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Reduced Sliding Friction of Lubricant-Impregnated Catheters

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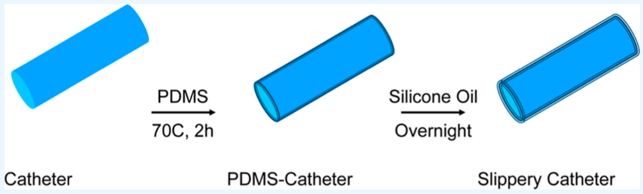
ABSTRACT: During urethral catheterization, sliding friction can cause discomfort and even hemorrhaging. In this report, we use a lubricant-impregnated polydimethylsiloxane coating to reduce the sliding friction of a catheter. Using a pig urethra attached to a microforce testing system, we found that a lubricant-impregnated catheter reduces the sliding friction during insertion by more than a factor of two. This suggests that slippery, lubricant-impregnated surfaces have the potential to enhance patient comfort and safety during catheterization.



INTRODUCTION

Approximately 15–25% of patients admitted to hospitals are indwelled with urinary catheters.[1,2] However, urethral catheters can cause discomfort or even injury. For example, 47–90% of patients experience catheter-related bladder discomfort; symptoms include a burning sensation, pain in the lower abdomen, muscle spasms, and a sense of urgency to urinate.[3−9] Another issue is catheter-associated urinary tract infections (CAUTIs), with more than 1 million cases occurring annually.[1,10−13] Discomfort and urethral injury can occur during insertion, especially for males (who have a longer urethra).[14] Long-term complications from urethral trauma can include strictures, incontinence, and infertility;[14] although rare, patient mortalities have also been reported.[15] The incidence rate for urethral trauma is about 0.3–1.3% of all catheters inserted; of those affected, over 80% had a complication that was Clavien-Dindo grade 2 or higher.[15−17]

There are two primary types of urologic catheters: intermittent and indwelling.[18−20] Intermittent catheters are inserted for just long enough to empty the bladder and then removed again, repeating the process multiple times per day.[21] Indwelling catheters are left in place after insertion, and urine is drained into a collection bag; a water-filled balloon holds the catheter in place within the bladder.[22] This latter type is also known as the Foley catheter, which was invented in 1929 by Frederic Foley.[1,23] For both types of catheters, several studies have compared the performance of uncoated versus coated catheters.[24−29] The most common choice is a hydrophilic polymer coating that becomes slippery when wet. Clinical studies have shown that the use of hydrophilic catheters significantly reduces the incidence of CAUTIs. It has also been demonstrated that catheters coated with hydrophilic polymers exhibit reduced surface friction, where the friction coefficient depends on the molecular weight of the selected copolymer.[30]

Pitcher plants are carnivorous plants that have modified leaves known as pitfall traps, a prey-trapping mechanism featuring a deep cavity filled with digestive liquid (Figure 1a).[31−33] The peristome enables the trapping of live prey, as it contains microridges impregnated with lubricant to render the surface ultraslippery.[34] Inspired by pitcher plants, researchers have engineered lubricant-impregnated surfaces (LIS) that are ultraslippery to immiscible test liquids.[35−38] To stably lock the lubricant in place, the surface is either micro/nanostructured[39,40] or highly absorbent.[41,42] Over the past decade, LIS have been shown to repel a wide variety of test liquids as well as exhibit antifouling,[43] antiscaling,[44] anti-icing,[45] enhanced condensation,[38] water harvesting,[46] and droplet sorting.[47]

