In vitro testing of an artificial muscle for the treatment of incontinence

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ABSTRACT

The burden of incontinence is profound, affecting individuals both physically and emotionally. Treatment pathways typically progress from conservative measures to surgical interventions, sometimes culminating in the implantation of artificial sphincters. The existing models including the AMS 800™ show high revision rates. Complications such as tissue erosion further underscore the need for innovation in this field. Here, we propose an approach utilizing Hydraulically Amplified Self-healing Electrostatic (HASEL) actuators to develop an advanced artificial urethral sphincter. By employing HASEL actuators arranged in a cuff configuration, we aim to address the limitations of current devices. Initial in vitro testing on porcine urethrae has shown promising results in controlling the water flow at a hydrostatic pressure of 20 cmH_2O, demonstrating the feasibility to mimic sphincter function. This approach holds potential to significantly enhance the quality of life for patients suffering from incontinence as they regain control over their bodies. Further research and clinical trials are warranted to validate the efficacy and safety of this approach.

Keywords: artificial muscles, fecal incontinence, urinary incontinence, biomedical engineering, hydraulically amplified self-healing electrostatic (HASEL) actuator

1. INTRODUCTION

1.1 Challenges in treating severe incontinence

The lives of individuals struggling with incontinence are profoundly impacted, enduring not only physical discomfort such as pain[1] but also grappling with emotional burdens including shame, social isolation,[2] and often depression.[3,4] Treatment pathways typically commence with pelvic floor exercises, progressing to adjustable sling systems for mild to moderate cases, and as a last resort, resorting to artificial sphincter implants for severe instances.[5] Throughout this treatment journey, absorbent pads serve as a necessary companion. The toll of caregiving for those managing incontinence is immense, leading to both physical and emotional exhaustion. Such strain can even culminate in instances of abuse.[6] Private caregivers, often family members, confront analogous challenges, frequently reporting physical discomfort such as back and joint pain, as well as disruption of their social lives.[7] In the pursuit of enhancing the well-being of both patients and caregivers, there is a pressing need for the development of advanced artificial sphincters. While the current model, AMS 800™, has demonstrated efficacy, it is with limitations.[8,9] Surgical intricacies and the high rates of re-operation, which can soar up to 30%,[10–12] are notable concerns. Complications such as tissue erosion, possibly stemming from prolonged pressure significantly contribute to device failures.[10,13–15]

Evolving artificial sphincter technology would not only decrease reliance on absorbent pads, thereby facilitating planning for caregivers and saving time,[5] but also hold promise in improving the overall quality of life for patients. Despite the strides made with AMS 800™, its dependence on hydraulic mechanisms and the necessity for frequent surgical interventions underscore the critical need for innovation in this field.[16] This applies to

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urinary incontinence as well as fecal incontinence. Success in advancing artificial sphincters lies in minimizing complications and maximizing longevity, offering a ray of hope for patients and lightening the burdens borne by caregivers. The use of HASEL technology could enable an implant that is compact to implant, adapts to the changing pressure conditions in the body and can be controlled very easily and patient-oriented from a mobile device such as a cell phone or smart watch (Fig. 1). HASEL actuators are pouches out of a dielectric flexible

