinal wall by a factor of about 7 over the non-patterned flat elastomer material. In this study, tests performed on fresh samples of pig small intestines are used to optimize the diameter of the micro-pillars to maximize the frictional forces. In addition, the effects of other factors such as the oil viscosity and applied normal forces are investigated. It is demonstrated that the proposed micro-pillar pattern based elastomer adhesive exhibits a maximal frictional force when the pillar diameter is 140 μm and coated silicon oil has a very high viscosity (10,000 cSt). It is also found that the frictional force of the micro patterned adhesive increases nonlinearly in proportion to the applied normal force. These adhesives would be used as a robust attachment material for developing robotic capsule endoscopes inside intestines with clamping capability.

Keywords. Capsule Endoscope, Gastro-Intestinal Tract, Micro-Patterned Adhesives, Biomedical Adhesives, Microtribology.

1. Introduction

Recently, endoscopic microcapsules (pill cameras) have been widely used for non-invasive imaging and screening of small intestines which were not previously accessible by wired endoscopes [1]. However, capsule endoscopes have some limitations for their position control that inhibited a precise diagnosis of the intestinal diseases since its movement only depends on the peristaltic intestine motion and gravity. Therefore, a clamping or locomotive mechanism for a capsule endoscope has been proposed by many groups recently to control its position [2-5]. These robotic clamping and locomotion mechanisms rely on a reliable, non-invasive and strong attachment mechanism utilizing friction inside the small intestines which is a very challenging problem. Therefore, a robust and non-invasive attachment mechanism using beetle inspired oil coated micro-patterned elastomer adhesives is proposed in this paper for a capsule endoscope clamping or crawling inside small intestines [6].

Nature has evolved to develop sub-optimal repeatable attachment mechanisms for robust and agile locomotion on a wide range of smooth and rough surfaces. These mechanisms mainly use liquid coated or dry micrometer or nanometer scale foot-hairs using capillary adhesion and/or van der Waals type of intermolecular forces [7, 8], claws using mechanical interlocking, and suction pads using vacuum suction. For a device that operates inside the intestine where the inner wall is very rough (covered with micro-villi), compliant, and slippery (due to mucus secretion), micro/nano-hairs are proposed as a robust and non-invasive attachment material in this study. Previous studies have shown that beetles, flies, crickets, and cockroaches use foot-hairs a few microns in diameter covered with a carbon based hydrophobic oil [9, 10]. In all of these fibrillar adhesive mechanisms, the major principle at work is the increase of contact area with a given rough surface through compliant fibers as thin as possible with high density to enhance the adhesion and friction. These high aspect ratio and high density hairs necessitate relatively rigid hair biomaterials such as beta-keratin in order to have minimal hair matting. However, soft elastomer materials with very low aspect ratio micro-pillars have been found to produce a similar adhesion enhancement effect [11]. Due to its simplicity of fabrication and integration, these elastomer micro-pillars are chosen in this work.

In this paper we investigate many parameters that should be optimized to maximize the frictional force between the adhesive and the intestinal wall. A custom frictional force

measuring system is used to determine the effect of geometrical (diameter, height, and spacing of the micro-pillars) and non-geometrical (surface wetting condition, velocity, and normal force) parameters on the resulting friction.

2. Materials Preparation

2.1 Micro-Pillar Adhesive Patterns

Polydimethylsiloxane (PDMS, Sylgard 184, Dow Corning Inc.), a soft elastomer, is selected as the material of the micro pattern because PDMS can be easily fabricated and is biocompatible. A master mold is fabricated using the optical lithography technique with the photoresist SU-8 (SU-8 2100, MicroChem Inc.). The SU-8 is spin-coated onto a silicon wafer with a thickness on the order of 50-300 μm. The thickness of the SU-8 layer determines the height of the resulting micro-pillars. A transparency mask is sufficient to transfer the micro-hole pattern during the UV exposure step. The mask pattern consists of half inch square patches of hexagonally packed circles. The circles are varied in diameter from 50-200 μm, and in edge-to-edge spacing from 25-225% of the circle diameter. PDMS is then poured over these micro-holes, de-gassed in a vacuum chamber, and cured without heating to prevent cracking of the SU-8 mold. Finally, the PDMS is peeled off to fabricate micro-pillars with different density, aspect ratio and diameter. A representative sample of the resulting molded micro-pillars is shown in Figure 1.