Germane to the above topic of catheters, biomedical devices with LIS exhibit antibiofouling.[43,48−52] For example, a lubricant-infused polydimethylsiloxane (PDMS) coating was applied to polyurethane catheters to reduce biofilm formation by an order of magnitude for a flow culture of *P. aeruginosa*.[53] A follow-up study showed that lubricant-infused PDMS was highly resistant to *P. aeruginosa* and *S. epidermidis* biofilms, even under static conditions for days.[54] Using a flow culture bioreactor, another study showed a 10^3–10^4 reduction of bacterial cell density for lubricant-infused PDMS compared to conventional PDMS for *P. aeruginosa* growth.[55] However, to date, there are no studies of how urethral catheters with LIS affect the sliding friction during urethral insertion and withdrawal. Given that multiple reports measure a substantive reduction in drag for fluid flows over a LIS surface,[56−58] we

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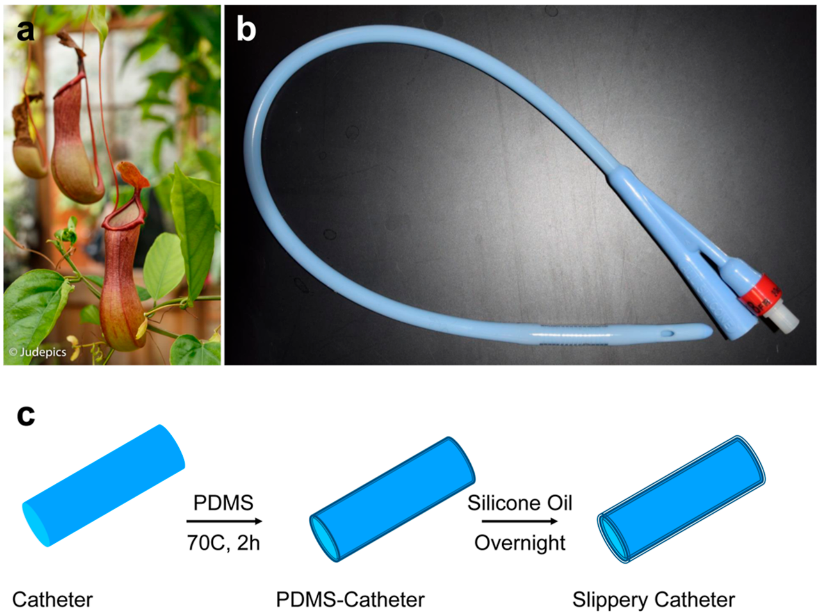

Figure 1. Lubricant-impregnated slippery surfaces are inspired by pitcher plants. (a) Pitcher plants exhibit a slippery surface for prey-trapping by impregnating a microstructured peristome with secreted nectar and rainwater. The photograph entitled "Pitcher Plant" is by Judith and is reprinted with permission under a CC BY-NC 2.0 Deed license, Copyright 2016. (b) Photograph of a Foley catheter, which passes through the urethra and into the bladder to drain urine. (c) Schematic of the fabrication process of lubricant-impregnated slippery surfaces on catheter tubes to reduce the sliding friction.

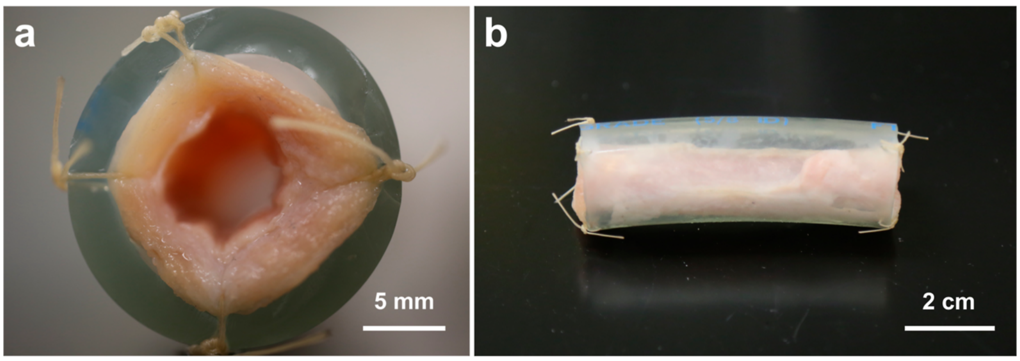

Figure 2. Photograph of the pig's urethra inside a tube. (a) Front view of the pig urethra inside the tube. (b) Side view of the urethra tube with a length of 7 cm.

hypothesize that LIS coatings also have the potential to reduce sliding friction during catheterization.

