# Center for Artificial Muscles
## Report 2023

Center
for Artifical
Muscles

EPFL

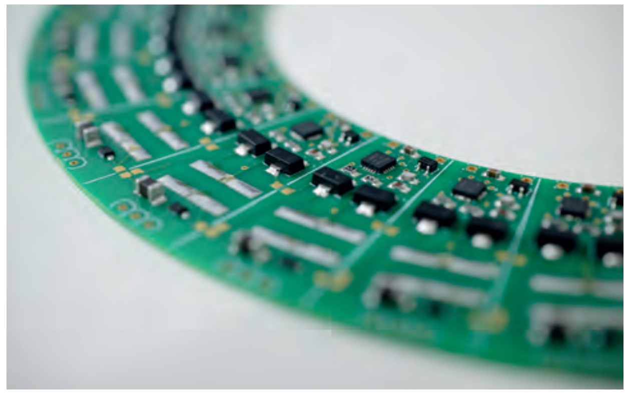
*“What a great human adventure to perform and to succeed in creating these new medical devices”*

**PROF. YVES PERRIARD**





# Introduction



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The path towards the application of dielectric actuators in the medical field is becoming clearer every year. On the one hand, advancements in the development of an active prosthesis for facial rehabilitation are paving the way for initial animal testing while, on the other, URODEA AG[1], has redefined its focus by aiming to provide a solution tailored for women, where the specific anatomy (i.e. shorter urethra) makes it more feasible to achieve a clinical proof of concept. Similarly, a biological platform is currently under development to cultivate cells of the urinary system, and the first artificial urethra has been successfully manufactured. Moreover, the tests on porcine aortae at the end of 2022 demonstrated that Dielectric Elastomer Actuators (DEAs) are emerging as a credible innovative solution for specific forms of heart failure in the eyes of clinicians, with significant changes in blood pressure of approximately 15%.

The progress outlined above is the result of a seamless and close collaboration between engineers and clinicians, that will bring tangible added value to patients. As these innovative developments continue to unfold, the synergy between technological expertise and medical insight is proving instrumental in advancing the application of dielectric actuators in the realm of healthcare. This collaboration promises to increase the functionality of medical devices, such as the active prosthesis for facial rehabilitation and cardiac assist devices, but also to address specific healthcare challenges, such as solutions for the treatment of incontinence in women.

u^b UNIVERSITÄT BERN

University of Zurich^UZH

1. a start-up offering non-invasive solution for urinary retention

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# Content




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# Team

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University of Bern

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# Scientific Highlights



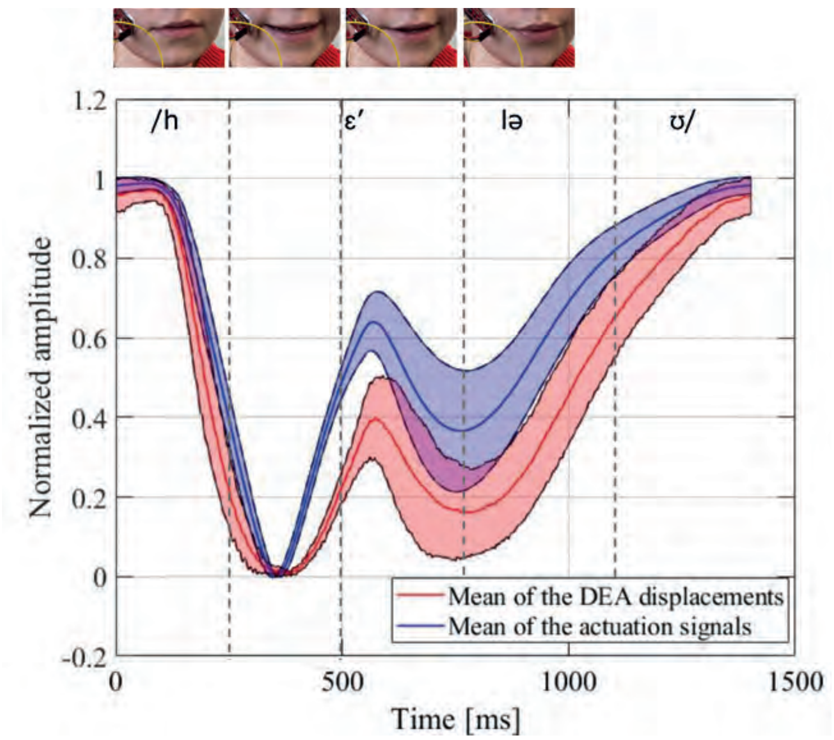
## Facial Reanimation

Facial paralysis is a highly burdening condition, resulting in a patient's inability to move the musculature on one or both sides of the face. This condition compromises the patient's ability to communicate and have facial expressions, thus dramatically reducing the patient's quality of life. The current treatment for chronic facial paralysis relies on a complex reconstructive surgery. In addition, the use of the patients' own muscle tissue entails a donor site morbidity and tissue regeneration may be limited leading to suboptimal results regarding facial reanimation.

Our team is working on a novel, less invasive dynamic facial reanimation approach. The use of a DEA is proposed to restore facial motion, thus avoiding the traditional two-stage free muscle transfer procedure and allowing for a faster recovery of the patient. A study of the facial muscles and neural interfaces, notably those responsible for mouth movement, has been performed to implement a realistic setup.

### Real time actuation of a DEA for a facial neuroprosthesis

A non-invasive neural interface based on myoelectric signals is used to establish a real-time control of the actuator. Visible motion of a skin model was produced in real time by synchronizing the actuator with the activity of a healthy muscle, with a maximal delay of 108 ms resulting from the signal processing and a delay of less than 30 ms related to the actuation of the DEA. This shows that the usage of DEA combined with a neural interface represents a promising approach for the treatment of facial paralysis.




In order to illustrate the use of artificial muscles for post-paralysis facial reanimation, an anatomically precise humanoid facial robot setup was then fabricated.

