POLITECNICO MILANO 1863

KU LEUVEN

# Development of miniature position sensing pneumatic artificial muscles for use in flexible surgical instruments for Fetoscopic Endoluminal Tracheal Occlusion


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# INTRODUCTION: Clinical need

**Congenital diaphragmatic hernia (CDH)**

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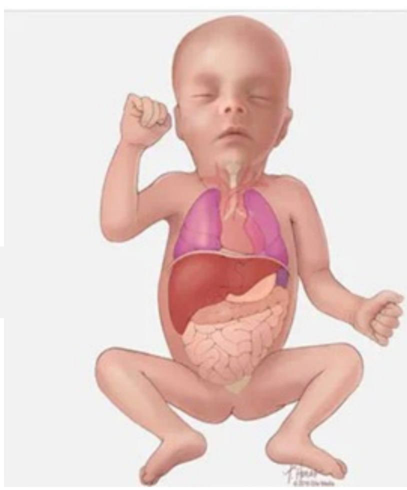
**Fetoscopic endoluminal tracheal occlusion procedure**

Lower complications

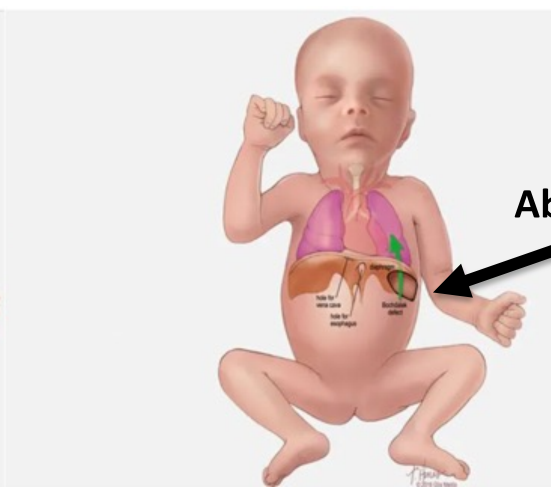
Better postoperative outcomes

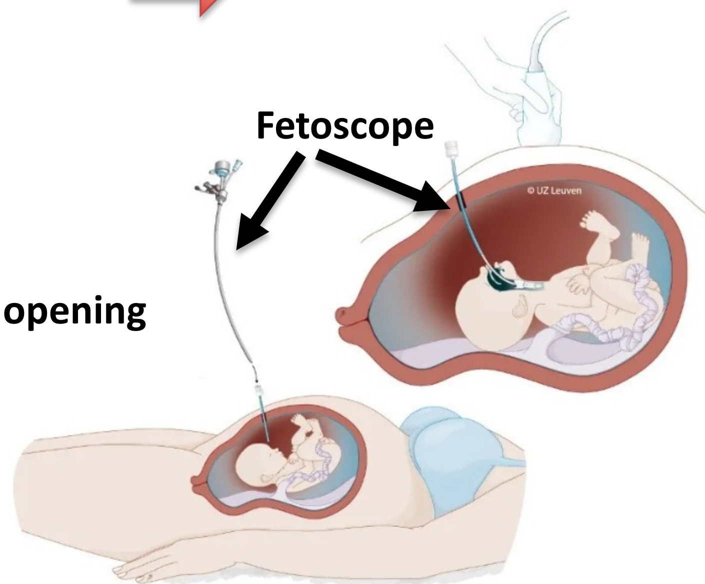
✗ Rigid structure with fixed curvature ⇒ Robotic systems

**Normal anatomy**



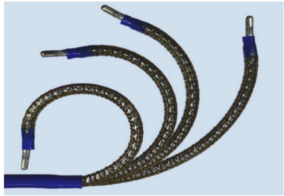
**With CDH**



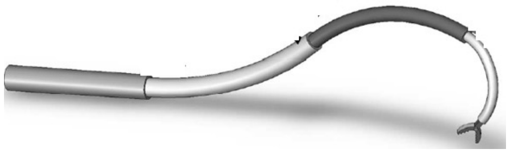



# STATE OF THE ART: Continuum robots

**Extrinsic actuation**



**Tendons**



**Concentric tubes**

**Intrinsic actuation**

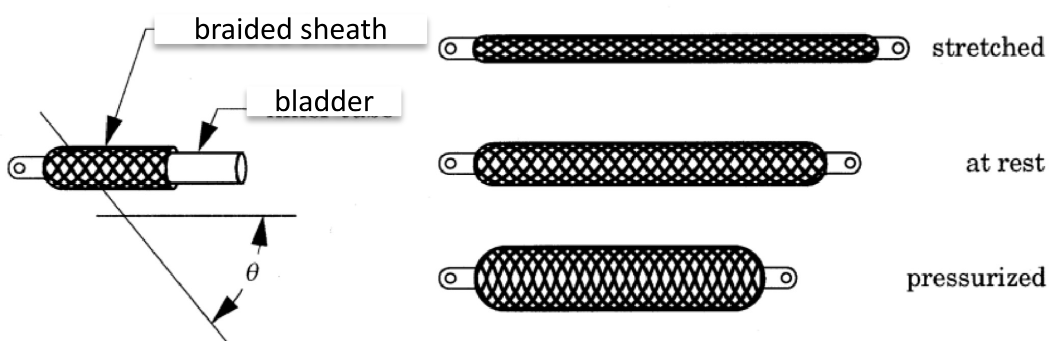

**Pneumatic artificial muscle**

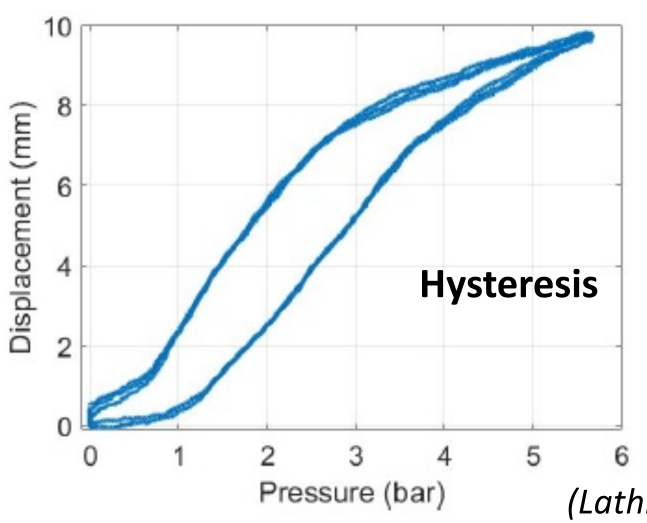
**Shape memory**

- Higher number of joints
- Increased level of maneuverability
- Higher potential for miniaturization