Here, we designed a LIS treatment for catheter tubes and measured the sliding friction during urethral insertion and withdrawal. The LIS treatment comprises a PDMS coating that was swollen with silicone oil (Figure 1c). The sliding friction was measured by inserting and withdrawing a catheter tube into a pig urethra fixed to a force transducer. Compared to the control case of an uncoated tube, the catheter with LIS decreased the sliding friction during insertion by more than a factor of 2. This indicates that LIS has the potential to substantively increase patient comfort and decrease the risk of complications during catheterization.

MATERIALS AND METHODS

Preparation of Pig Urethra Tubes. Test samples were prepared by sewing pig urethras within autoclaved tubes with an inner diameter of 15.875 mm (Figure 2a). The fresh urethra was cut from a deceased pig body and directly sewn into a tube in a veterinary laboratory at the Virginia-Maryland College of Veterinary Medicine. The urethra tubes were frozen to keep fresh, and thawed overnight in a refrigerator and rinsed with buffer solution (0.9% sodium chloride) before testing. Both the pig urethra and the autoclaved tube were approximately 7 cm long (Figure 2b). The pig urethra is physiologically comparable to the human urethra and is, therefore, a suitable candidate as a model system for study.[59,60]

Fabrication of Lubricant-Impregnated Tubes. Clear polyvinyl chloride (PVC) tubing (Finger Lakes Extrusion Corp., Flextubing 8870-4245) of inner diameter D_i = 3.175 mm and outer diameter D_o = 6.35 mm was cut into 10 cm-long test segments to mimic a catheter tube. The choice of 10 cm for the catheter tube length was to ensure that a significant portion of the tube could remain external to the urethra to keep it attached to the force testing system. The French size of a urethral catheter is 14−16 for adult men, 10−12 for adult women, and 8−10 for female pigs, where the French size is the diameter in millimeters multiplied by 3.[61] Each tube was rinsed with ethanol and deionized water, dried at room temperature, and treated with oxygen plasma (PlasmaEtch Inc., USA) to

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tailor surface characteristics and increase surface receptivity for the polymer coating. PDMS (Dow Sylgard 184) was prepared by mixing the silicone elastomer base with a silicone elastomer curing agent in a 10:1 ratio in a plastic container. The mixture was stirred for 5 min with a wood dowel and allowed to sit at room temperature until there were no appreciable bubbles remaining. Afterward, the plasma-treated catheter tubes were rinsed in the PDMS solution to obtain a uniform coating on the tube's exterior (the tube's interior was plugged). The PDMS-coated catheters were cured in an oven at 70 °C for a curing time of 2 h. As a result, only the outer surface of the catheters received the PDMS layer, which covalently binds the polymer surface with the PDMS coating (thickness of a few microns). To transform a dry PDMS coating into a LIS, a PDMS-coated tube was submerged overnight in a graduated cylinder containing 10 cSt (0.93 g/mL at 25 °C), 100 cSt (0.96 g/mL at 25 °C), or 1000 cSt (0.97 g/mL at 25 °C) silicone oil. After the tube was pulled from the oil bath, it was hung vertically for several hours to drip off any excess silicone oil. For PDMS submerged in silicone oil for 12 h, the mass swelling ratio is approximately SR ≈ 2.1 due to impregnation.[53] This large swelling ratio is because, in the presence of a chemically compatible solvent, the polymer chains of PDMS extend to maximize polymer−solvent interactions throughout the polymer matrix.[37,53,62]