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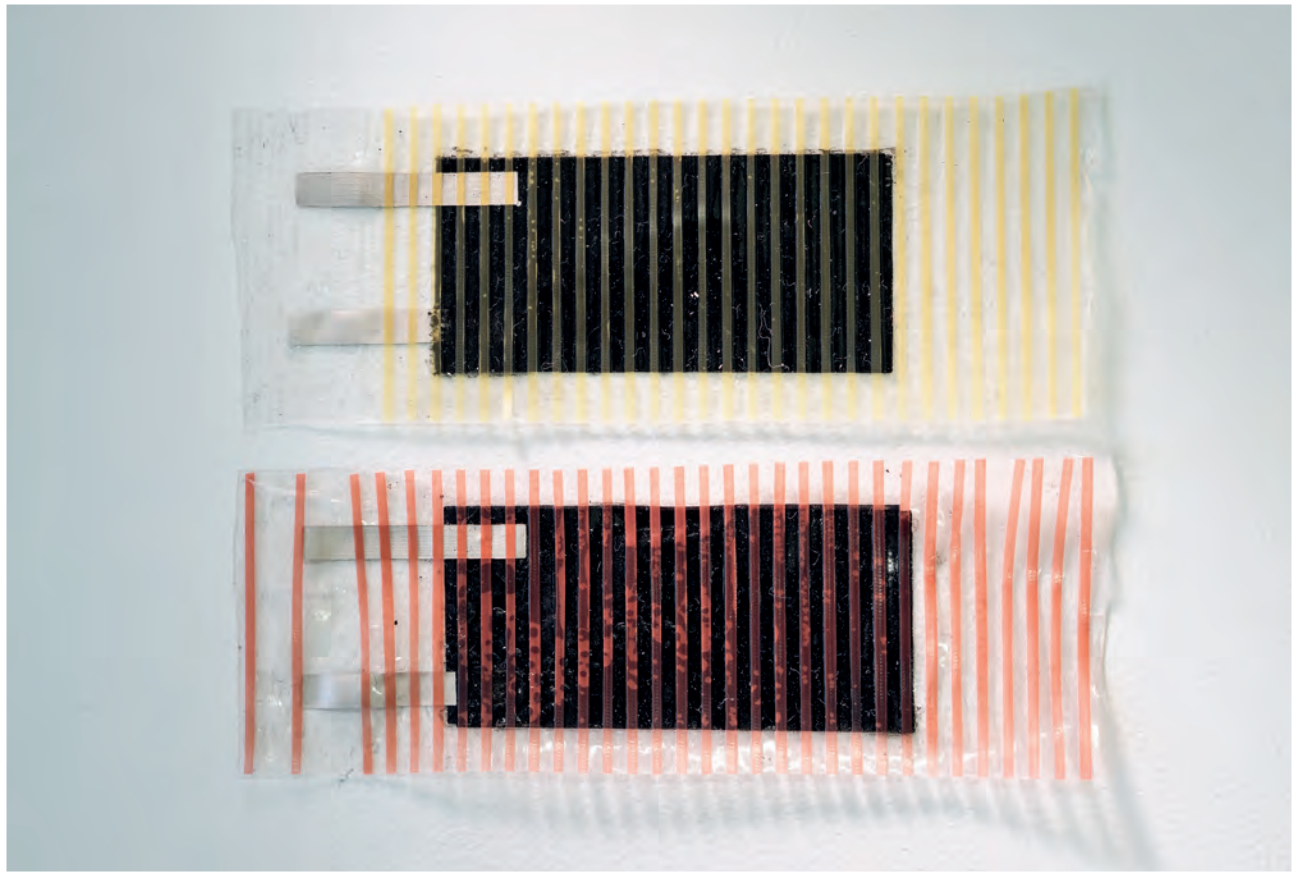
## Fiber reinforcement of DEAs to enhance their performance

In order to favor large uni-axial deformations, DEAs should be constrained in the other direction. This can be achieved by reinforcing the DEA with unidirectional fibers. The behaviour of uni-axial fiber-reinforced DEAs (uFRDEAs) was established and the proposed model innovates by taking into consideration fiber properties such as Young's modulus and dimensions. A novel fabrication process for reinforced DEAs was developed by using 3D printed fibers with 4 different materials, namely Nylon, PETG, ABS and PLA, and different fiber coverages are considered. Fiber reinforcement is shown to increase uni-axial strain up to 75% in the manufactured DEAs when compared to traditional DEAs. This behavior corresponds to the one predicted by the proposed model.

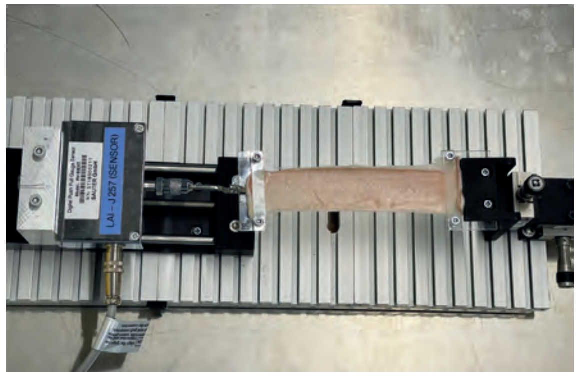


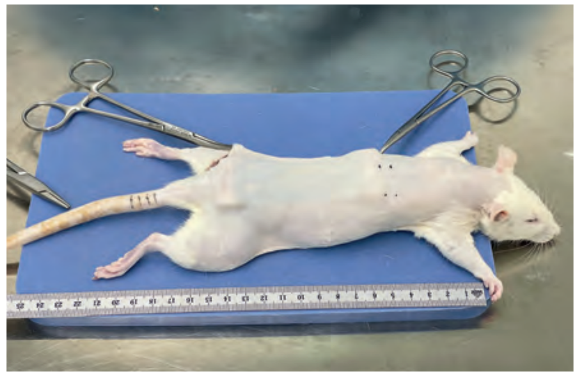


Scientific Highlights

## Rat cadaver experiments

Animal experiments are planned in 2024 and preliminary studies on cadaveric animal tissue were performed. The animal model considered is rat's back tissue, as its mechanical properties are closest to human skin tissue. The aim of the experiments was (i) to study the mechanical properties of the tissues and (ii) to determine adequate insertion points for the actuator.





# Cardiac assist devices

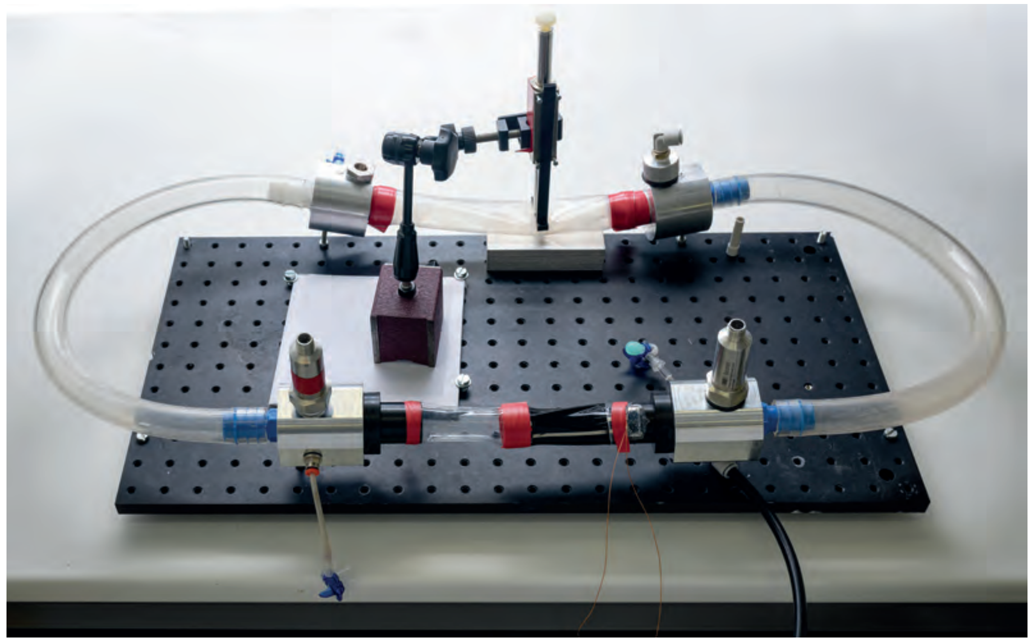
## Impedance pump for Fontan circulation support

We are investigating a new approach to address heart failure following Fontan-type of reconstruction due to congenital defects. Our solution involves a pump using bladeless technology with Dielectric Elastomer Actuators (DEAs). This pump can be integrated into the Fontan reconstruction by replacing the traditional synthetic conduit without further additional changes.