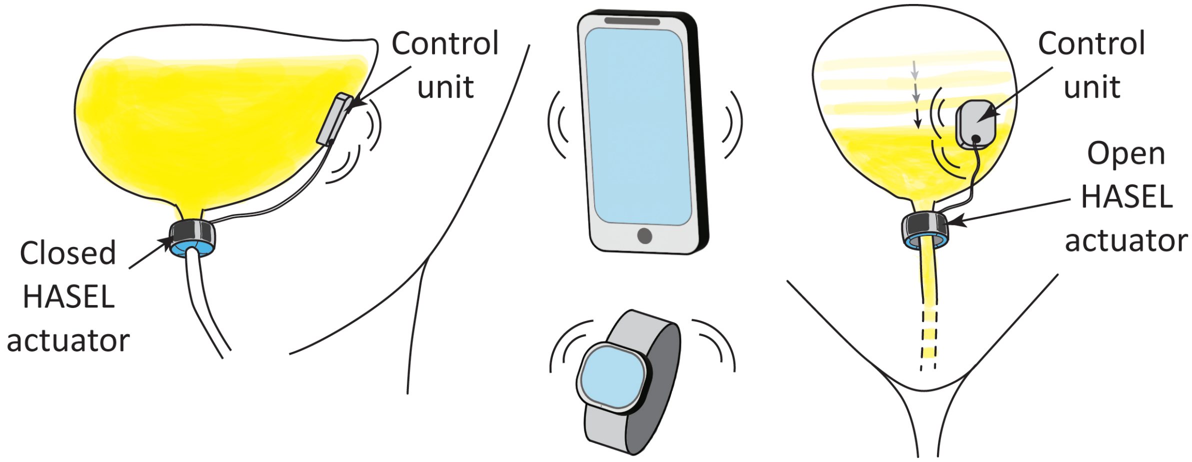


Figure 1. Concept visualization: The HASEL artificial urethral sphincter is characterized by the incorporation of a cuff that is controlled by a unit in the abdomen. This cuff, reminiscent of conventional artificial sphincters, exerts pressure to effectively prevent urine leakage and provides rapid adaptability to allow micturition. Furthermore, the integration of wireless communication enables additional functions that promote improved operation by doctors and patients.

material filled with dielectric fluid with electrodes on two opposite sides, which usually cover around 50% of the pouch area. If a voltage is applied to these electrodes they start to attract each other. An increase in voltage leads to continuous closing of electrodes and thus to the continuous deformation of the fluid-filled pouch resulting in a change of length and width.[17] That means HASEL actuators are inherently compliant and directly convert electrical into mechanical energy through electromechanical coupling,[18] reaching an energy efficiency of about 20%,[19,20] maximum strain between 15% and 24%, and blocking force up to 18 N to 45 N,[20,21] and a peak specific power comparable to mammalian muscle.[17,20]

1.2 Sphincter devices

Research into the development of artificial sphincters has been ongoing for decades,[22] aiming to address the limited treatment options available for a diverse range of incontinent patients. Various mechanisms have been explored, including magnetic attraction, elastic spring forces, hydraulics, self-expanding materials, shape memory alloys, and electromotive closing mechanisms.[23] Among the commercially available artificial sphincters for fecal incontinence treatment are the hydraulic implant Acticon Neosphincter, which received FDA approval in 2001,[24] the prosthetic anal system (PAS),[25] and A.M.I. Soft Anal Band.[23] In the realm of urinary incontinence treatment, the AMS 800™ stands out as the gold standard.[26] It comprises a silicone-rubber device featuring an occlusive cuff, a manual pump, and a pressure-regulating balloon.[23] The Zephyr ZSI 375 artificial urinary sphincter, comparable to the AMS 800™, utilizes a dedicated, manually driven pump unit instead of a pressure-regulating balloon.[23] There are several attempts with limited progress to realise artificial sphincters on the basis of electroactive polymer actuators and devices, see e.g.[27–36] So far, HASEL technology has not been considered for the implementation into artificial sphincters for severe incontinence treatment. Therefore, the present study focuses on the HASEL principle for artificial muscles with the aim to demonstrate feasibility.

2. METHODOLOGY

2.1 Device design

A cuff consisting of four pouches was designed for the use of HASEL actuators in the treatment of incontinence. The pouches are connected to each other in such a way that the parts covered with electrodes is directed outwards and only the pouch parts without electrodes make up the cuff circumference itself (Fig. 2). If no voltage is applied, the cuff lies loosely around the hollow organ. As soon as a voltage is applied, the dielectric liquid in the pouches is forced from the outward facing part of the cuff inwards due to the zipping of the electrodes. This closes the hollow organ and stops liquid from passing through. This concept achieves an even greater reduction in diameter during activation than, for example, a conventional circularly arranged peano HASEL. To ensure problem-free actuation, electrodes on top of each other/opposite each other are connected alternately either to the high electric potential or to ground. Furthermore, a short extension of the pouch at the end of the electrode area serves as a buffer to prevent a short circuit.