Setup of the Sliding Friction Tests. A microforce testing system (MTS, Tytron 250) was used to measure the sliding friction between a pig urethra and a catheter. This Tytron 250 load unit works together with TestStar software and a force transducer, whose load capacity ranges from 1 mN to 250 N. Before a test, a frozen pig urethra tube was thawed overnight in a refrigerator. The urethra tube was rinsed with a buffer solution (0.9% sodium chloride, Irrigation USP) before any given trial. The rinsed urethra tube was placed on a fixed platform on the MTS containing the force transducer, and the catheter tube was placed on the opposing translation stage. The insertion and withdrawal processes were achieved using the software to translate the catheter tube at a fixed speed of 5 mm/s. The choice of 5 cm for displacement was to ensure that the front end of the catheter tube would not go beyond the end of the urethra tube during insertion. The friction as a function of displacement was captured by the force transducer and generated by the TestStar system software. Five different types of catheter tubes were tested, respectively: uncoated (U), a dry PDMS coating (PDMS), PDMS infused with 10 cSt silicone oil (LIS-10), PDMS infused with 100 cSt silicone oil (LIS-100), or PDMS infused with 1000 cSt silicone oil (LIS-1000). All silicone oils were purchased from Sigma-Aldrich. Three trials were carried out to calculate the averages and standard deviations.

■ RESULTS AND DISCUSSION

PVC tubing was used as a representative catheter tube material. Material choices for Foley catheters include silicone, latex, or PVC;[63] we elected to use PVC as it is also commonly used for intravascular catheters.[64] Also, the stiffness of the PVC tubing (relative to silicone) made it easier to install on the microforce testing system for repeatable insertion. Five different types of tubes were tested: uncoated PVC (U), a dry PDMS coating (PDMS), and PDMS coatings infused with 10 cSt silicone oil (LIS-10), 100 cSt silicone oil (LIS-100), or 1000 cSt silicone oil (LIS-1000). The dry PDMS-coated tube approximates the material of a silicone catheter, while three different silicone oils were tested to determine whether the viscous resistance of the lubricant affects the sliding friction. PDMS is a popular material choice for LIS because it is highly compatible with silicone oils in particular, and the hydrophobicity of PDMS minimizes the chances of water displacing the oil.[53]

A microforce testing system was used to measure the sliding friction between the pig urethra and catheter during insertion and removal. Figure 3 shows how the sliding friction measurements were obtained. Prior to insertion, the very tip of the catheter tube was manually placed at the entrance of the fixed pig urethra to ensure alignment. Subsequently, the MTS was actuated to induce linear insertion of the catheter at a fixed rate of 5 mm/s, followed by withdrawal at 5 mm/s. The total displacement in both directions was approximately 5 cm. Between trials for a given catheter type, the urethra was rinsed with a buffer solution. When switching to a different catheter type, an entirely new urethra was used to avoid cumulative tissue damage, conflating the comparison of tube performance.