# STATE OF THE ART: McKibben muscles

## McKibben Pneumatic Artificial Muscles




*(Lathrop et al., 2021)*

Tolerance to large deformations

Small size

Large forces to weight ratio

✗ Hysteresis → integrated sensor

# STATE OF THE ART: Integrated sensors

## Resistive sensors

Little to no hysteresis

✗ Quadratic relationship

✗ Complex manufacturing

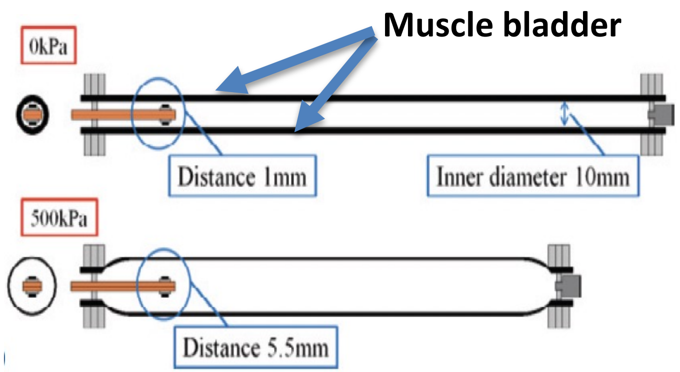

*(King et al.,2017)*

## Optical sensors

No hysteresis

✗ Non-linear relationship

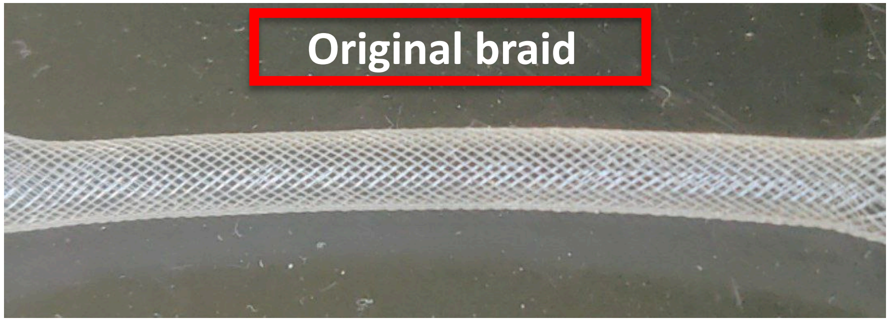
✗ Complex manufacturing

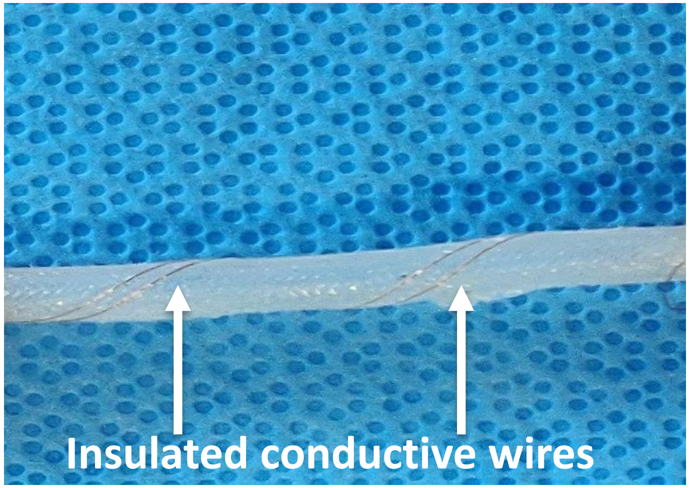



*(Akagi et al., 2012)*

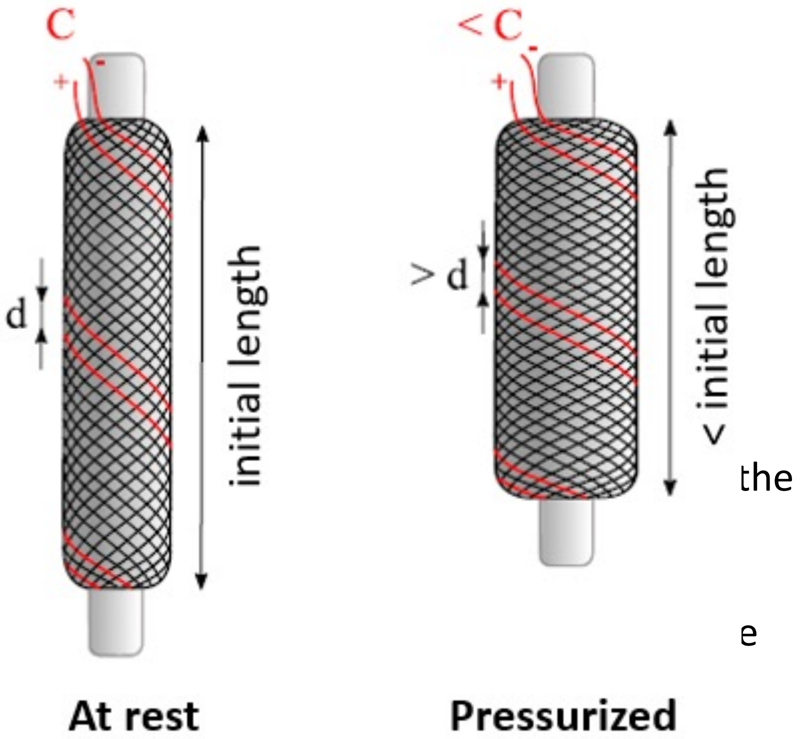
# STATE OF THE ART: Capacitive sensor

## Manufacturing




## Theoretical model



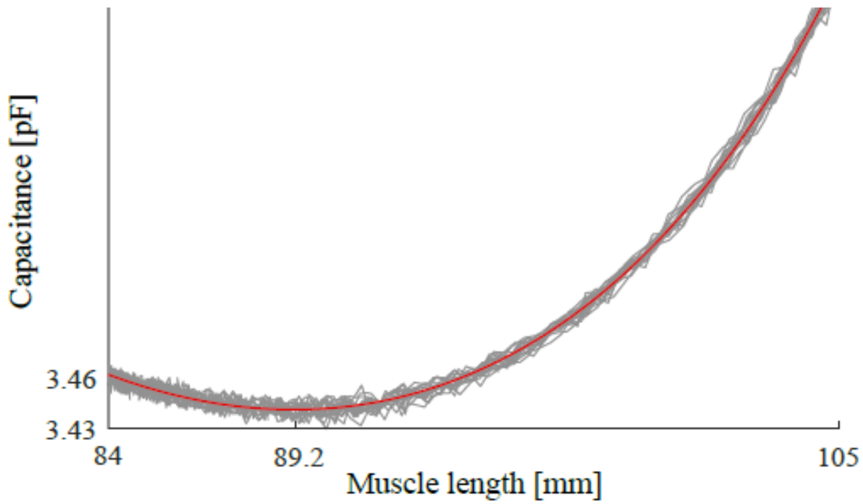

*(Legrand et al., 2019)*

# STATE OF THE ART: capacitive sensor

Theoretical model

$$C = \frac{\pi \epsilon l_c}{\ln\left(\frac{d}{r} + \sqrt{\frac{d^2}{4r^2} - 1}\right)}$$

