Measurement and Instrumentation at the tissue-machine interface

INSCIT, Bento Gonçalves, RS, Brazil

August 30, 2018

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Distinguished Lecturer, IEEE Instrumentation and Measurement Society
SM, IEEE Engineering in Medicine and Biology Society

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The Instrumentation and Measurement Society's Field of Interest is

the science, technology and application of instrumentation and measurement.

"To measure is to know"

- Lord Kelvin, 1883

Instrumentation & Measurement Society
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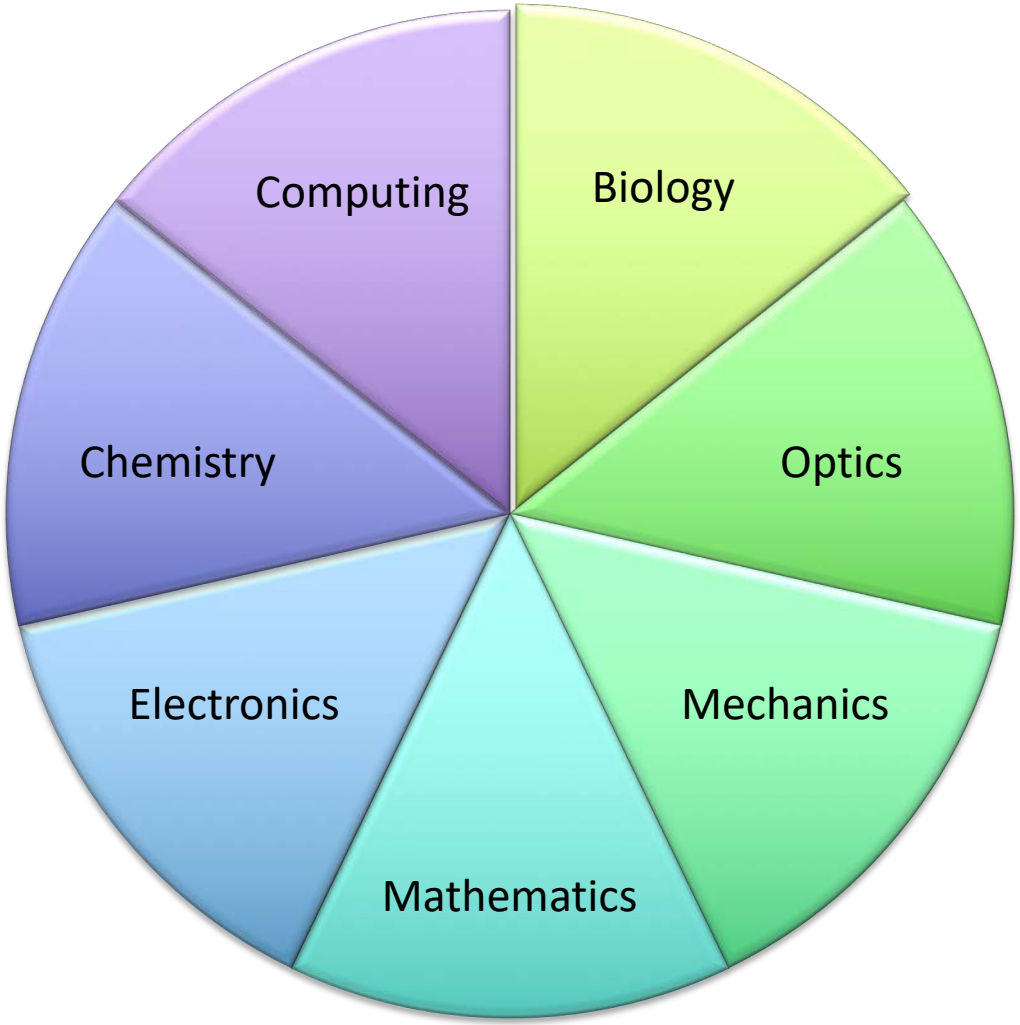
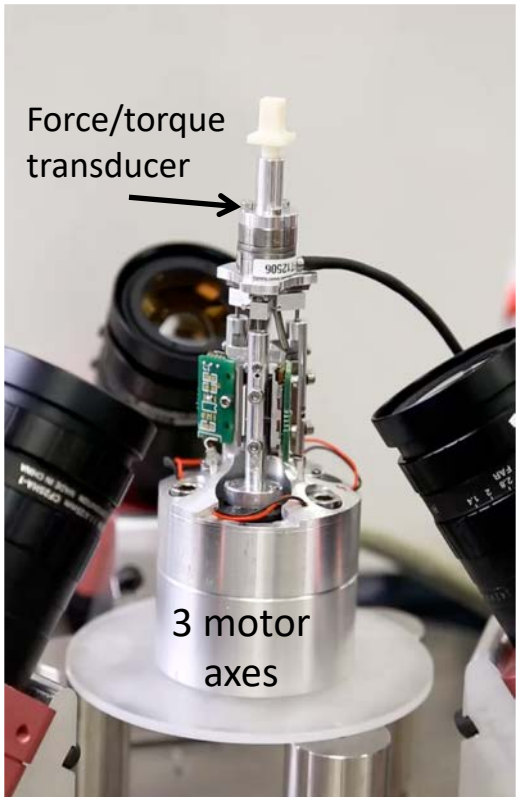
Bioinstrumentation