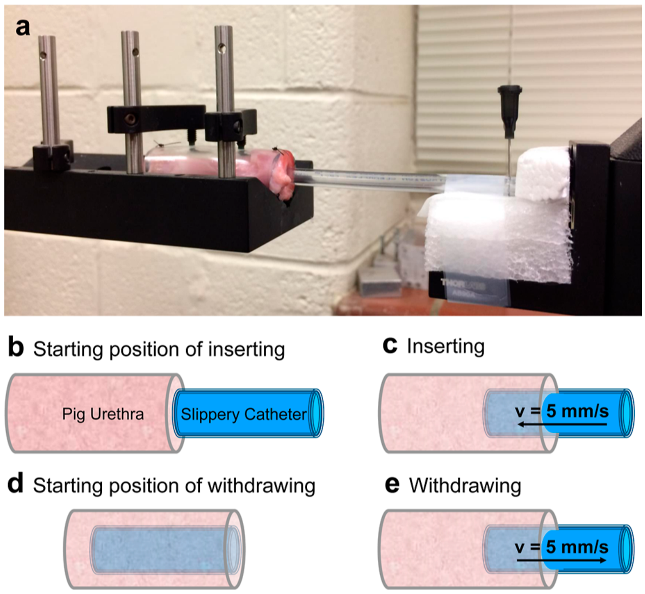

Figure 3. Sliding friction test between pig urethra tubes and catheters. (a) Photograph of the sliding friction measurement with the pig urethra and PVC tube fixed on the platforms. The platform with the pig urethra is static, while the platform with the PVC tube is inserted into the pig urethra and then withdrawn. (b) Initial insertion position of the pig urethra and PVC tube. (c) Inserting process with a speed of 5 mm/s. (d) Initial withdrawal position of the pig urethra and PVC tube. (e) Withdrawing process with a speed of 5 mm/s.

Figure 4a graphs the sliding friction as a function of the displacement during insertion. For the first half of the insertion process, the friction does not vary appreciably among the five types of catheter tubes. We expect that this is due to the leading edge of the catheter tube being the dominant source of friction early on. This is supported by the fact that the sliding friction almost instantaneously jumps to $F \approx 200$ mN at the beginning of insertion and only increases weakly with displacement. After a displacement of about 30 mm, the friction force doubles to $F \approx 400$ mN, indicating that the sliding friction from the catheter's surface area begins to outcompete that of the leading edge. Consequently, the curves diverge for all five types of catheter tubes as the surface area continually increases with continued insertion, exhibiting

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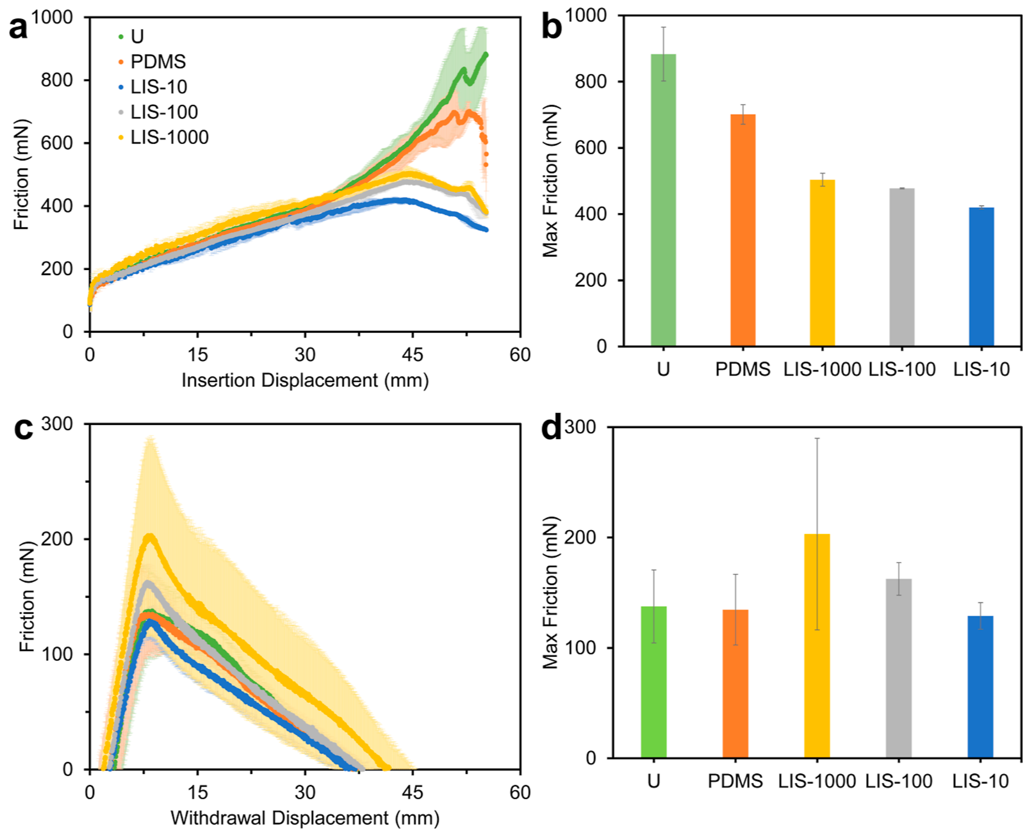