$C$= capacitance
$\epsilon$= permittivity of the medium between the wires
$l_c$= conductive wires length
$d$= distance between the conductive wire
$r$ = conductive wires radius




*(Legrand et al., 2019)*

# AIM OF THE WORK

Easy-to-make **self-sensing pneumatic artificial muscle**

- limited **hysteresis** (≈1 bar)
- **Linear** relationship
- suitable **size** (5-10 cm)

**Theoretical model**
**Muscle contraction → sensor output**

↓

**Prototypes' manufacturing and testing**

↓

**New prototypes vs previous capacitive muscle comparison**

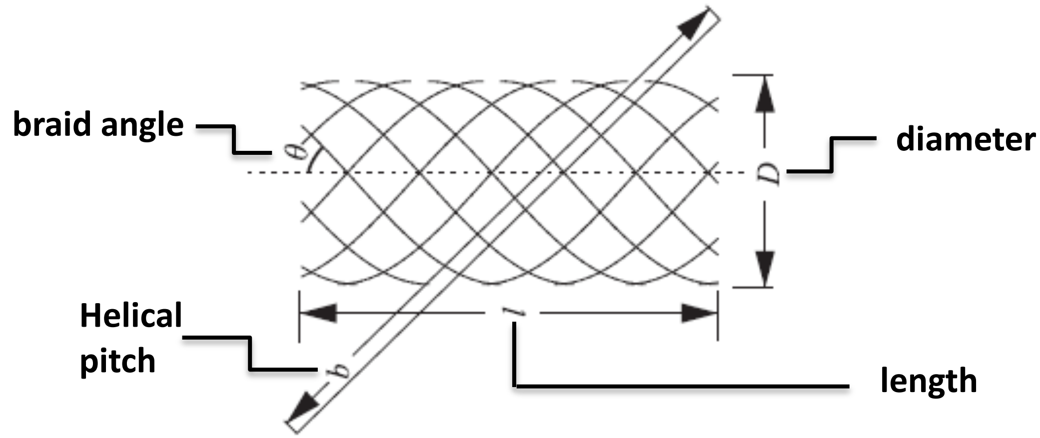
# METHODS: inductive muscle

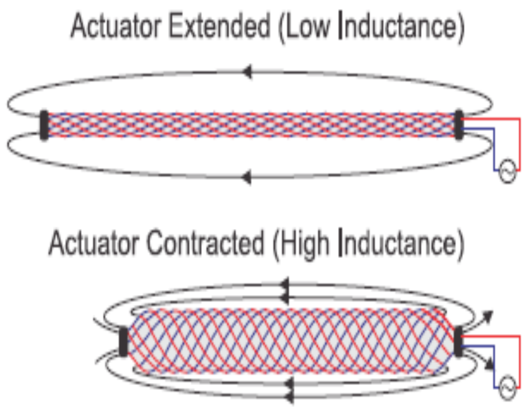
The prototype was obtained as the **miniaturized version** of the muscle developed by *Felt et al (2016).* *Ecoflex* (silicone) was used to fabricate a second (novel) **coated version** of the muscle.

**Theoretical model**

$$L = \frac{\mu n_c^2}{4\pi cos^2(\vartheta_0)} \cdot l_0 \cdot (\frac{l_0}{l} - \frac{l}{l_0}\ cos^2\vartheta_0)$$

- $L$= inductance
- $\mu$= magnetic permeability of free space
- $n_c$= number of coils
- $\vartheta_0$= initial braid angle
- $l_0$= initial muscle length
- $l$= current muscle length



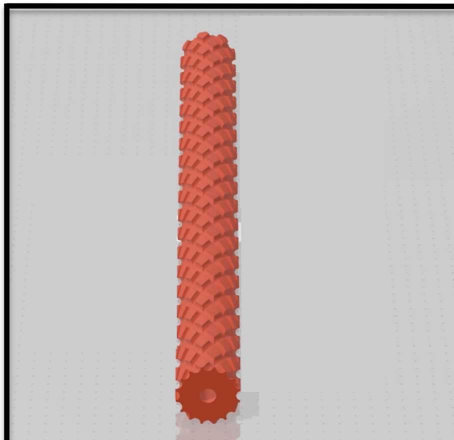




(Felt et al.,2016)

# METHODS: inductive muscle



- **3D printed template**

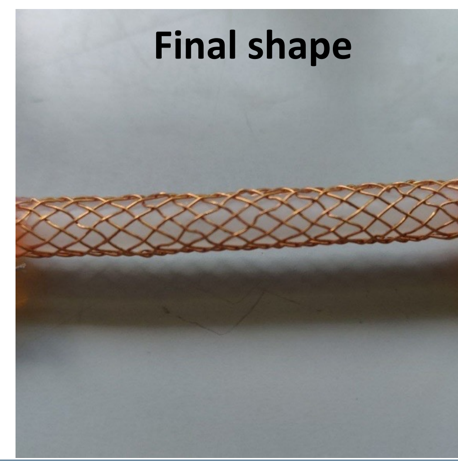


| Parameter | Value |
|---|---|
| Length ($l_0$) | 5 cm |
| Diameter (**D**) | 4 mm |
| Braid angle ($\vartheta$) | 30° |
| Helical pitch (**b**) | 21.76 mm |