The DEA pump operates as a passive conduit when not activated. However, when activated, it actively supports (and increases) the blood flow in the pulmonary arteries. The DEA tube inflates like a balloon, creating waves essential for efficient pumping. Importantly, the pump does not obstruct the flow, and, in the event of a malfunction, continues to function as a conventional passive Fontan conduit.

Measuring 50mm in length and 30mm in diameter, our DEA-based pump achieves significant flow rates within a closed-loop setup, reaching up to 1.20 $L.min^{-1}$ at an activation frequency of 4 Hz. It can amplify existing flow rates from 1 to 2.2 $L.min^{-1}$ and from 2 to 2.8 $L.min^{-1}$. The device operates at low internal pressures, ranging from less than 10 mmHg to more than 20 mmHg. Flow properties can be controlled by adjusting input signal parameters such as frequency and amplitude.

In summary, our valveless impedance-driven pump using DEA technology is very promising as an innovative cardiac assistance; for instance, to support a failing right ventricular circulation. Further research and development in this area could lead to innovative and more effective solutions, especially for patients suffering from right ventricular failure following Fontan-type reconstruction.



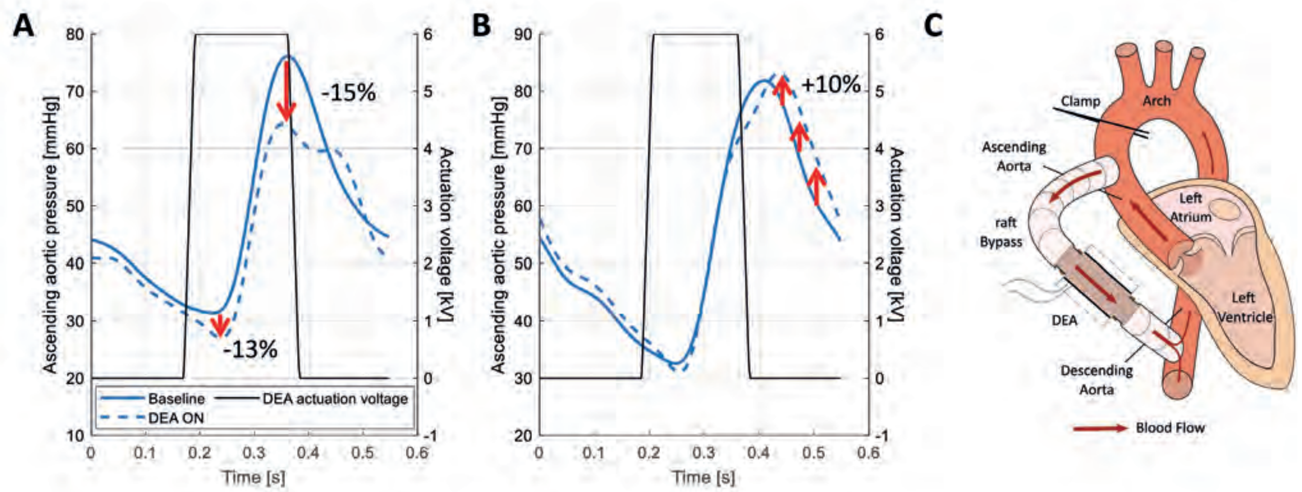




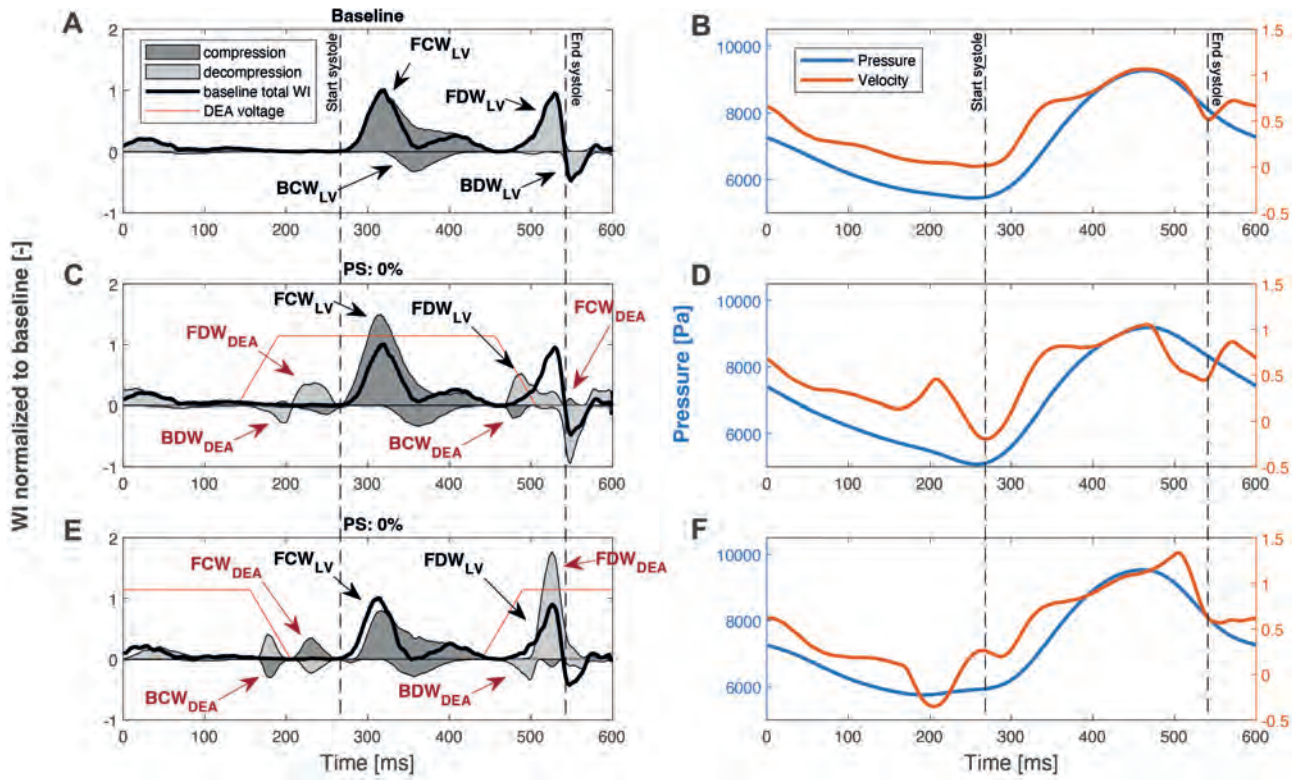


## In vivo experiments of the augmented aorta

In late 2022, we performed in vivo experiments with an improved and pre-stretched DEA device which was implanted near the ascending aorta in a porcine model. The new design improved the energy provided to the heart and the volume displacement of the device. Compared to our previous design without pre-stretch (in vivo experiments in 2021), we were able to reduce the end-diastolic pressure and peak aortic systolic pressure by up to 2.5 and 6.5 times (13% and 15% respectively, compared to baseline) and increase the early diastolic aortic pressure by up to 5 times (10% compared to baseline). These results are comparable to the reported levels of support provided by intra-aortic balloon pumps (IABPs) in terms of reduction in end-diastolic pressure. Moreover, we were able to measure the DEA effects on ventricular pressure-volume characteristics and observed a reduction in stroke work as well as a small increase in stroke volume. Additionally, we observed that, by changing the activation/deactivation timing within the cardiac cycle, we could increase or decrease left ventricular pressure, stroke volume and stroke work and thereby achieve different desired effects for patients. This is a noticeable difference compared to obstructive devices such as IABPs, which are inflated during diastole only.