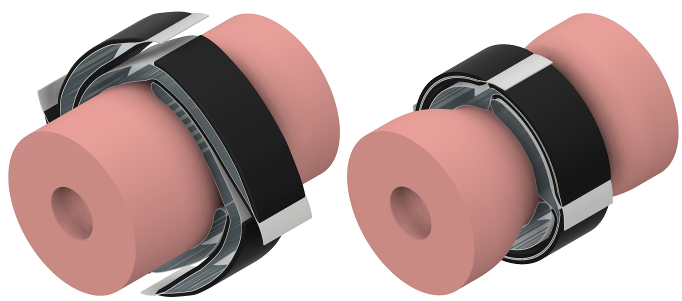


Figure 2. Device design model: The flexible artificial muscle is wrapped around the hollow organ. In its uncontracted state, the urethra remains open to enable the passage of fluid. Upon application of voltage, the opposing electrodes (depicted in black) are attracted to each other, inducing the movement of the dielectric liquid within the HASEL pouches. This results in both a shortening and thickening of the Cuff, thereby exerting pressure and causing closure of the urethra.

2.2 HASEL manufacturing

HASEL actuator pouches were 35 mm in width and 25 mm in height. The electrode area was approximately 35 mm by 16 mm, therefore covering 56% of each pouch side. Note that an area of approx. 35 mm by 2 mm of each electrode surface was painted beyond the oil-filled area to ensure a zipping start during actuation. In order to achieve the desired overlap of the pouches, the cuff was assembled through heat-sealing two biaxially-oriented polyethylene terephthalate films (Mylar 850, 15 μm, Mylar specialty films, USA) to each other manually with a soldering iron at approx. 230°C. Following the manual sealing of the initial lines, the top sheet was carefully folded along the designated folding lines, as depicted in Fig. 3, ensuring the even alignment of all sections of the film atop one another.

In a second step the outlines of the pouches including filling ports were heat sealed at approx. 255°C with a repurposed 3D printer as a three-axis CNC heat sealing machine (Fig. 4b)) similar to the way it was developed and demonstrated by Mitchell et al.[37] For all heat sealing procedures a 25-μm Kapton film was placed over the Mylar sheets to prevent excessive melting of the polymers and to ensure an even heat transfer to the sheets. The already mentioned extension areas of the pouches for preventing short circuits were also sealed by hand. After that, the electrodes were painted with Carbon Paint (Ted Pella, Inc., CA, USA). Filling ports were dimensioned to result in a width of 1.4 mm after heat sealing. HASEL pouches were each filled with 1.4 ml of silicone oil (M5, low-viscosity, Carl Roth GmbH + Co. KG, Karlsruhe, Germany) using a peristaltic dispensing pump before being finally sealed with a soldering iron. Afterwards, the pouch extensions were reinforced with standard adhesive tape to prevent the start area of the zipping fronts from being kinked. Wires were soldered to copper tape and then attached to the electrode surfaces. Four holes were punched on each side of the open cuff through which the cord was later pulled to close the cuff using punch pliers.