In addition to the bare dry micro-pillars, silicone oil is used to coat the pillars similar to the adhesion mechanisms seen in beetles and crickets. Silicone oils with viscosities varying from 50 to 10000 cSt (Dow Corning Inc.) are spun onto a flat glass surface and the PDMS micro-pillars are pressed on to this thin oil layer, resulting in a uniform oil coating transferred on to the micro-pillars as can be seen in Figure 2.

2.2 Intestine Samples

Pig small intestine from a freshly slaughtered pig is used to have measurements close to *in vivo* small intestine surface and mechanical properties. The intestine is cut into sections about 15 cm long, cleaned with water, and stored in a pH 7.4 phosphate buffered saline solution (BP399, Fisher Scientific Inc.) to maintain tissue properties. Just prior to testing,

the samples are slit open lengthwise such that the inside lining of the intestine was exposed when laid flat.

3. Experimental Setup

For the performance tests of micro patterned adhesive, a customized friction measurement system setup which can measure the frictional force between the micro patterned adhesive and the gastro-intestinal surface is introduced. The overall system is shown in Figure 3. The measuring system can be simply divided into a test bench unit and control unit.

The test bench unit is manufactured as seen in Figure 4. First, the intestinal specimen is tightly clamped to the base and the micro patterned adhesive is attached to the bottom of the weight case. The weight case has a U-shape structure to avoid any edge effects and has a cavity in which weights can be added to increase the applied normal force. The weight case is connected with a string to a load cell (GSO-50, Transducer Techniques Inc.) as close to the base as possible to decrease any measurement error caused by rotational moment. The load cell is fixed on the motorized stage which is controlled by a precision linear actuator (CMA-25CCCL, Newport Inc.). When the load cell is moved by the stage, the string pulls the adhesive sample across the intestinal surface, transmitting the frictional force back to the load cell.

In the control unit of the Figure 3, the motorized stage is commanded through a motion controller (ESP300, Newport Inc.), which communicates via the serial port with C software running in a real-time Linux environment. This software also processes the force data from the load cell which first passes through a signal conditioner/amplifier (TMO-2, Transducer Techniques Inc.) before being converted to digital data by a 12 bit DAQ board (MIO board, National Instruments Inc.).

4. Experimental Results

Using the setup in Figure 3, friction of various micro-pillar adhesive patches with 13 x 13 mm^2 area are measured on pig small intestinal surface to determine the effects of geometric and non-geometric design parameters of the micro-pillar based adhesive on friction.

At first, the edge to edge spacing of the pillars is varied from 50% to 100% of the pillar diameter. As the result, while the sparsely distributed pillars (large spacing) display reduced friction, the higher density pillars resulted in similar friction. Next, the height of the pillars is varied from 60 to 300 μm, and it is observed that pillars with 60-150 μm height showed similar friction, while the pillars with more than 150 μm height exhibited a 15% decrease in friction due to the increased pillar compliance and bending which reduces and randomizes the effective contact area of the pillars. The velocity with which the stage pulled the adhesive across the intestinal surface is varied from 0.01 to 0.2 mm/s, and no correlation is observed with the resulting frictional force. Based on these results, a spacing of 75%, height of 125 μm, and velocity of 0.02 mm/s are selected for the remainder of the experiments.

4.1 Diameter Optimization

The diameters of the micro-pillars are varied from 50 to 200 μm in increments of 10 μm and the resulting frictional forces are measured. Each test is repeated 5 times with an applied normal force of 103.7 mN. Flat PDMS samples are also tested for comparison. The results are shown in Figure 5. A clear optimal point can be seen at 140 μm. At this diameter, the frictional force is about 58 mN, an increase by a factor of 3.5 over flat PDMS. The remainder of the tests uses this optimal diameter.