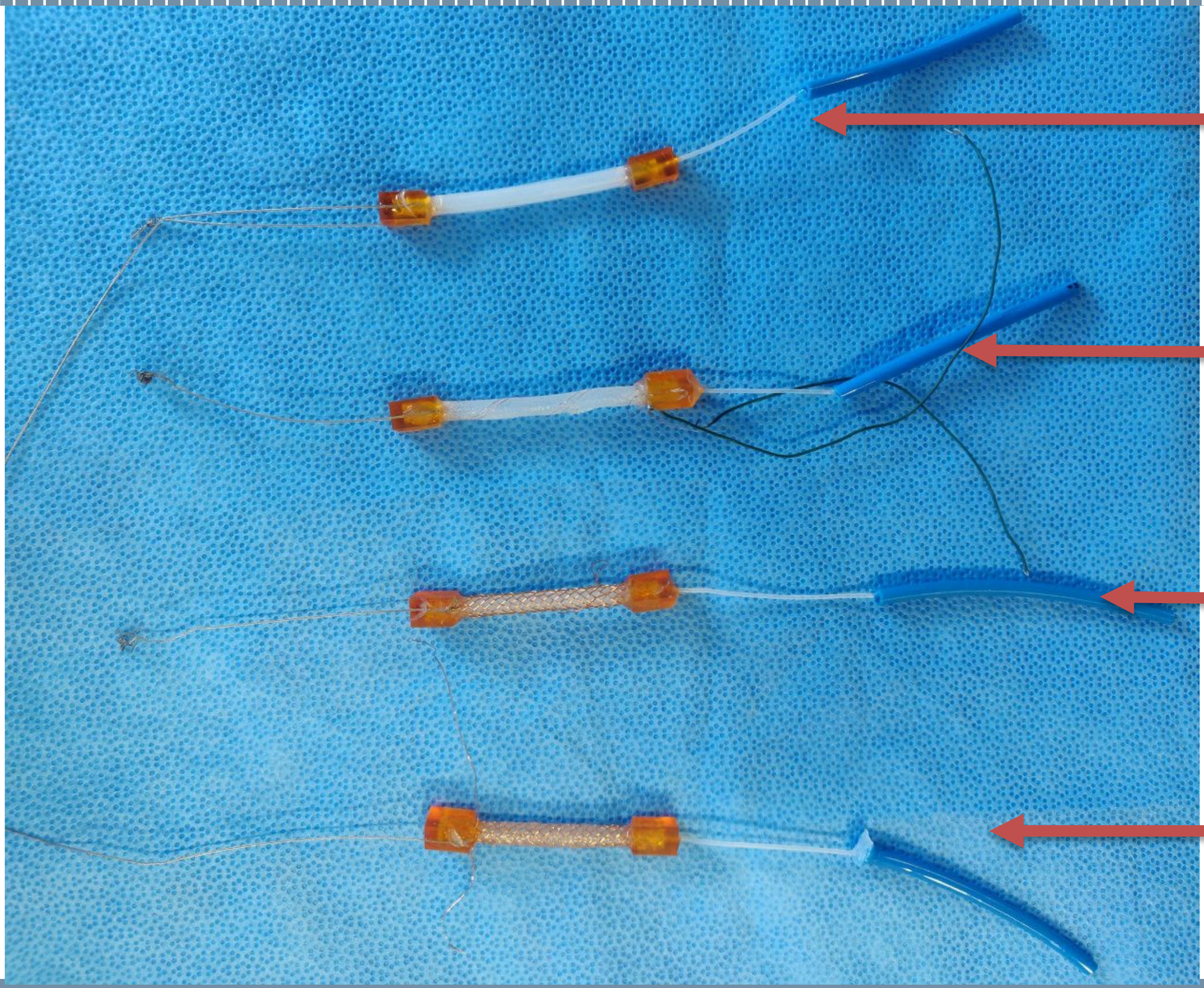
- **Magnetic wire**

- **Tube (bladder)**

| Parameter | Value |
|---|---|
| Wire material | Insulated copper |
| Wire diameter | 0.2 mm |
| Tube material | Silicone |
| Tube internal diameter | 3 mm |
| Tube external diameter | 4 mm |
| Tube length | 5 cm |



# METHODS: final prototypes



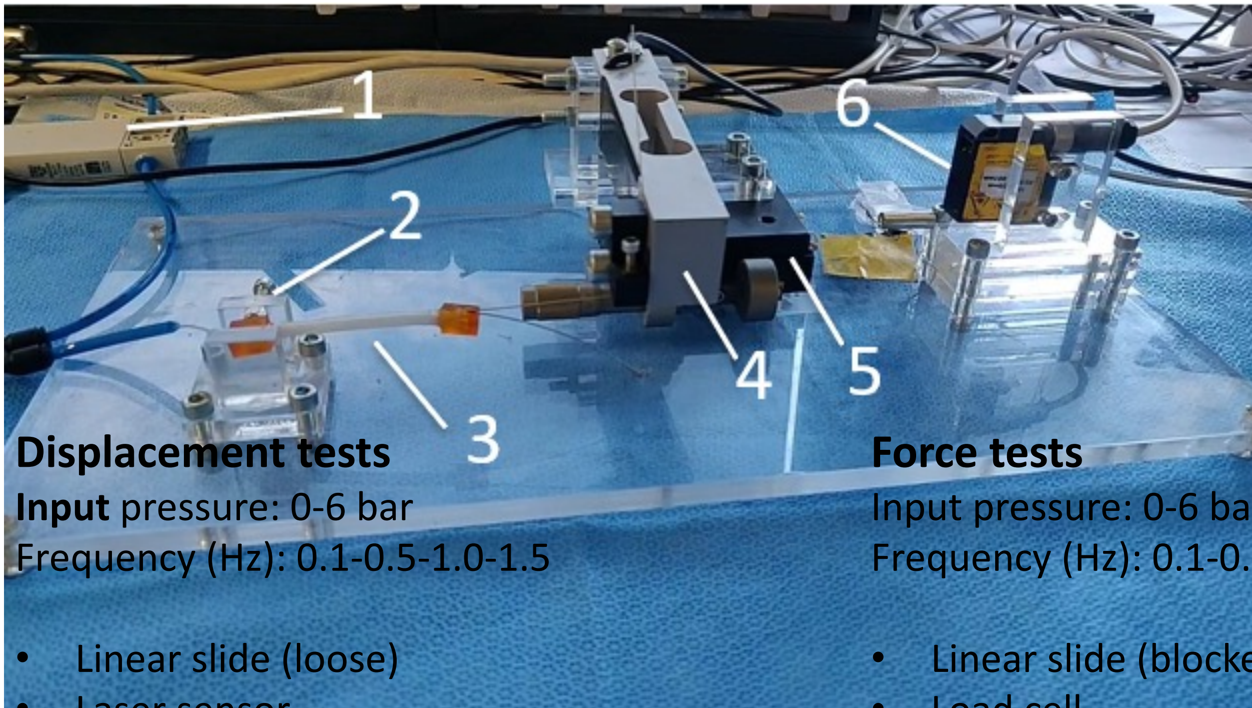
Baseline muscle

Coated capacitive muscle

Coated inductive muscle

Uncoated inductive muscle

# TESTS:
# Set-up and protocol




1. Proportional valve
2. Fixed clamping to the frame
3. Pneumatic artificial muscle
4. Load cell
5. Linear slide
6. Laser sensor