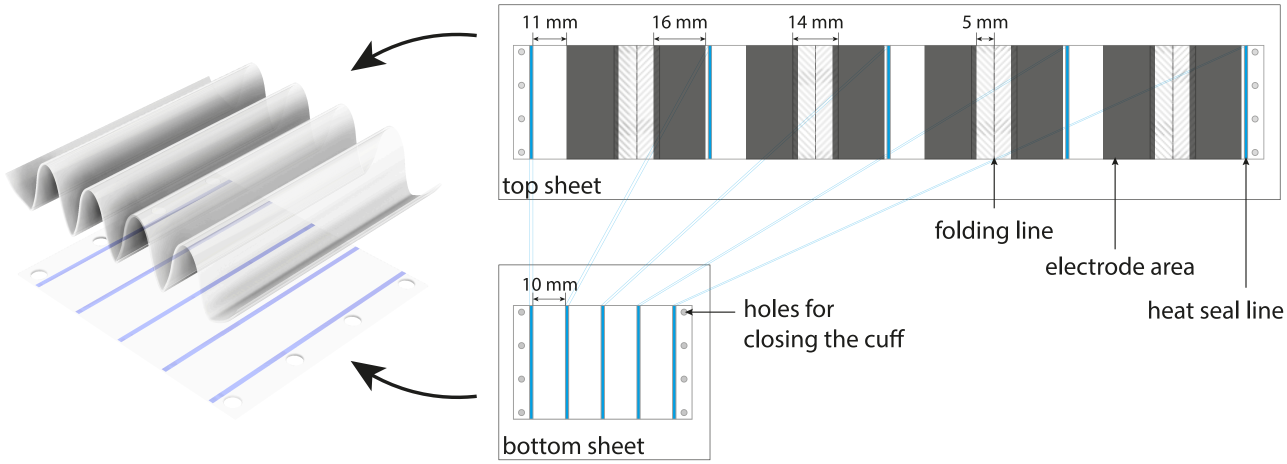


Figure 3. Layout of the Mylar sheets required to assemble the Sphincter. Blue lines show the first heat seal lines, which are created manually. The areas where the electrodes will be painted on later are shown in dark gray. The hatched areas are also heat sealed in subsequent steps and serve as protection against short circuits.

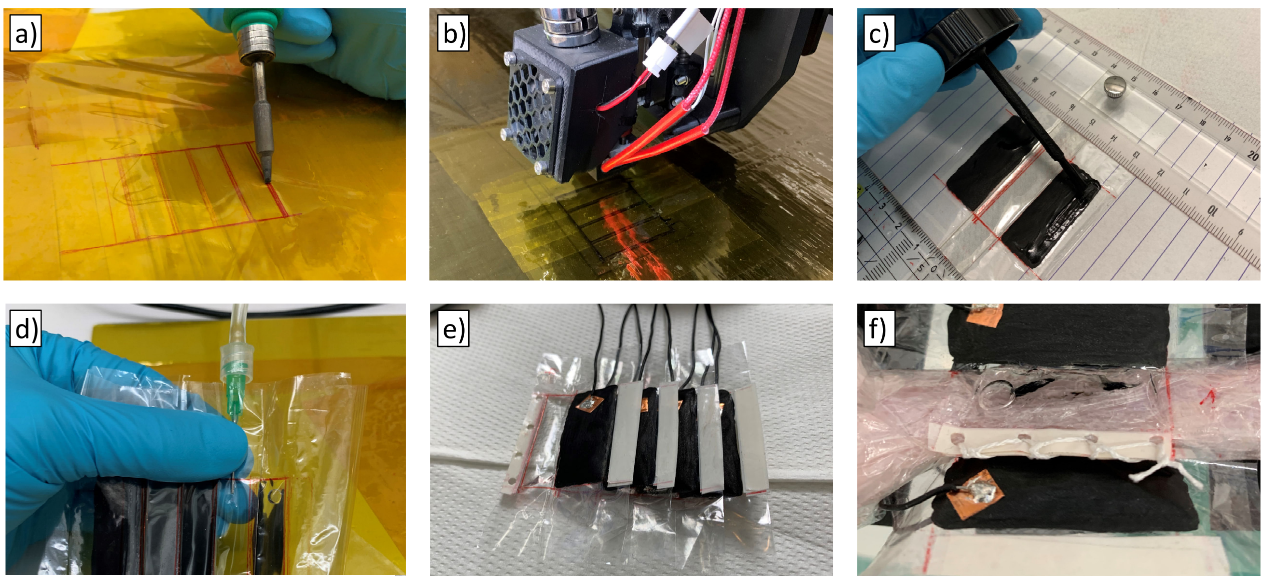


Figure 4. Step-wise manufacturing of HASEL sphincters: a) The first seal lines are made manually with a soldering iron, b) Outlines of the pouches and filling ports are heat-sealed via CNC machine, c) Electrodes are painted with carbon paint, d) Pouches are filled with silicone oil via the filling ports, e) Wiring of the electrode areas and reinforcement of the pouch end sections were attached, f) The cuff was tied around an explanted porcine urethra.