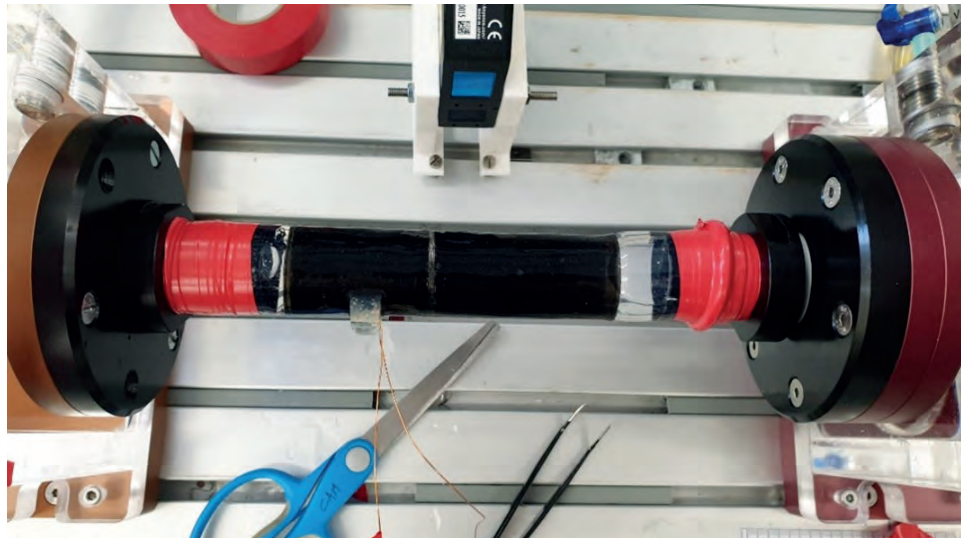

The hemodynamic influence of the DEA device on the aortic wave energy was investigated using the in vivo results of the DEA implanted in the descending aorta of pigs from our 2021 experiments. Wave intensity was calculated from simultaneous recording and assessment of aortic pressure and flow. We demonstrated that the DEA generated two decompression waves (one travelling upstream and one downstream) at activation (dilation) and two compression waves upon deactivation. We focused on the waves travelling upstream towards the heart and observed that the DEA-generated waves interfered with the left ventricular-generated waves and that the timing of these waves affected the hemodynamic effects of the DEA. The best hemodynamic effects were observed when the DEA decompression wave arrived just before the opening of the aortic valve and the DEA compression wave arrived just before aortic valve closure, resulting in lower end-diastolic pressure, higher early diastolic aortic pressure, and lower hydraulic work (an estimate of left ventricular stroke work).






## In vitro experiments - efforts to reduce invasiveness

In 2023, we worked on reducing the DEA device implantation invasiveness by wrapping the DEA around the aorta instead of replacing a segment of the aorta with a tube-graft including the DEA. The DEA without pre-stretch was wrapped around a silicone aorta and tested in vitro in a pulsatile mock loop under physiological pressure and flow conditions (120/70mmHg aortic pressure, and 4-4.5L.min$^{-1}$ cardiac output). The results obtained were comparable to similar tests performed without wrapping with DEA without pre-stretch. They are promising but have to be validated in vivo. The results could be further improved by applying pre-stretch to the wrapped DEA similar to the in vivo tests described above.



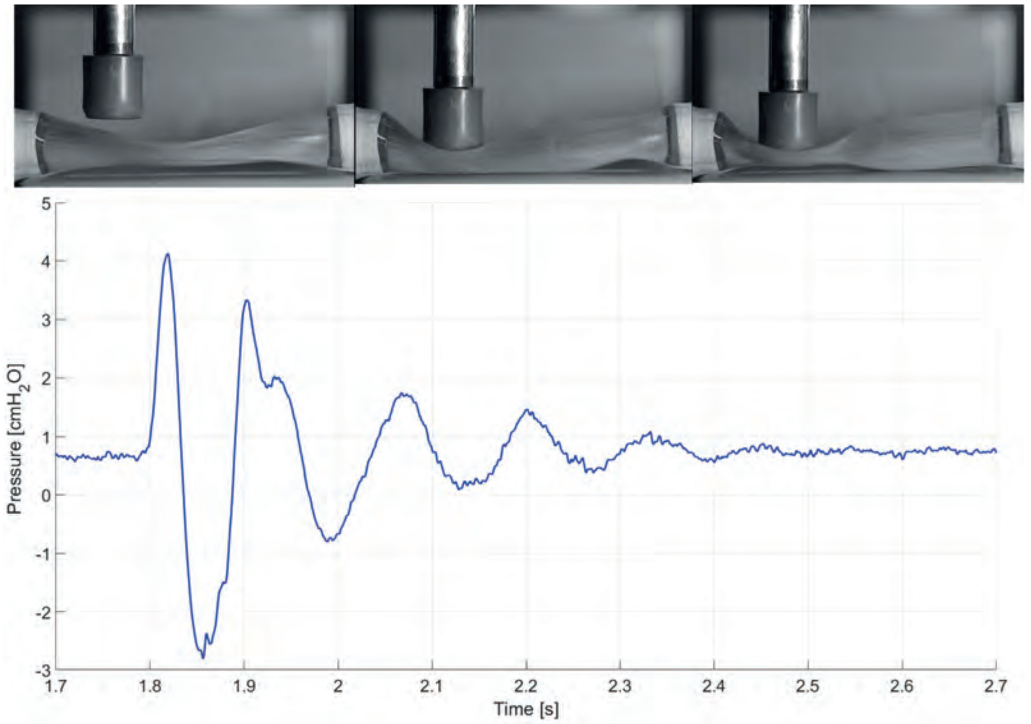
# Urology

## URODEA AG

Current solutions to assist urinary bladder emptying, including catheters, are invasive and can lead to frequent urinary tract infections (UTIs). URODEA AG aims at developing non-invasive/minimally invasive solutions, based on the impedance pumping principle to reduce the risk of UTI by avoiding direct contact with urine.