**Displacement tests**
**Input** pressure: 0-6 bar
Frequency (Hz): 0.1-0.5-1.0-1.5

- Linear slide (loose)
- Laser sensor

**Output**: muscle contraction (mm)

**Force tests**
Input pressure: 0-6 bar
Frequency (Hz): 0.1-0.5-1.0-1.5

- Linear slide (blocked)
- Load cell

**Output**: Force generated (N)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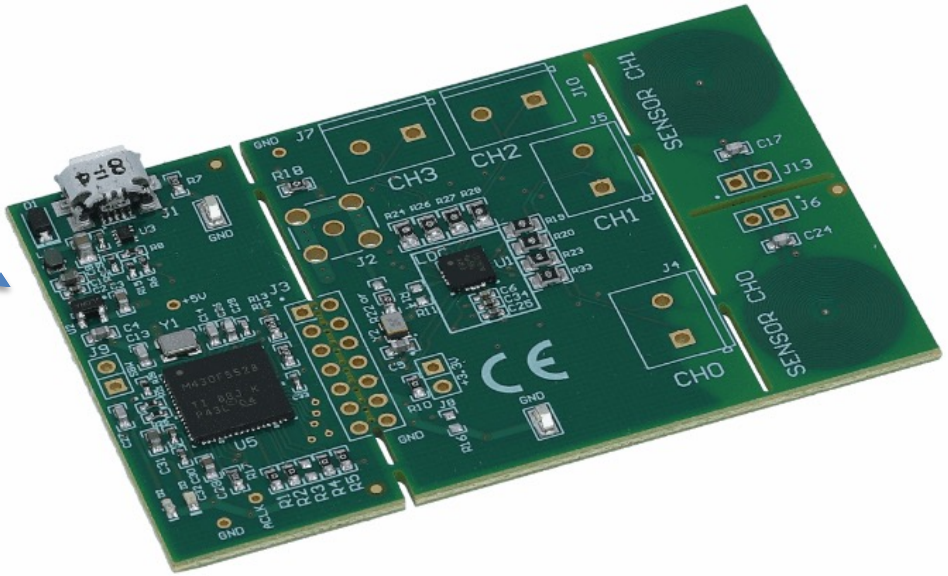
# TESTS: Set-up and protocol