4.2 Silicone Oil Coating Effect

Various silicone oils with viscosities of 50, 200, 500, 5000, and 10000 cSt are coated on to the 140 μm diameter micro-pillars, and a normal force of 104 mN is applied. The experimental results are shown in Figure 6. It can be seen that higher viscosity results in an increased frictional force. When the viscosity of the silicone oil is 10000 cSt, the frictional force reaches 130 mN, around twice the value obtained with the dry micro-pillar adhesive patch. However, low viscosity silicone oils below 500 cSt result in similar frictional forces with the dry micro-pillars. Therefore, silicone oil with a high viscosity above 500 cSt is selected in this study. In addition, the oil viscosity should be selected by considering the biocompatibility and coating performance.

4.3 Preload Effect

Basic friction theory dictates that as the applied normal force increases, the frictional force must also increase. Normal forces in the range of 69-131 mN are applied to a

micro-pattern with all the previously found optimal parameters. The experimental results of the variation of normal force are shown in Figure 7. Friction force is a nonlinear function of preload which is different than macroscale friction on hard surfaces which has a linear relation. This nonliearity is due to the microscale friction which is a function of the material elasticity, viscous liquid layer shear, and microscale adhesion. Detailed modeling and analysis of this microtribological effect is a future study. In proposed clamping mechanisms [5], the applied normal force can be increased by the actuation force of the clamping device which is limited by the specific actuator output force, consumed power, and size and weight of the device. Therefore, these factors have to be considered during the design of the clamping device.

5. Conclusion

For clamping endoscopic capsule devices in small intestines, micro-patterned PDMS adhesives are proposed and the effects of the geometrical and non-geometrical parameters are investigated on the adhesive friction on fresh pig small intestines using a custom frictional force measuring. This study focuses on the optimization of the micro-patterned adhesive in order to maximize the frictional force for reliable clamping inside the small intestines. Through various intestine friction tests, an optimal diameter of the micro-pillars is found to be about 140 μm for given pillar spacing of 75% of the pillar diameter. In addition, both increased viscosity and increased normal force are found to raise the frictional force. With the same normal force, the micro-patterned adhesive with a 10000 cSt silicone oil coating resulted in 7 times the friction of a flat, dry PDMS sample. However, we have to consider that the viscosity of the silicone oil is limited by the coating uniformity, and the applied normal force of the micro-patterned adhesive is restricted by the actuation force of the clamping mechanism. Consequently, these micro-pillar based wet adhesives would be used to develop non-invasive and reliable clamping mechanisms for a robotic endoscopic microcapsule.

Acknowledgements

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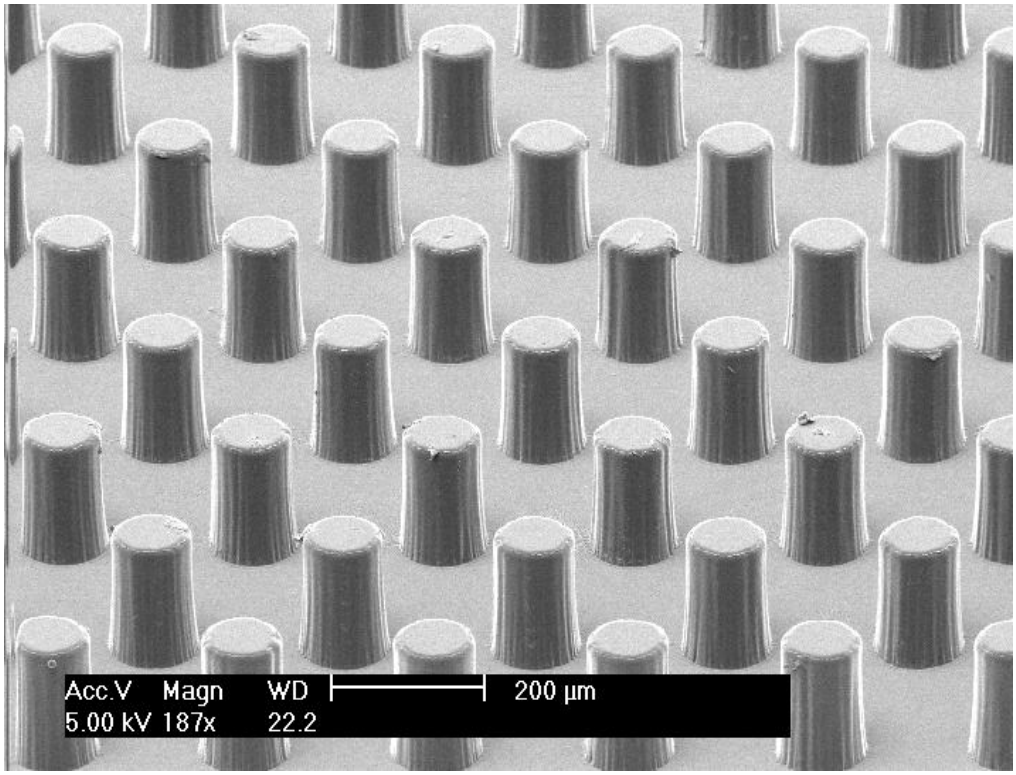