We recently developed a prototype for men and successfully tested its safety in ten patients over the past year. However, we were not able to prove the efficacy of the device in terms of reducing residual bladder volume in patients.

Currently, our primary goal is to establish proof-of-concept in both female and male patients, a crucial step is in discussions with potential investors to secure substantial financial support and accelerate our path to market. For this purpose, we are working on a prototype for female patients. Anatomically, women have a shorter urethra than men, resulting in less wave-damping (which negatively affects the impedance pumping performances). Based on this assessment our latest in vitro experiments with short urethra models mimicking women's urethra and recent discussions with our urological partners lead to the hypothesis that a device for women will have a significantly higher efficacy than that of the male version. Obtaining proof-of-concept in female patients will also help us to improve/optimize potential applications in men.






Scientific Highlights

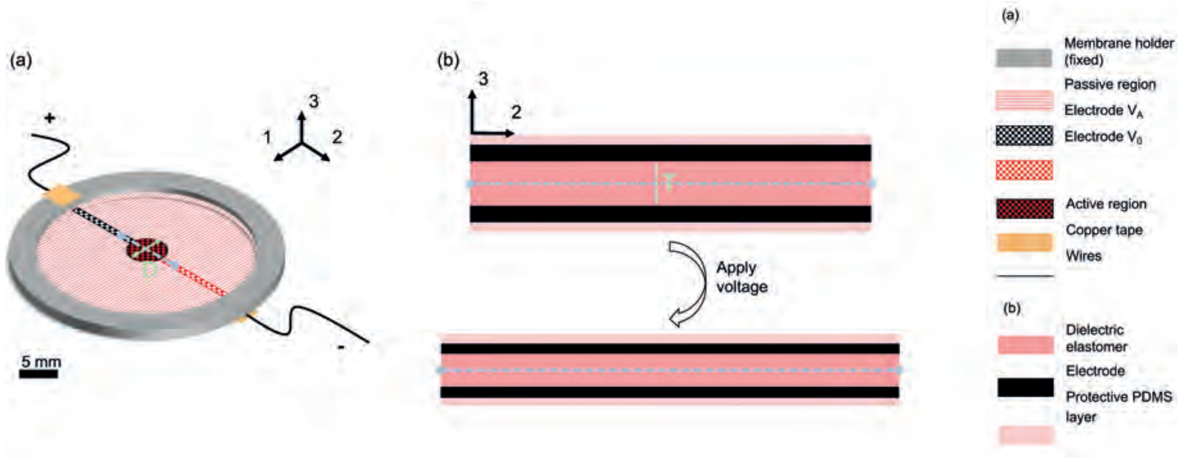
## Artificial Bio-Bladder

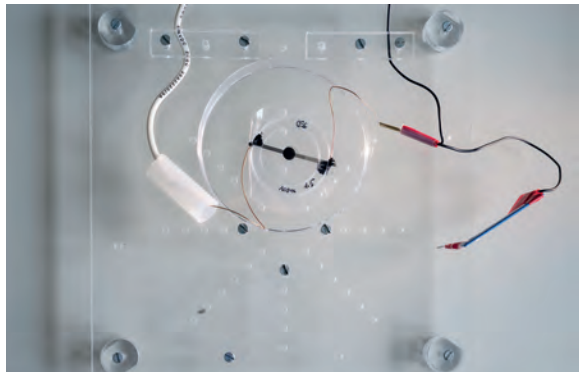
We are currently developing an in vitro artificial bladder that mimics the function of the urinary bladder by stretching urothelial and smooth muscle cells cyclically thanks to a DEA.

One aspect is the optimization of the DEA design. Different design factors, such as the geometric dimensions of the electrodes, the thickness of the dielectric elastomer or the pre-stretch, have various influences on the functionality of the device.

Based on the acquired knowledge, the circular design consisting of two electrode layers was further modified. On the one hand, the electrode was split into smaller parts to improve possible deformations and strains and, on the other hand, the number of electrode layers was increased to better shield the excited electrodes from the environment.

A second aspect is the thermal behaviour of the DEA: due to the temperature-sensitive application of a cell stretcher, various experiments were carried out using different high voltage signals differing in frequency and amplitude and which correspond to signals that also occur in the later application. The frequency and amplitude thresholds at which the self-heating of the DEA is critical for the survival of the cells were determined.

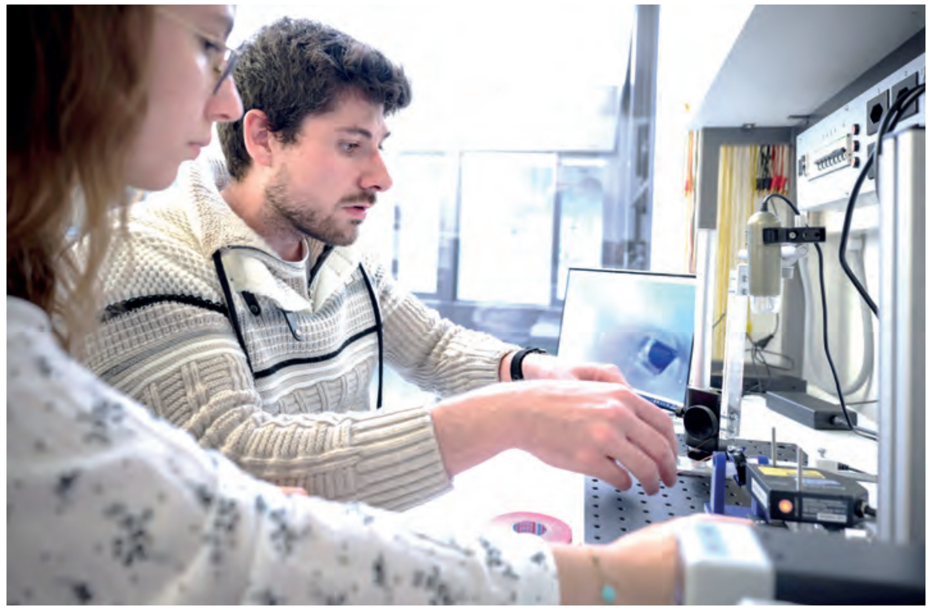


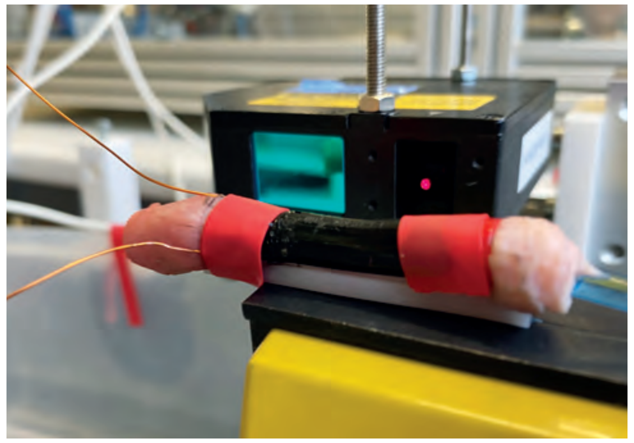
## Artificial Urinary Sphincter (AUS)

Urinary incontinence (UI) is a urological disorder that affects millions of people worldwide. One of the most promising long-term treatments for this condition is the use of an artificial urinary sphincter (AUS).