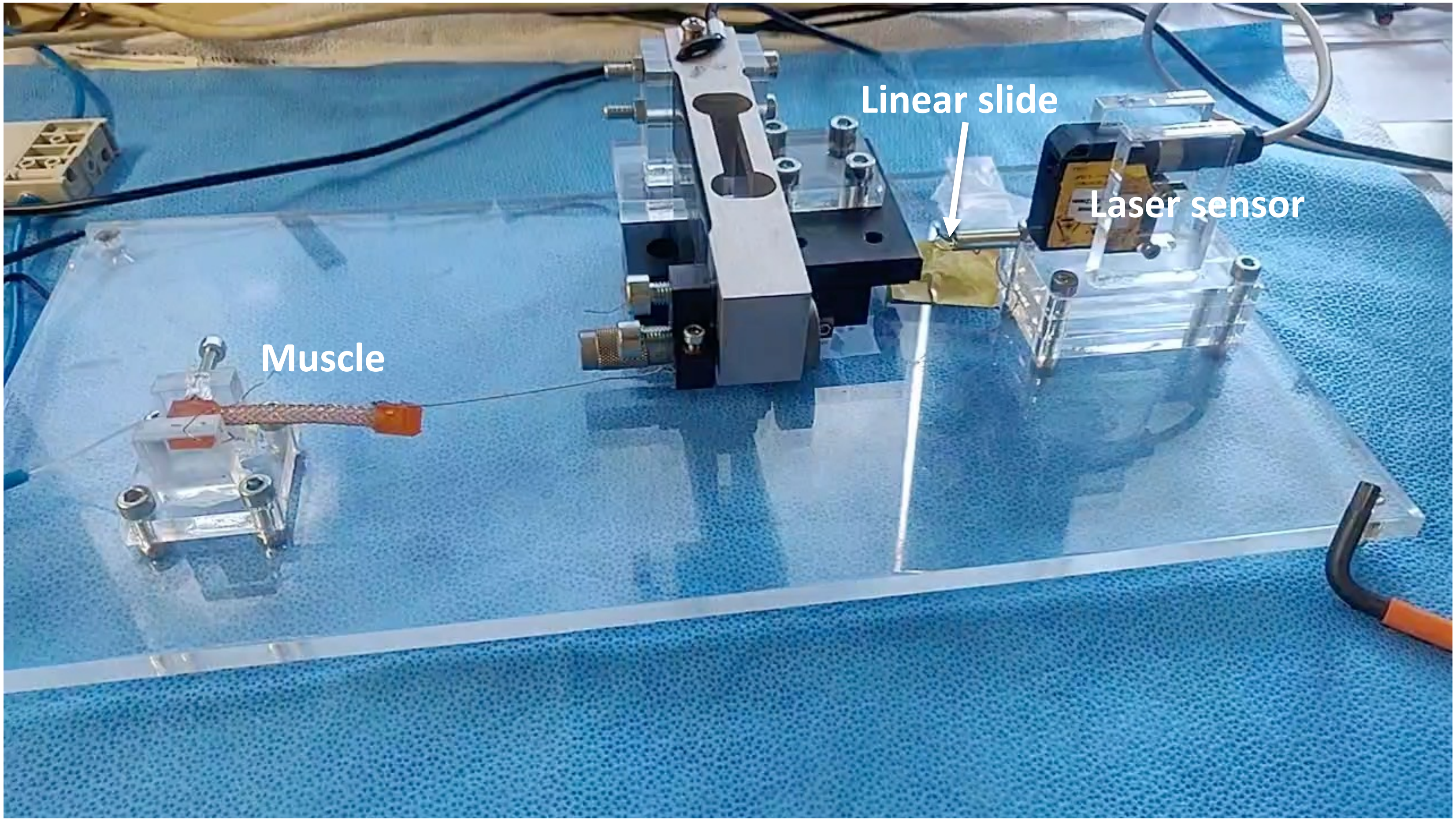
## Displacement & Force tests

LDC sensor



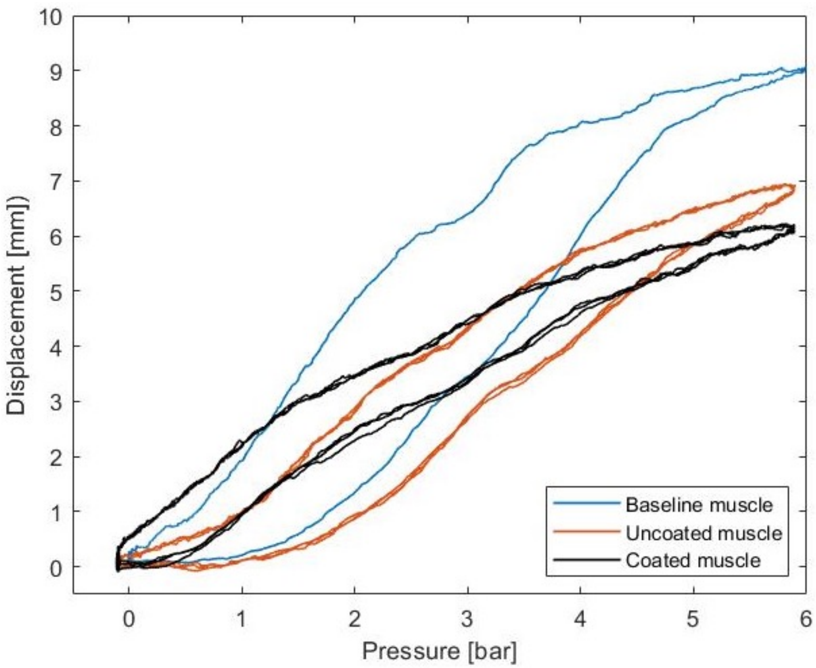
# TESTS: Displacement test





# RESULTS: Mechanical results

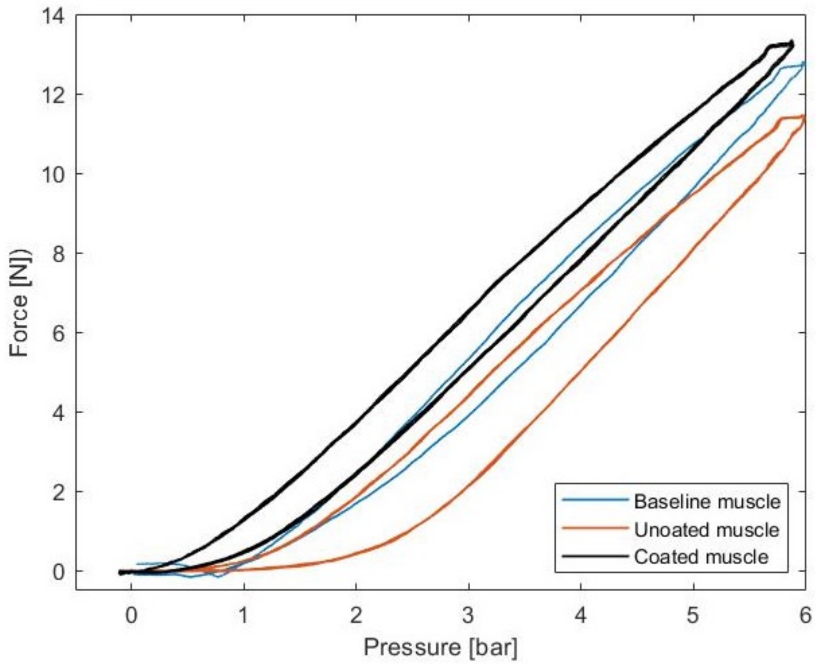
## Pressure-Displacement 0.5Hz




**Displacement**

Coated inductive muscle: 12.4%
Uncoated inductive muscle: 14.0%
Baseline muscle: 18.22%

## Pressure-Force 0.5Hz



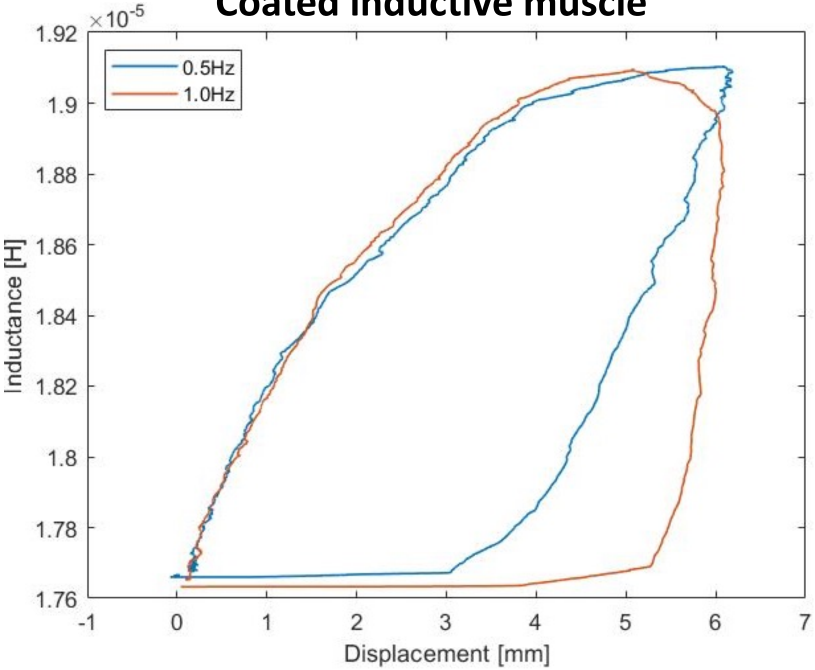

**Force**

Coated inductive muscle: 13.3N
Uncoated inductive muscle: 11.5N
Baseline muscle: 12.8N