Figure 1. Scanning electron microscope micrograph of a sample PDMS micro-pillar array with around 100 µm diameter, 150 µm height, and 140 µm spacing.

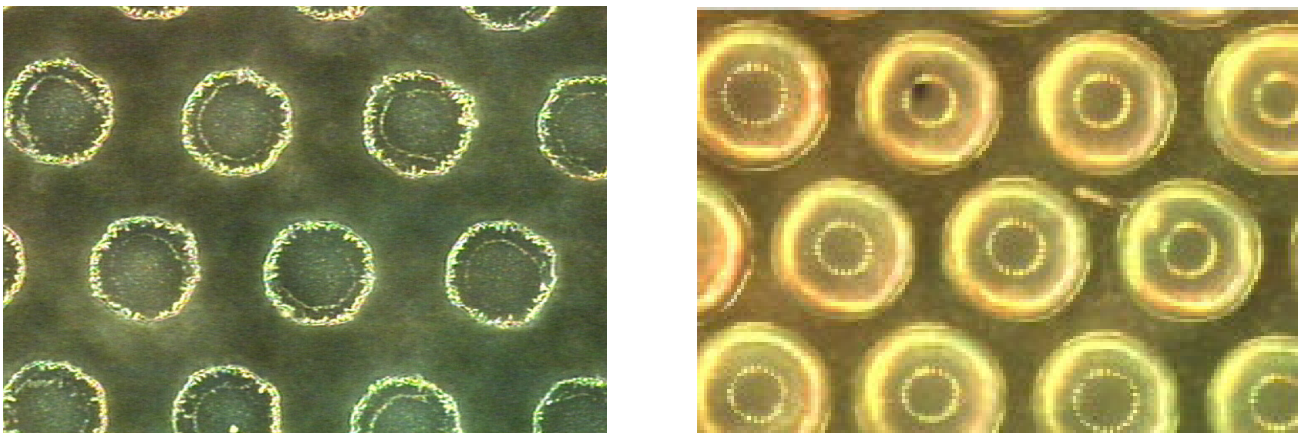

Figure 2. Top-view optical microscope image of the dry micro-pillars (left image), and top-view image of the silicone oil (10000 cSt) coated micro-pillars (right image) where the micro-pillars have 140 μm diameter, 125 μm height, and 75% (105 μm) spacing.