The AUS is a medical device that is implanted around the urethra to provide continence control by constricting the lumen. In 2023 we carried out mechanical tests on porcine urethras to define the properties with accuracy. This step is essential to understand the different mechanical constraints that would be applied to our AUS.







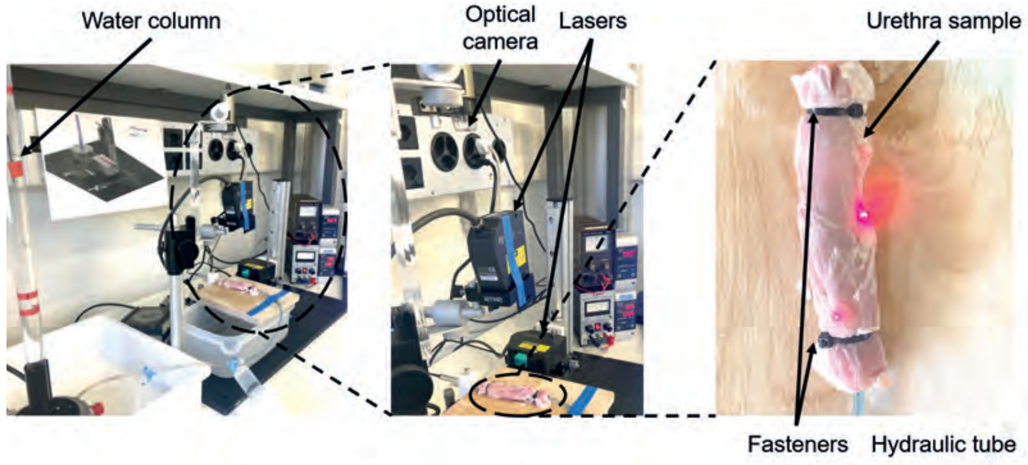
***First DEA based AUS***
We tested ex vivo our first DEA-AUS on porcine urethra and our results demonstrated that an additional mechanical structure would be a solution to improve the performance of our AUS.

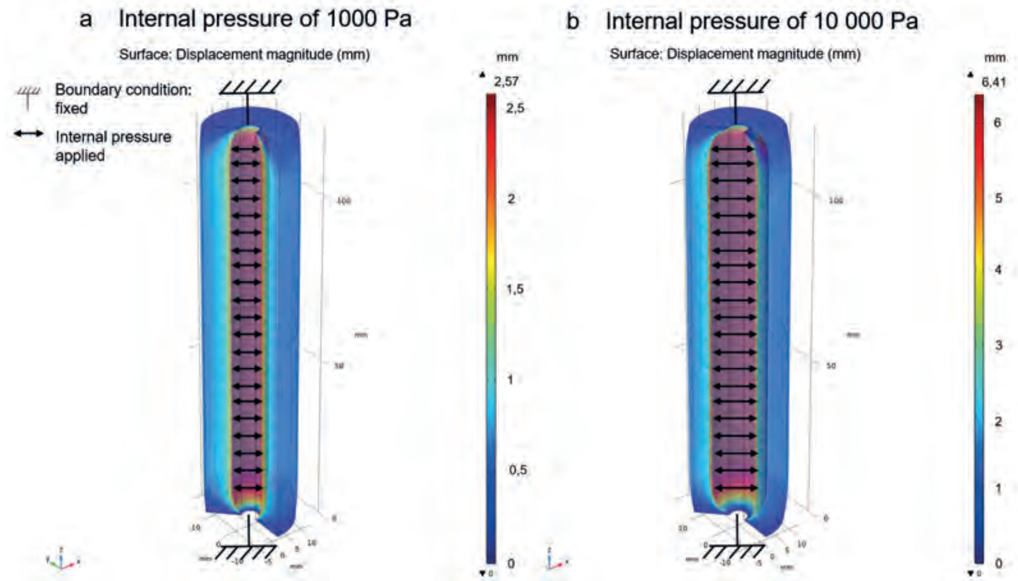




***Mechanical characterization of porcine urethra***
Understanding the biomechanics and, in particular the mechanical properties of the urethra, is a key to design an effective AUS for the treatment of urinary incontinence. However, performing tests on human urethras presents significant challenges due to ethical considerations and the limited availability of human tissue samples. As a result, ex vivo tests were performed to study the mechanical properties of the porcine urethra. Among various candidates, porcine urethras have features closest to human urethras, making them a suitable replacement for studying the mechanical properties of the human urethra.

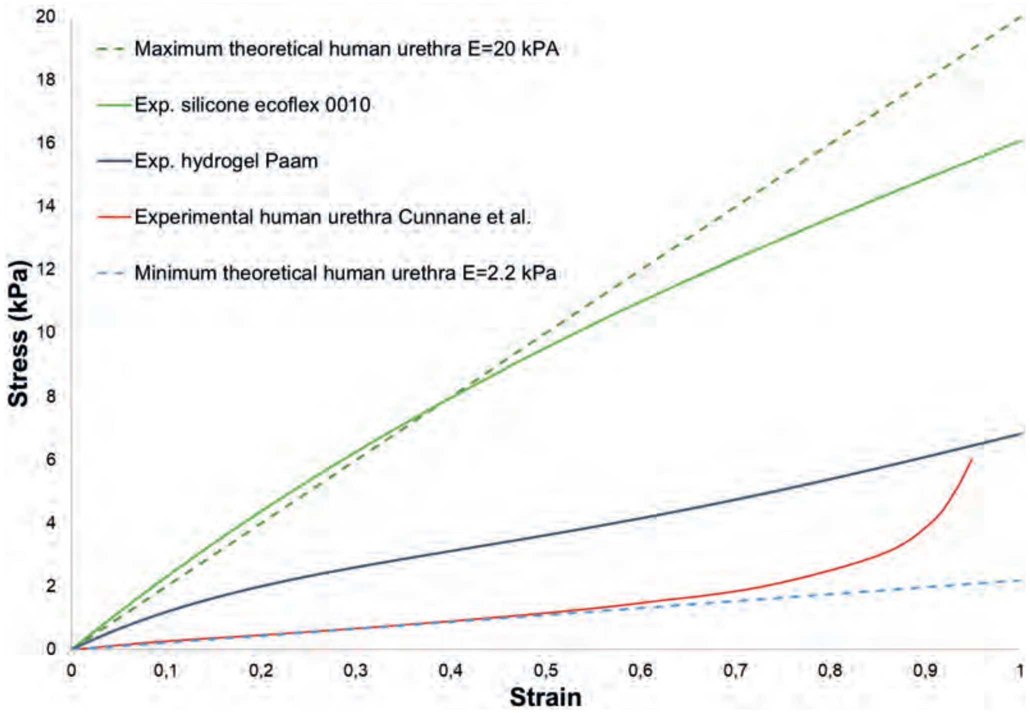
Within the Center for Artificial Muscles (CAM), we performed several tests on porcine urethras to characterize the mechanical properties as accurately as possible.