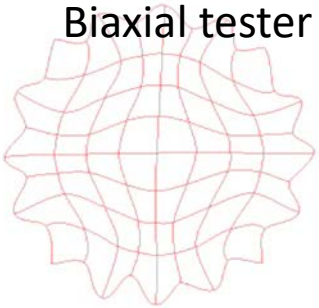


Automated robotic devices



Force sensitive microrobot

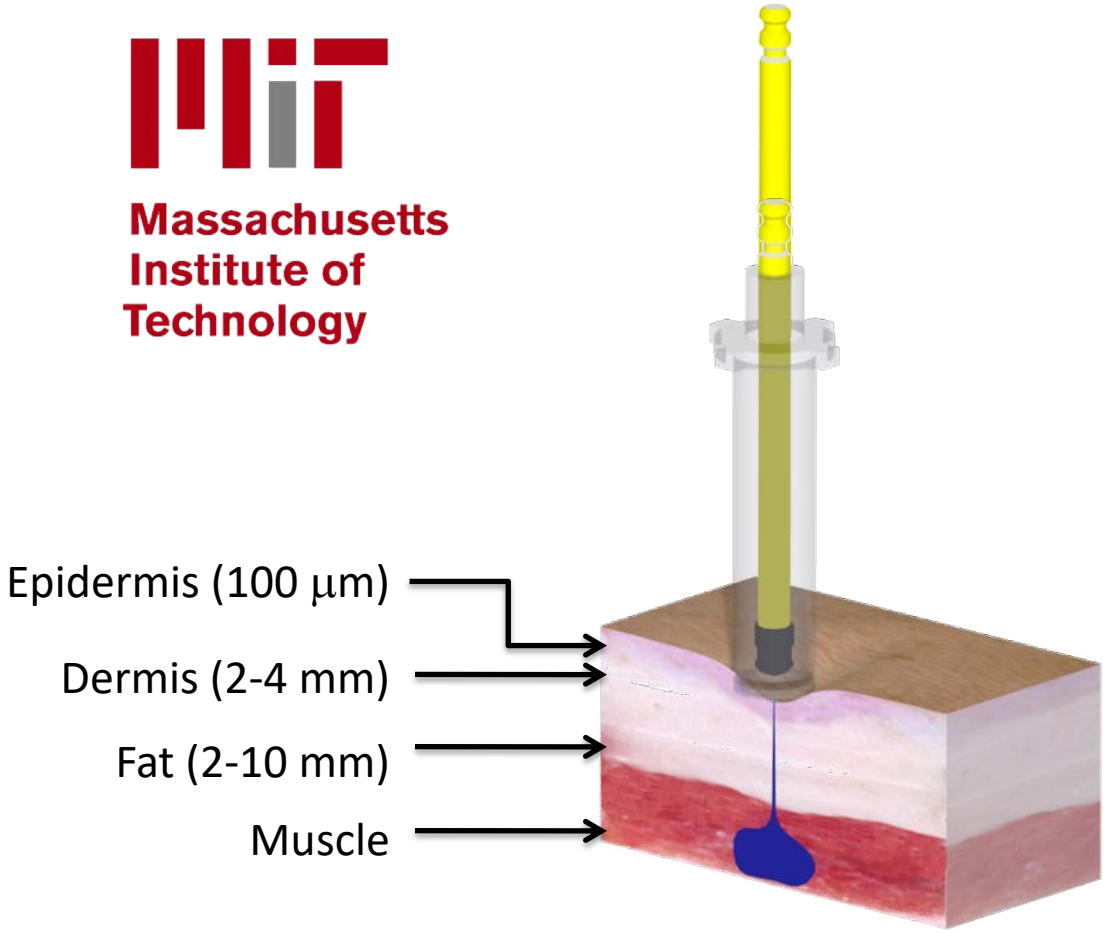