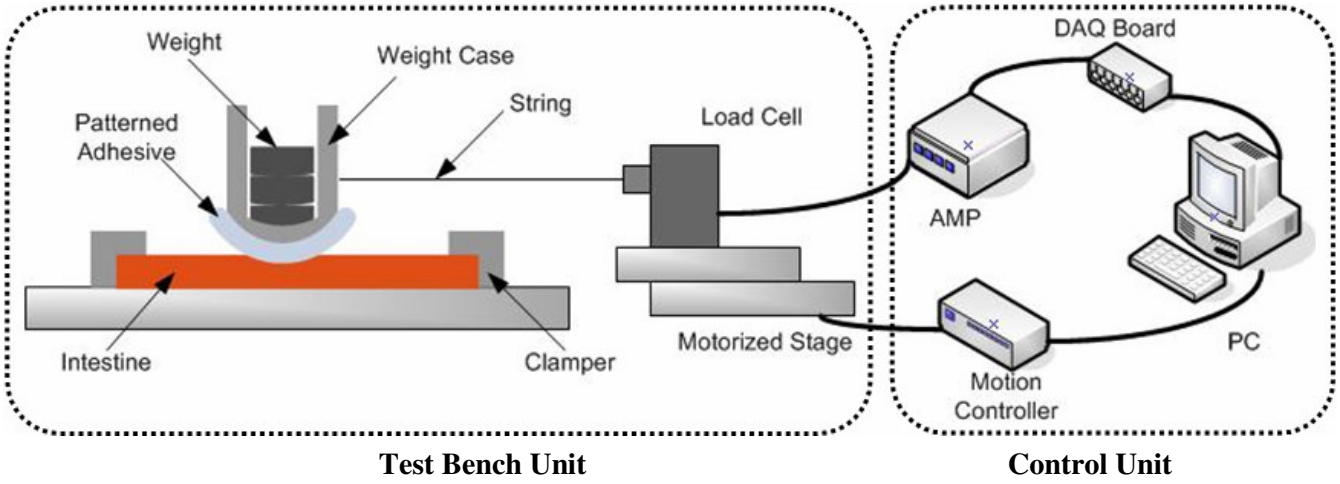

Figure 3. Schemetic diagram of the custom friction measuring system.

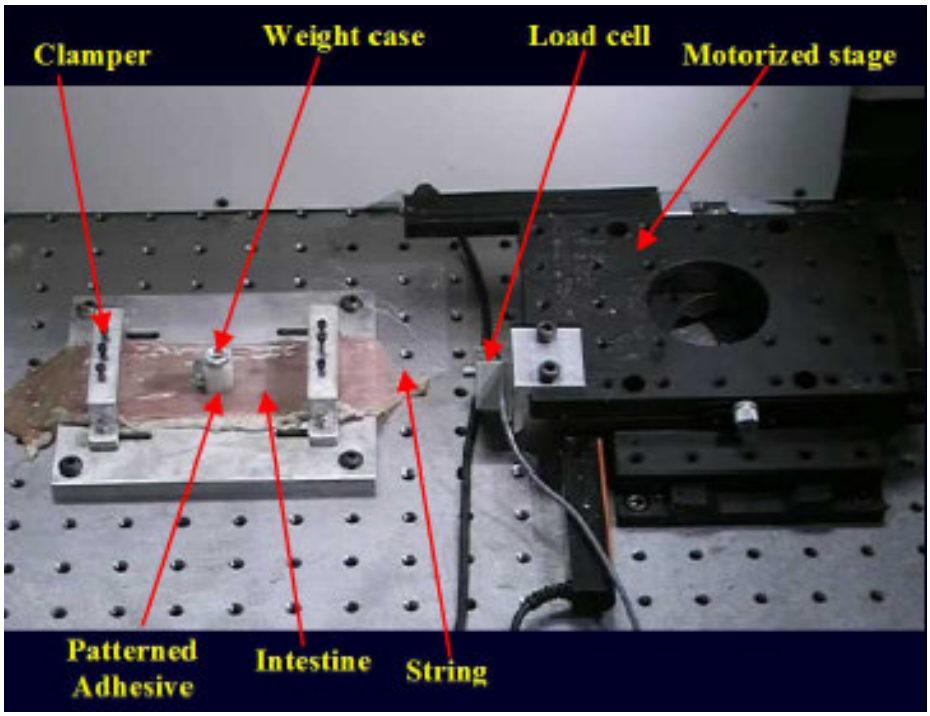

Figure 4. Photo of the custom intestine friction measurement system setup.