# RESULTS: Electrical results

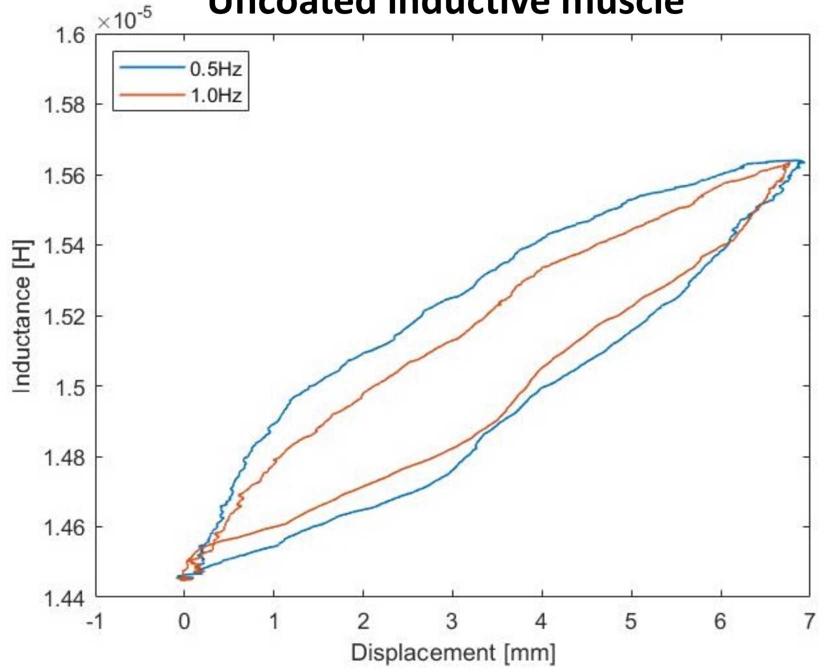


**Displacement-Inductance 0.5Hz vs 1.0Hz**
**Coated inductive muscle**




- ✗ Large hysteresis
- ✗ Loss of sensitivity
- ✗ Worst behavior for higher frequencies

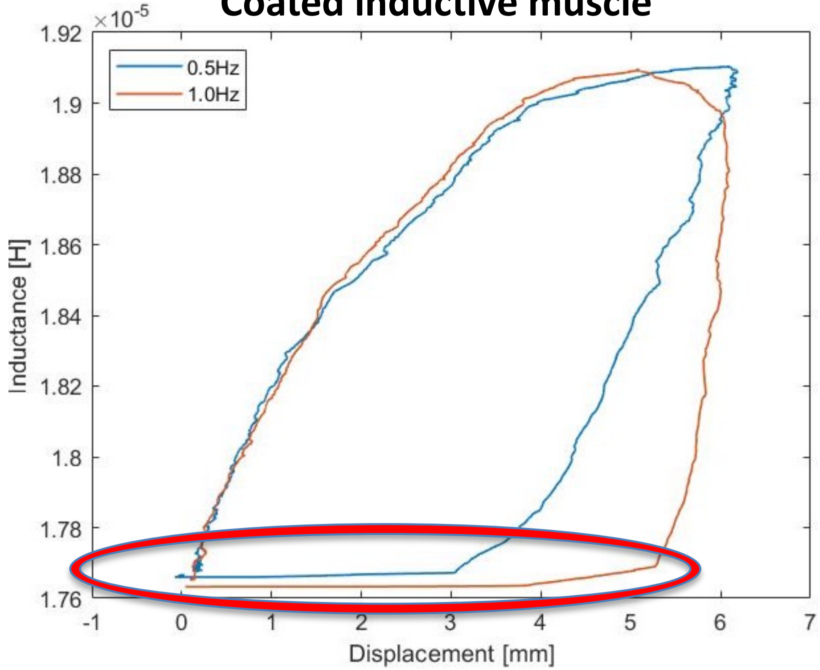
**Displacement-Inductance 0.5Hz vs 1.0Hz**
**Uncoated inductive muscle**