2.3 In vitro testing

Fresh porcine urethrae (domestic pig) were stored in saline solution at approximately 8°C. Saline solution was changed every two days. We adapted the method shown by Marti et al.[38] to imitate the bladder pressure in human bodies, usually termed intravesical pressure, with a hydrostatic pressure. From a physiological point of view, the sphincter must exert sufficient force to maintain continence. This force results in an external pressure acting on the urethra from the outside.[38] A cylindrical water reservoir was connected to a porcine urethra via a faucet. With a transparent tube connected to the water reservoir it was possible to monitor the hydrostatic pressure during experiments. In the following tests, the urethra of a female domestic pig was used as a experimental model. The urethra was still attached to the bladder and exhibited dimensions approximating a length of 75 mm extending from the bladder neck to its outlet, with a circumference measuring approximately 34 mm, see Fig. 5b). The remaining part of the bladder was secured to the outlet of the faucet with cable ties, allowing the urethra, including the bladder neck, to be freely movable. To prevent the urethra from hanging down, it was placed on two support arms, each 2 cm wide. For safety reasons, the urethra was then loosely wrapped with cling film. It can be presumed that this had no significant influence on the mechanical properties of the urethra. Subsequently, the cuff was tied around the urethra with thin rope (DC40 Dyneema SK75, Liros GmbH, Niederstotzingen, Germany) and connected to a high-voltage amplifier (20/20C, Trek, Inc., New York, USA). When connecting the wires, it was ensured that the electrodes, which are opposite each other and only separated from each other by the ambient air (i.e. one electrode from each of two different pouches), were connected to the same potential. After opening the faucet, an unipolar ramped (100 kV/s) repeating impulse signal with a maximum of 6 kV was generated to periodically actuate the HASEL cuff. The hydrostatic pressure amounted to approx. 20 cmH_2O (∼20 mbar) by the time the voltage was applied.

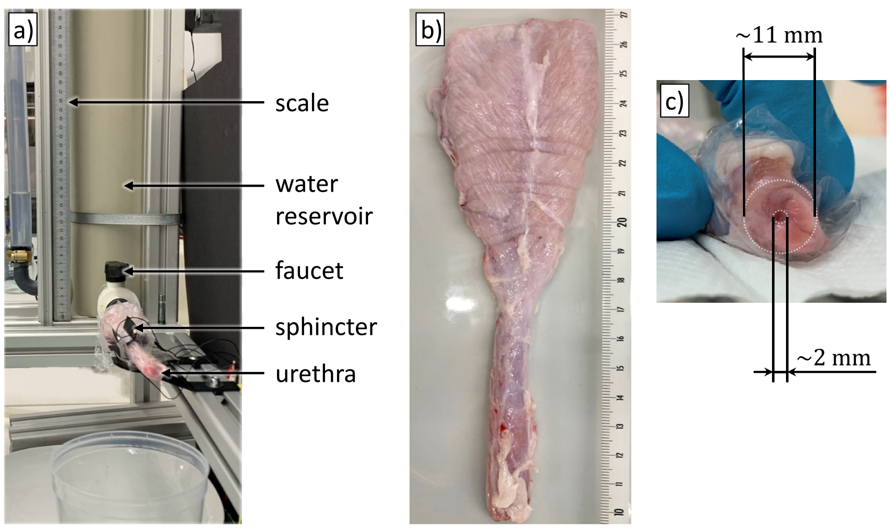


Figure 5. a) Experimental setup for in vitro testing of the HASEL sphincter with an explanted porcine urethra consists of a water-filled cylinder with faucet. The hydrostatic pressure simulating the bladder pressure can be monitored via a transparent tube next to a scale. b) Female domestic pig urethra used for experiments. c) Approximate outer and inner diameter of the urethra shown in b).

3. RESULTS

By arranging the HASEL pouches in an overlapping manner, it is possible to create a cuff that allows for space-saving and efficient reduction in diameter. The choice of pouch number is limited in that it has to be an even number. The reason for this is that in this configuration the electrodes of different potentials must always be separated from each other by the polymer layer. A cuff with four pouches as it is shown in Fig. 6 exhibits a satisfactory stroke for the desired application of incontinence treatment. The in vitro tests on porcine urethrae demonstrate that it is possible to imitate a sphincter muscle with a cuff consisting of HASEL actuators. As can be seen in the following video frames (Video 2), the water flow is stopped at a hydrostatic pressure of 20 cmH_2O (∼20 mbar). The power consumption of HASEL actuators is maximal a few Watts for a duration of a second, i.e. about 1 J or even less is necessary for actuation. These actuators can be regarded as a leaking capacitor. Yoder et al.[39] have measured the power consumption of a very similar device (BoPET-HASEL) and found 0.44 J to charge the actuator. To hold the contraction, a power of 0.94 mW was required. Assuming similar functionality for the electrode surface area of 22.4 cm^2, one finds for the present device 0.06 J per contraction (charging the actuator). A power of 130 mW is necessary to keep the actuator in contracted state.