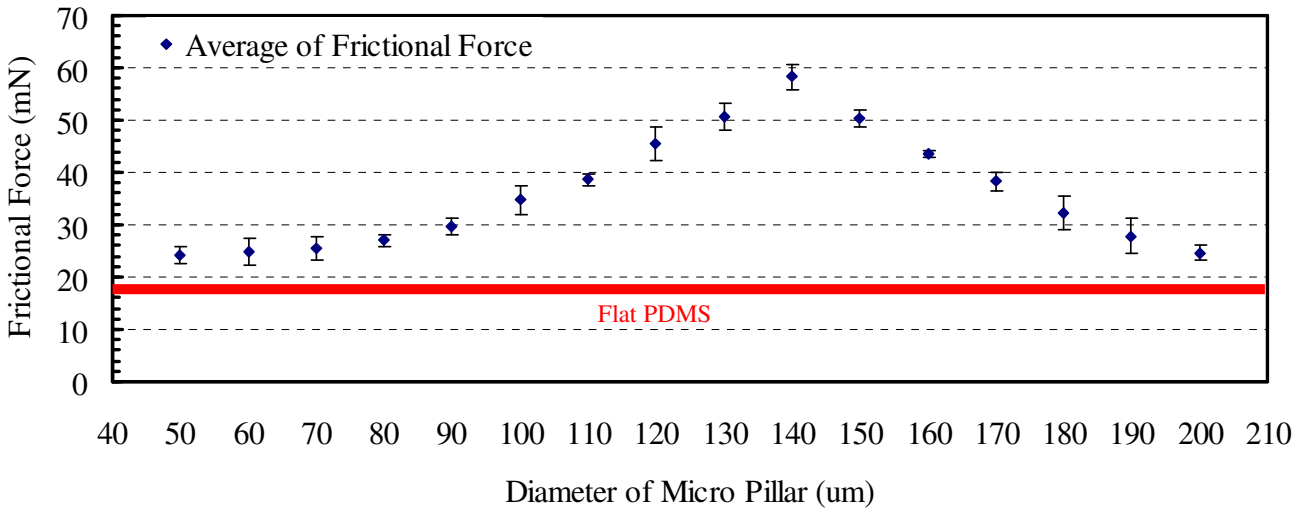

Figure 5. Effect of micro-pillar diameter on intestinal friction: Frictional force measurements for different diameter micro-pillar patches with 13 mm x 13 mm area, 125 µm height, spacing with 75% of the diameter size, 103.7 mN applied normal force, 0.02 mm/s stage velocity, and no silicone oil coating.