*Artificial urethra*
Exploring porcine urethra testing has proven to be intriguing. However, it poses challenges due to notable variations in morphology and dimensions when compared to human counterparts. Recognizing these limitations, we have embarked on a new research endeavor to address these issues and enhance the relevance of our studies. We are searching for a polymer that could replace human urethra in order to carry out our future experiment on this artificial urethra.

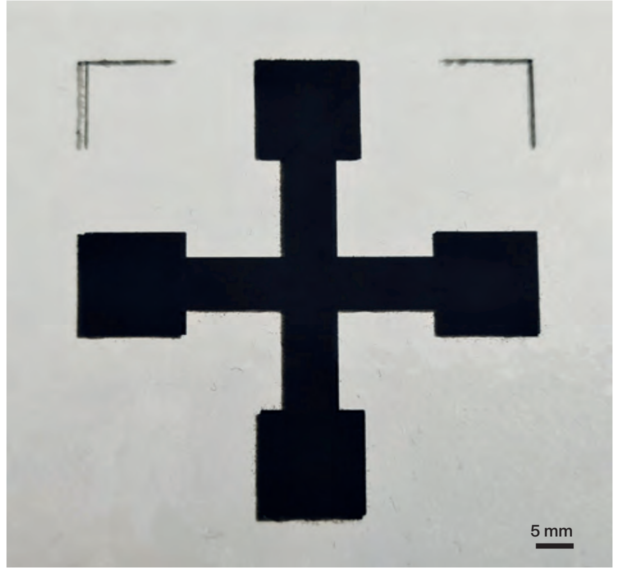
Promising results have been found and lead our future research towards hydrogel and silicone.





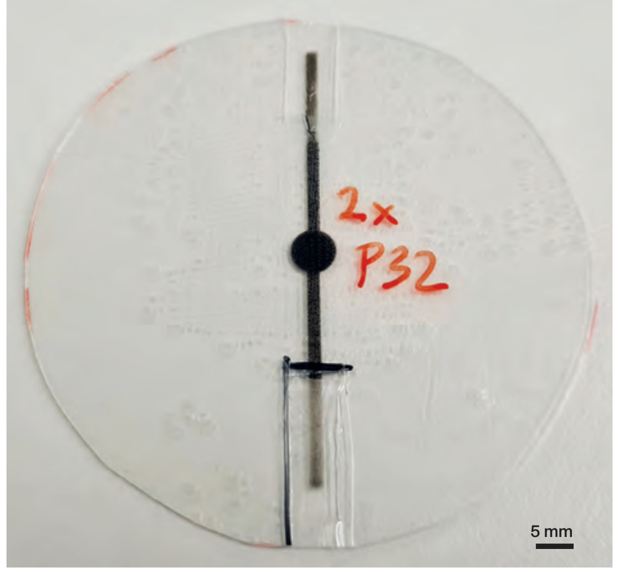



# Cross-functional developments




## Inkjet printing

Inkjet printing is a very interesting manufacturing process, opening the possibility of fast DEAs prototyping. This tool can be used to create electrode designs that would not be possible with screen printing. However, the composition of the inks used is the key to the process, and the properties of the material used are very important. We began by focusing on the manufacture of carbon ink that could be used to print a DEA and also began to study the printing of fibers and conductive silver ink.



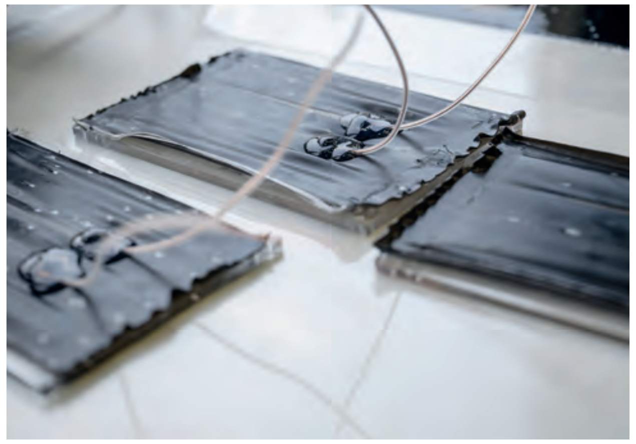

## Pad printing

Pad printing is a process dedicated to mass production. This machine, acquired in 2023, enables the quick manufacturing of large quantities. Dimensions and ink are the key points in this process. While the printing of small electrodes is well established, the needs of the cardiac device require larger electrodes and represent a first challenge. We have already looked at the ink, which is the second challenge, and after several trials, it was possible to obtain the first actuators.

A study is currently underway to compare the different manufacturing methods (screen printing, inkjet printing and pad printing) and actuator characteristics.

## Water diffusion

Water diffusion through silicone membranes is a critical phenomenon that promotes electrical breakdowns. The presence of water in the dielectric active layer would compromise the correct functioning of the actuator. Another research focus is the coating of both side of the device with a hydrophobic membrane to prevent the water diffusion. Looking at the current advancements, styrene-block-isobutylene-block-styrene (SIBS) seems to be an interesting solution, although it is very difficult to adhere a material to silicone if it is untreated or not silicone-based. Here, the idea is to combine silicone with SIBS to create a material that is applied on the DEA, adhesive to silicone and hydrophobic. The proportion of components used is critical because too much silicone will not prevent from water diffusion and too much SIBS will not be adhesive enough.



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# Next steps

In the fall 2024, our research in the cardiovascular field will enter a new phase by addressing comprehensive tests on pigs with a particular focus on the use of an even more sophisticated system designed to deliver a substantial 40% alteration in blood pressure. This innovative approach involves a revamped actuator, as well as a distinct activation protocol aimed at maximizing the resonance with the inherent dynamics of the cardiovascular systems.

Building upon the knowledge acquired through extensive rat trials, our aspiration extends beyond the realm of physiological changes. Through these tests, we aim to showcase that our flexible actuators have the potential to transcend physical limitations and enable the exchange of emotions among patients struggling with paralysis. This ground-breaking avenue could revolutionize the way we perceive and address the emotional well-being of people facing mobility challenges.

Simultaneously, we are actively addressing complications in the urinary system for which a pioneering tool is being developed and strategically crafted to enhance the process of urination. This novel approach looks promising to improve urinary function. Furthermore, our commitment extends to the development of a state-of-the-art artificial sphincter, currently undergoing meticulous refinement. The artificial sphincter will undergo rigorous testing, primarily on the advanced artificial urethra.