Figure 4. Sliding friction graphs for the insertion and withdrawal processes. (a) Friction of the insertion process as a function of the insertion displacement for different types of catheters. The insertion displacement is set to zero in Figure 3b. (b) Bar graph of the maximum friction during the insertion process. (c) Friction of the withdrawal process is a function of the withdrawal displacement for different types of catheters. The withdrawal displacement is set to zero in Figure 3d. (d) Bar graph of the maximum friction during the withdrawal process. All values represent the average of three separate trials, with error bars corresponding to the standard deviation.

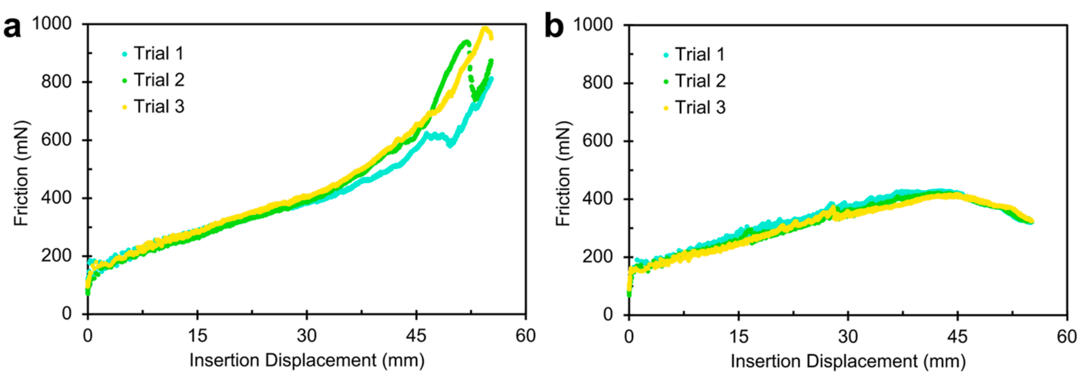

Figure 5. Sliding friction during catheter insertion, showing the variation across three trials on the same pig urethra. (a) For the uncoated (U) PVC catheter, the maximum friction increased from trial to trial. (b) In contrast, the lubricant-impregnated catheters show minimal trial-to-trial variation in maximal sliding friction, as shown here for the LIS-10 catheter.

markedly different maximal friction values by the end of the insertion process, where the friction force is maximal.

The maximal friction force for each type of catheter surface is compared in Figure 4b. As expected, the uncoated tube exhibited the highest maximal friction force compared to the other tubes (F_U = 880 ± 80 mN, n = 3 trials). The catheter with the dry PDMS coating was slightly better, with F_{PDMS} = 700 ± 30 mN, due to PDMS being softer than PVC. The Young's modulus of PVC is approximately 3.4 GPa, compared to only 2.85 MPa for PDMS using a 10:1 cure ratio.[65,66] The lubricant-infused PDMS coatings performed markedly better with $F_{LIS\text{-}10}$ = 420 ± 5 mN, $F_{LIS\text{-}100}$ = 478 ± 2 mN, and $F_{LIS\text{-}1000}$ = 500 ± 20 mN. The two key takeaways are that LIS catheters roughly halve the sliding friction of dry catheters and that the slipperiness of the LIS catheters improves weakly with decreasing lubricant viscosity.

Figure 4c graphs the sliding friction versus displacement for the reverse process of catheter withdrawal from the urethra. The friction curves readily increase with displacement during the initial 10 mm withdrawal and are independent of the catheter type. Both of these facts suggest the dominance of the receding edge in generating friction during early withdrawal.