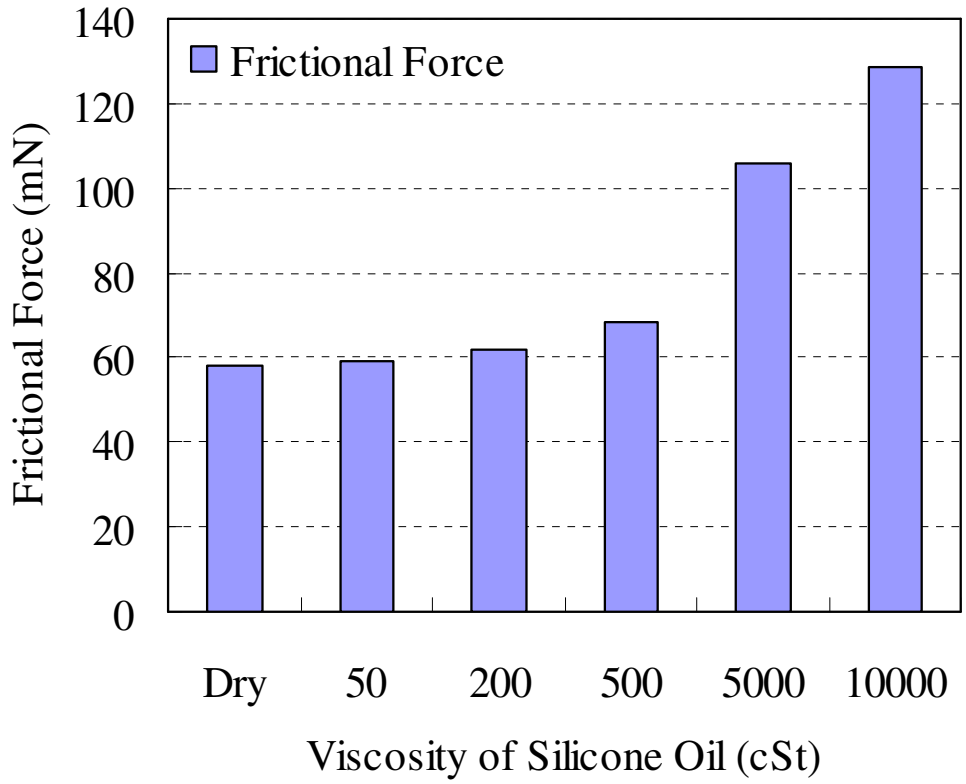

Figure 6. Effect of oil coating on intestinal friction: Frictional force measurements for 13 mm x 13 mm area micro-pillar patches with 140 μm diameter, 125 μm height, 75% (105 μm) spacing, 103.7 mN applied normal force, and 0.02 mm/s stage velocity.

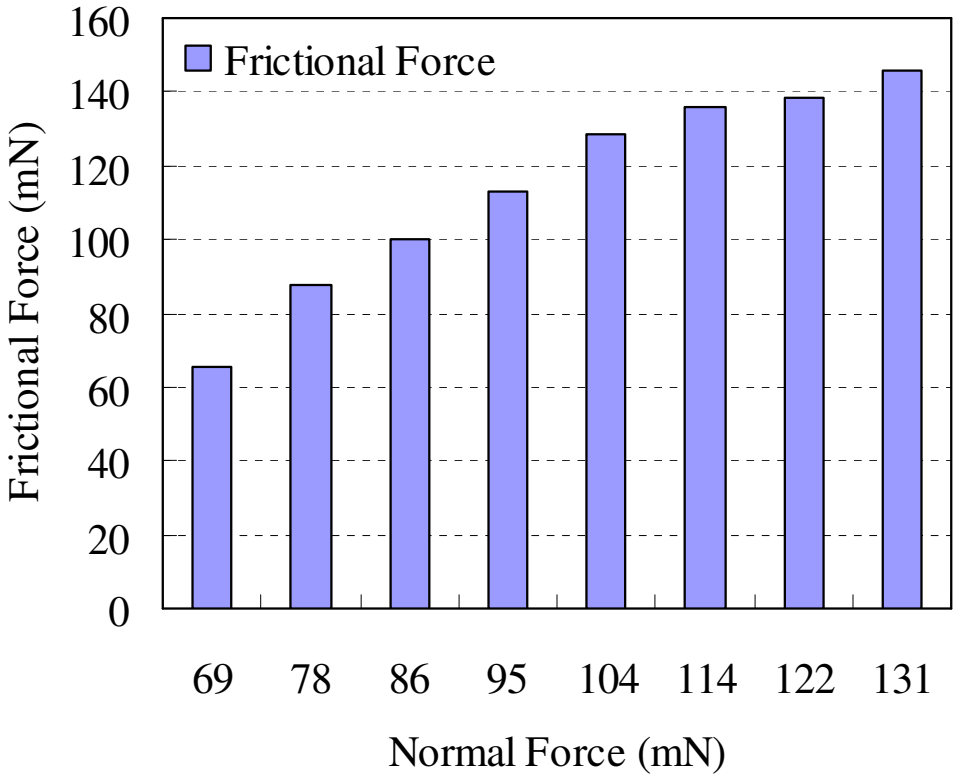

Figure 7. Effect of normal force on intestinal friction: Frictional force measurements for 13 mm x 13 mm area micro-pillar patches with 140 μm diameter, 125 μm height, 75% (105 μm) spacing, 0.02 mm/s stage velocity, and 10000 cSt silicone oil coating.