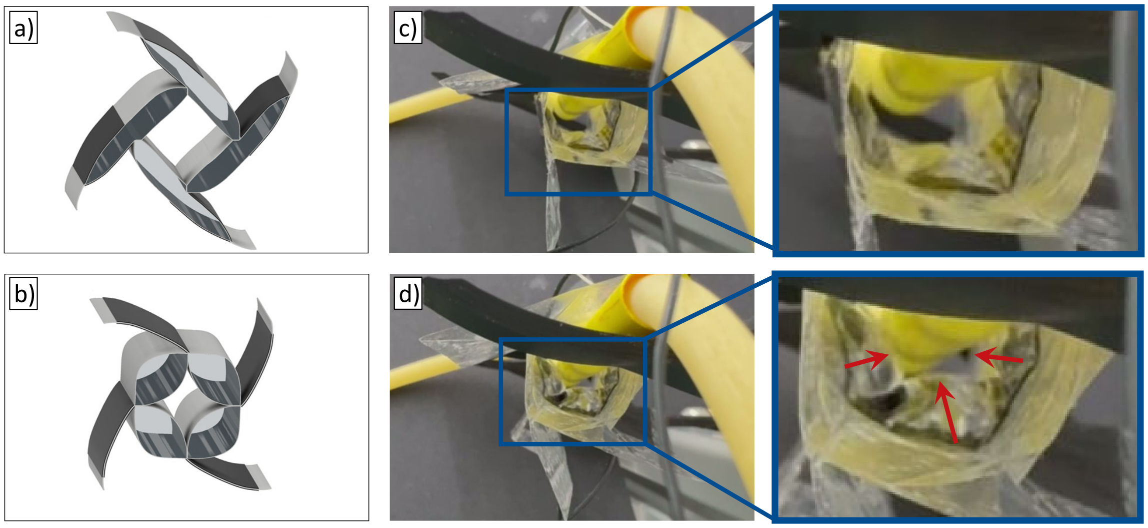
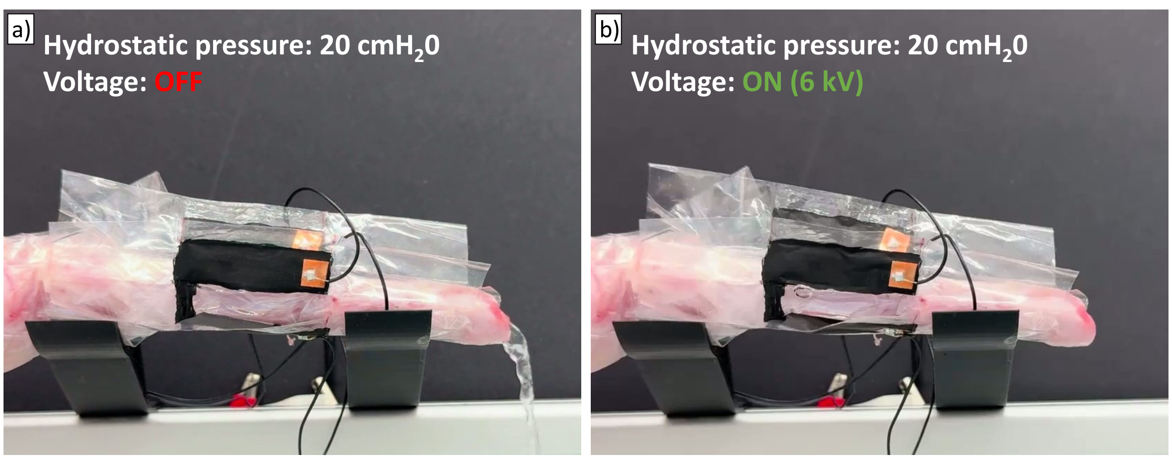


Figure 6. (Video 1) Deformation behavior of the actuator from relaxed state (top row) to actuated state (bottom row). Vizualizations in a) and b) show a CAD-generated model. Video frames in c) show HASEL cuff loosely wrapped around a tube and in d) when a voltage of 6 kV is applied. http://dx.doi.org/10.1117/12.3012817.1