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The curves then diverge weakly as they peak around 15 mm displacement, followed by a smooth decrease to zero friction as the withdrawal is completed. It follows that the friction of the catheter's surface area becomes dominant at the peak of each curve, such that F decreases linearly for the remaining withdrawal.

Finally, the maximal friction force during withdrawal is graphed in Figure 4d for each catheter type. The LIS-10 catheter still exhibited the smallest friction of $F_{LIS\text{-}10} = 129 \pm 12$ mN. Surprisingly, LIS-1000 featured the highest maximal friction of $F_{LIS\text{-}1000} = 200 \pm 90$ mN, compared to $F_U = 140 \pm 30$ mN, $F_{PDMS} = 130 \pm 30$ mN, and $F_{LIS\text{-}100} = 162 \pm 15$ mN. However, when considering the much larger error bars of the friction measurements during withdrawal, there is no obvious difference between the catheter types. Further, these maximal friction values for withdrawal are substantially smaller than for insertion, in some cases by nearly an order of magnitude. It is, therefore, only for insertion and not for subsequent withdrawal that LIS catheters seem to have the potential to reduce patient discomfort and injury. The general trends shown in Figure 4, of a two-step friction force during insertion (insertion-dominant followed by a kinetic area-dominant) and a much weaker force during withdrawal, are consistent with a recent report.[65]

For the noninfused catheters only, the sliding friction consistently increased when iterating across the three trials with the same urethra sample. This can be seen in Figure 5a, where the maximum friction force was $F_U \approx 800$ mN for trial 1 but increased to $F_U \approx 1000$ mN by trial 3. In contrast, there was minimal trial-to-trial variation for the infused catheters, where the maximal friction was only $F_{LIS\text{-}10} \approx 420$ mN for every trial (Figure 5). The trial-to-trial increase in the sliding friction for the PVC catheter strongly implies cumulative tissue damage, whereas the consistent and low sliding friction of the LIS catheter implies minimal tissue damage.

The high-purity silicone oil impregnated in the catheters should be safe. Silicone is widely used in the medical sector due to its high biocompatibility and desirable clinical performance.[67] For example, the safety of breast implants involving silicone has been demonstrated to be nontoxic by the National Institutes of Health.[68] As discussed earlier, medical tubing infused with silicone oil has the added benefit of lower bacterial attachment to reduce the chances of bacterial infections.[53] If desired, the concept of reducing sliding friction with lubricant-impregnated urethral catheters should also extend to other choices of biocompatible working fluids (ex: perfluororodecalin).[51] Durability tests were not possible in the present study; however, it is well-known that the ultralow contact angle hysteresis of lubricant-infused PDMS is stable for many days even under rugged conditions.[53,69]

■ CONCLUSIONS

We have shown that a lubricant-impregnated coating reduces the sliding friction of a catheter, complementing its antibiofouling capabilities that have already been demonstrated.[53] By infusing PDMS coatings with silicone oil, we designed lubricant-impregnated catheter tubes that decreased the sliding friction during urethral insertion by more than two times compared to an uncoated PVC catheter tube. Measurements were obtained by sewing a fresh pig urethra within a supporting tube, fixing the sample to a force transducer, and inserting an opposing catheter at a fixed translation rate. While decreasing the viscosity of the lubricant did weakly decrease the sliding friction, all LIS catheters performed dramatically better than an uncoated catheter. The catheter type did not appreciably affect the friction of withdrawing the catheter, but this is less important as the sliding friction during withdrawal was substantively less than insertion anyway. Fruitful avenues for future research could include testing noninfused versus infused catheters comprised of pure silicone or latex (rather than PVC or PDMS-coated PVC), clinical trials to quantify the real-life increase in patient comfort and decrease in complications, and imaging the urethra postinsertion to correlate the differences in friction and trial-to-trial variation with the extent of internal damage. It would also be interesting to quantify the relationship between friction reduction and biofilm development.

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Notes

The authors declare no competing financial interest.

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