These multifaceted initiatives emphasize our unlimited dedication to promote significant advances in medical technology, with the final objective of alleviating healthcare challenges and improving the overall well-being of individuals suffering from different medical conditions. The integration of cutting-edge design, precise activation mechanisms and a holistic approach to physiological complexities defines our pursuit of pioneering innovative medical solutions.



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# Dissemination



## Invited Talks

The Artificial Muscle Center: a success among many innovative applications of electromagnetism in microtechnology, Yves Perriard, Imperial college, London, England, June 26-28, 2023

Dielectric Elastomer actuators as medical assist devices, Yoan Civet, FMNT, Grenoble, France, April 5, 2023

Center for Artificial Muscles, Noël de l'innovation, P&TS, Neuchâtel, Switzerland, December 18, 2023

## Journal papers


Dielectric Elastomer Actuator-Based Valveless Impedance-Driven Pumping for Meso- and Macroscale Applications, A. Benouhiba, A. Walter, S.E. Jahren, T. Martinez, F. Clavica, D. Obrist, Y. Civet and Y. Perriard, *Soft robotics, 2023, 2022.0244*

Hemodynamic effects of a dielectric elastomer augmented aorta on aortic wave intensity: An in vivo study, A. S.E. Jahren, T. Martinez, A. Walter, L. Ferrari F. Clavica, D. Obrist, Y. Civet and Y. Perriard, *Journal of Biomechanics, 2023-08-25, Vol 159*

Real-time actuation of a dielectric elastomer actuator neuroprosthesis for facial paralysis, S. Konstantinidi, C. Imholz, T. Martinez, A. Benouhiba, A. Walter, Y. Civet, N. Lindenblatt and Y. Perriard, *Smart Materials in Medicine, Vol. 5, Issue 1, 2024*

Uni-axial reinforced dielectric elastomer actuators with embedded 3D printed fibers, S. Konstantinidi, T. Martinez, B. Tandon, Y. Civet and Y. Perriard, *2023 Smart Mater. Struct. 32* 125011

## Conferences

Dielectric elastomer actuator based cardiac assist devices: In vitro and in vivo study, T. Martinez, A. Benouhiba, S.E. Jahren, A. Walter, F. Clavica, P.P. Heinisch, E. Bufflé, Markus M. Luedi, J. Hörer, D. Obrist, T. Carrel, Y. Civet and Y. Perriard, *$37^{th}$ EACTS Annual Meeting, European Association for Cardio-Thoracic Surgery, Vienna, Austria, October 4-7, 2023*

Valveless DEA-based impedance pump as a cardiac assist device, A. Benouhiba, A. Walter, S.E. Jahren, T. Martinez, F. Clavica, P.P. Heinisch, D. Obrist, Y. Civet and Y. Perriard, *$37^{th}$ EACTS Annual Meeting, European Association for Cardio-Thoracic Surgery, Vienna, Austria, October 4-7, 2023*

In vivo validation of a novel soft aortic counterpulsation device based on dielectric elastomer actuators, S. E. Jahren, T. Martinez, P.P. Heinisch, F. Clavica, A. Walter, E. Bufflé, T. Carrel, Y. Civet, J. Hörer, D. Obrist and Y. Perriard, *Gordon Research Conference, Waterville Valley, NH, United State, May 27, 2023*

Study of Potential Factors and their Interaction in Dielectric Elastomer based Cell Stretcher, S. Holzer, F. Hartmann, F. Öz, T. Martinez, Y. Civet and Y. Perriard, *$26^{th}$ International Conference on Electrical Machines and Systems (ICEMS), Zhuhai, China, 2023*

An Experimental Approach for the Design of Uniaxial Fiber Reinforced Dielectric Elastomer Actuators, S. Konstantinidi, J. Asboth, A. Walter, T. Martinez, Y. Civet and Y. Perriard, *$26^{th}$ International Conference on Electrical Machines and Systems (ICEMS), Zhuhai, China, 2023*

Mechanical characterization of porcine urethra: non linear constitutive models and experimental approach, Q. De Menech, S. Konstantinidi, T. Martinez, A. Benouhiba, Y. Civet and Y. Perriard, *$7^{th}$ International Conference on Advances in Biomedical Engineering (ICABME), Beirut, Lebanon, 2023*

In vivo experiments of a DEA based cardiac assist device, T. Martinez, S.E. Jahren, F. Clavica, A. Walter, P.P. Heinisch, E. Bufflé, T. Carrel, J. Hörer, D. Obrist, Y. Civet and Y. Perriard, *$12^{th}$ International conference on Electromechanically Active Polymer (EAP) transducers & artificial muscles, Bristol, England, June 6-8, 2023*

Valveless Impedance-driven pump via DEAs, A. Benouhiba, Y. Civet and Y. Perriard, *$12^{th}$ International conference on Electromechanically Active Polymer (EAP) transducers & artificial muscles, Bristol, England, June 6-8, 2023*

Equibiaxial cell stretcher based on dielectric elastomer actuator, S. Holzer, Y. Civet and Y. Perriard, *$12^{th}$ International conference on Electromechanically Active Polymer (EAP) transducers & artificial muscles, Bristol, England, June 6-8, 2023*

Contractile DEAs with embedded structured fibers, S. Konstantinidi, A. Thabuis, T. Martinez, Y. Civet and Y. Perriard, *$12^{th}$ International conference on Electromechanically Active Polymer (EAP) transducers & artificial muscles, Bristol, England, June 6-8, 2023*

Dielectric elastomer actuators for facial paralysis, S. Konstantinidi, C. Imholz, T. Martinez, A. Benouhiba, A. Walter, Y. Civet, Y. Perriard and N. Lindenblatt, *$59^{th}$ Annual Meeting Swiss Plastic Surgery, Basel, 2023*

In vivo validation of a novel soft aortic counterpulsation device based on dielectric elastomer actuators, S. E. Jahren, T. Martinez, P.P. Heinisch, F. Clavica, A. Walter, E. Bufflé, T. Carrel, Y. Civet, J. Hörer, D. Obrist and Y. Perriard, *Annual Meeting of the Swiss Society of Biomedical Enginnering, Allschwil, Basel, Switzerland, September 13, 2023*

# Thank you !

The establishment of this consortium owes its existence to the generosity and dedication of the Werner Siemens-Stiftung. Thanks to the Foundation's support, the Center for Artificial Muscles has demonstrated its proficiency in utilizing soft actuators for medical purposes through in vivo experiments.

Charlotte (left) and Marie, who established the Werner Siemens Foundation

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***"With the development of flat actuators, the engineering of artificial muscles for facial reanimation in patients has become a real possibility.  This will provide new and less invasive reconstructive options for patients with facial paralysis."***

**PROF. NICOLE LINDENBLATT**

***"An amazingly innovative approach that brings together scientists, engineers and medical specialists to find novel solutions in the field of heart failure."***

**PROF. THIERRY CARREL**

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