Video 2. Showing the sphincter loaded with a hydrostatic pressure of 20 cmH_2O. a) The voltage is off, the HASEL sphincter is relaxed and the water can pass through the urethra. b) A voltage of 6 kV is applied to the electrodes, the HASEL sphincter is actuated and the water flow has been stopped successfully. http://dx.doi.org/10.1117/12.3012817.2

4. DISCUSSION

To achieve better treatment options for both urinary and fecal incontinence, further approaches need to be explored. This work shows a possibility for a HASEL-based artificial sphincter muscle. The porcine urethrae used in this work are considered adequate experimental material to perform first in vitro experiments. The comparability of pig urethrae to human urethrae has already been confirmed several times with experimental results and numerical simulations.[40] The urethrae of female pigs in particular have been described as good substitute material in the past.[38,41] It should be noted that even if the comparison between pigs and humans is given, these were in vitro experiments conducted under air atmosphere and at room temperature. It can be assumed that the urethra may behave somewhat differently in the body under physiological conditions.

In this work, it was shown that the passage of fluid could be stopped at an internal urethral pressure of 20 cmH_2O. Physiological urethral pressures in humans range up to 140 cmH_2O.[42] For in vivo scenarios, maintaining continence would require adjusting the device pressure linearly with bladder pressure.[38] Thus, an increase in force must be achieved in the further development of HASEL sphincters. The force that a HASEL actuator can exert is directly related to its geometry, the electrode surface and the filling level of the pouches.[21] With further iterations of the prototypes, an optimum could be found here. Furthermore, a bench top power supply weighing multiple kilograms was used for these initial experiments. These dimensions are not suitable for an implant.

The development of smaller power supplies is a fundamental component of further research steps. Hydraulically amplified low-voltage electrostatic (HALVE) actuators have been developed by Gravert et al., whose mode of operation is very similar to that of HASEL actuators. These actuators use high permittivity dielectrics to significantly reduce the required actuation voltages from a few kilovolts to approximately one kilovolt. At this reduced voltage, the power supply is significantly reduced in size and weight, weighing only 13g for one channel.[43] Exploring high permittivity dielectrics could be one path forward to reduce the required voltages for a implantable artificial HASEL sphincter.

There are already approaches to arranging HASEL actuators in a circular fashion in order to support certain bodily functions. Wang et al. demonstrated an artificial circular muscle employing a 12-unit Peano-HASEL actuator rolled around a silicone rubber tube. They report a theoretical cross-sectional area reduction of about 41% of the original size at maximum strain in the actuated state.[20] In contrast, the design proposed herein provides a more streamlined structure, enabling a reduction in urethral diameter without exerting additional stress on the tissue via actuator movements along the urethra as it would be the case with the design presented by Wang et al.[20]

In order to be able to safely implant an artificial sphincter made of HASEL actuators later on, the functionality of the device must be guaranteed, but much more importantly, of course, the safety of the patient. The HASEL sphincters used here were first prototypes. In the future, however, these could be encapsulated in polydimethylsiloxane (PDMS), for example, to protect the electrodes from moisture and ultimately the patient from the applied voltage. PDMS is a well-known biocompatible flexible material that is already frequently used for encapsulating medical devices.[44,45] Silicone elastomers are generally considered to be relatively permeable to gases and vapors, which can limit the use of silicone elastomers for encapsulation purposes. However, this could be remedied by a careful combination of materials.[45] The prototypes presented here were tied together with thin rope, which is well suited for this purpose. For a later clinical application, a suitable suturing strategy could be developed together with surgeons, as surgeons usually also suture tissue.[46] Similar to the current gold standard AMS 800™, a HASEL sphincter could be easily designed for cuff circumference lengths to suit the individual patient. This would also be a possibility to accommodate the anatomical conditions of men and women.

In conclusion, the development of advanced artificial sphincters, such as the HASEL-based design presented here, holds promise for significantly improving the quality of life for patients suffering from incontinence. Moving forward, further research and clinical validation will be crucial to realizing the full benefits of this technology and driving meaningful advancements in the field of incontinence treatment.

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