Limited hysteresis
Similar behaviour for each frequency

# RESULTS: Electrical results

## Displacement-Inductance 0.5Hz vs 1.0Hz
## Coated inductive muscle

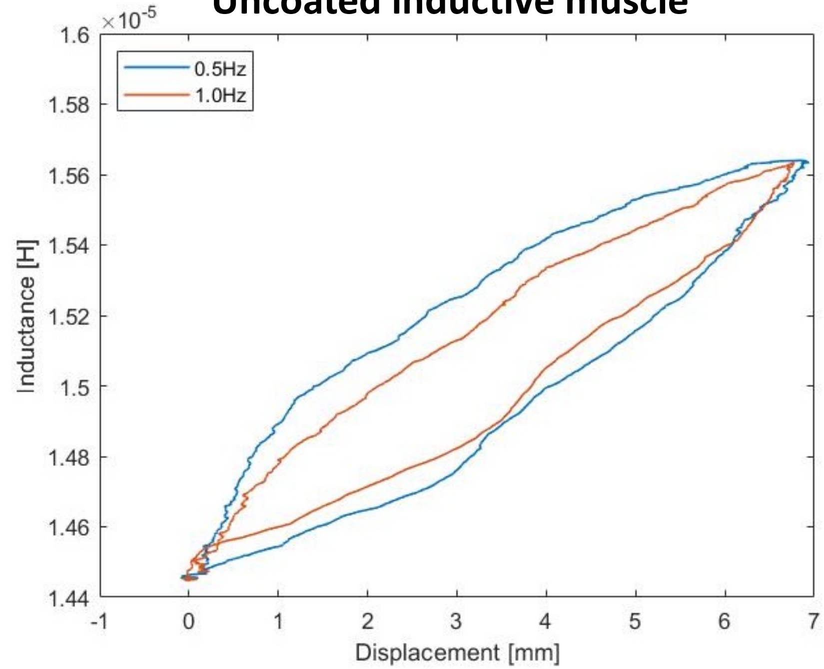



✗ Large hysteresis

✗ Loss of sensitivity

✗ Worst behavior for higher frequencies

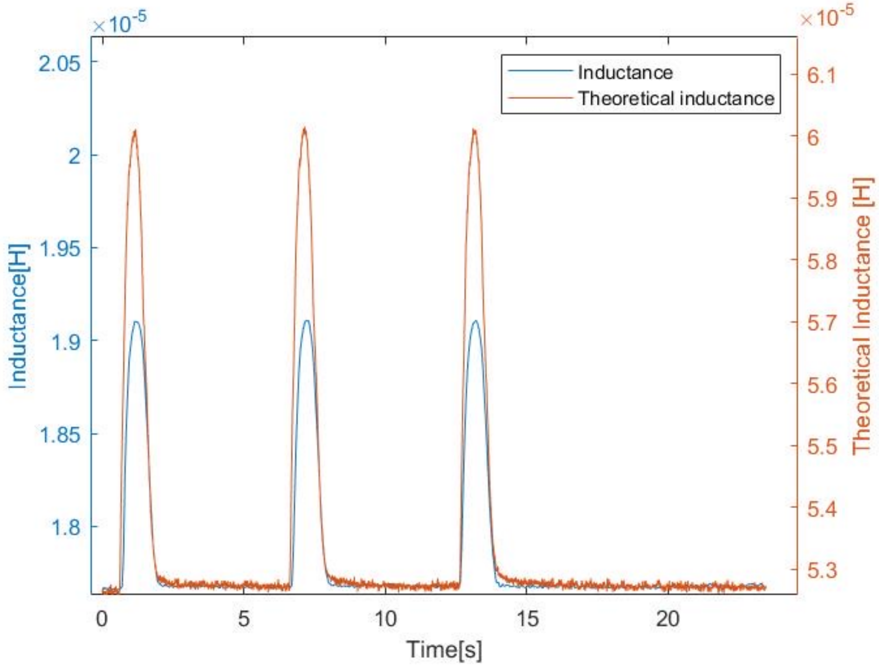
## Displacement-Inductance 0.5Hz vs 1.0Hz
## Uncoated inductive muscle

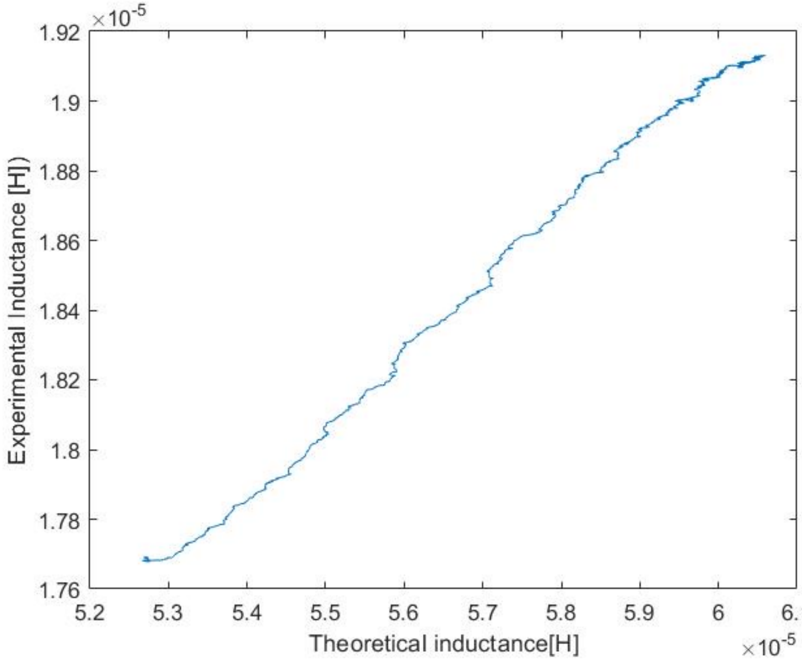



Limited hysteresis

Similar behaviour for each frequency

# RESULTS: Theoretical model




- Time synchronization
- Linear relationship
- Scaling factor ≈ 3



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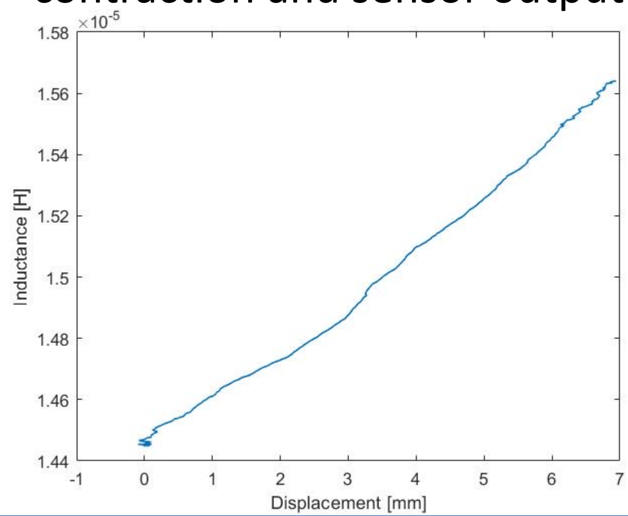
# DISCUSSION: Inductive vs capacitive

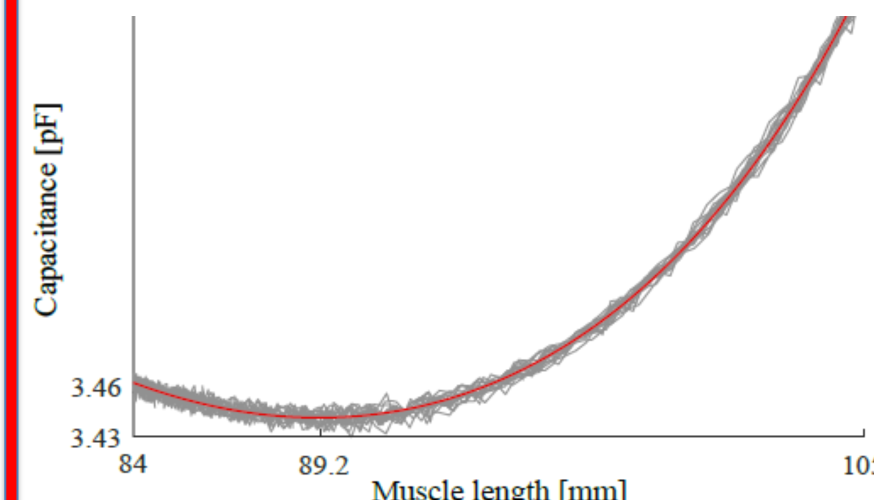
## Advantages

- **Easier** manufacturing process
- Adjustment of the braid to the **desired angle**
- **Linear relation** between muscle contraction and sensor output




## Limitations

- **Higher** hysteresis
- **Reduced** contraction



# CONCLUSIONS: Results and future work

## Scientific results

- **Limited hysteresis** in mechanical (≈**1 bar**) and electrical tests (uncoated inductive muscle)
- Successful **miniaturization** (**30cm → 5cm**) of the procedure
- **Novel information** for the coated inductive muscle
- **Linear relation** between muscle contraction and inductive sensor output

## Future work

- Theoretical model
- Braid wire
- Loaded conditions
- Ferromagnetic materials

Thank you for the attention!