Biaxial tester

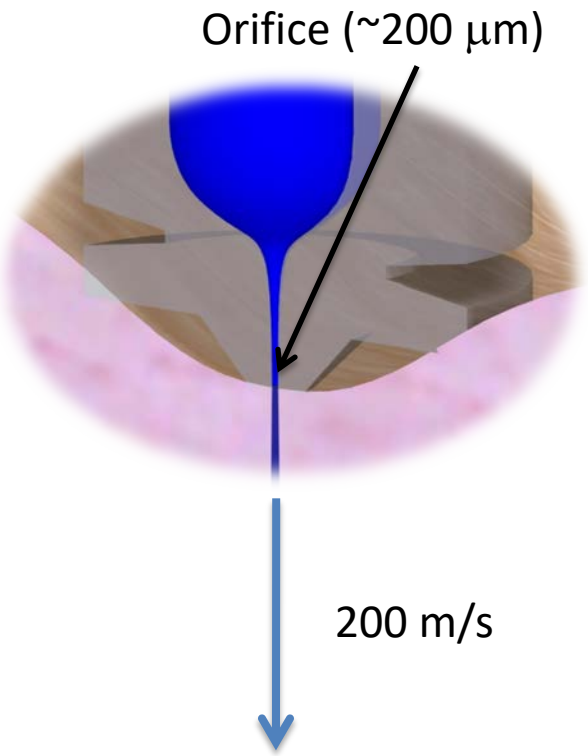


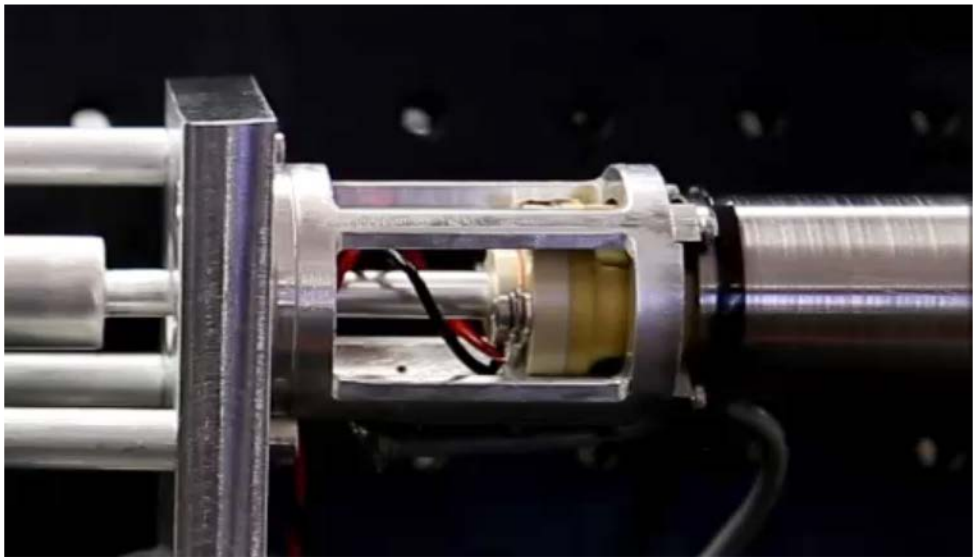
Pelvic floor elastometer

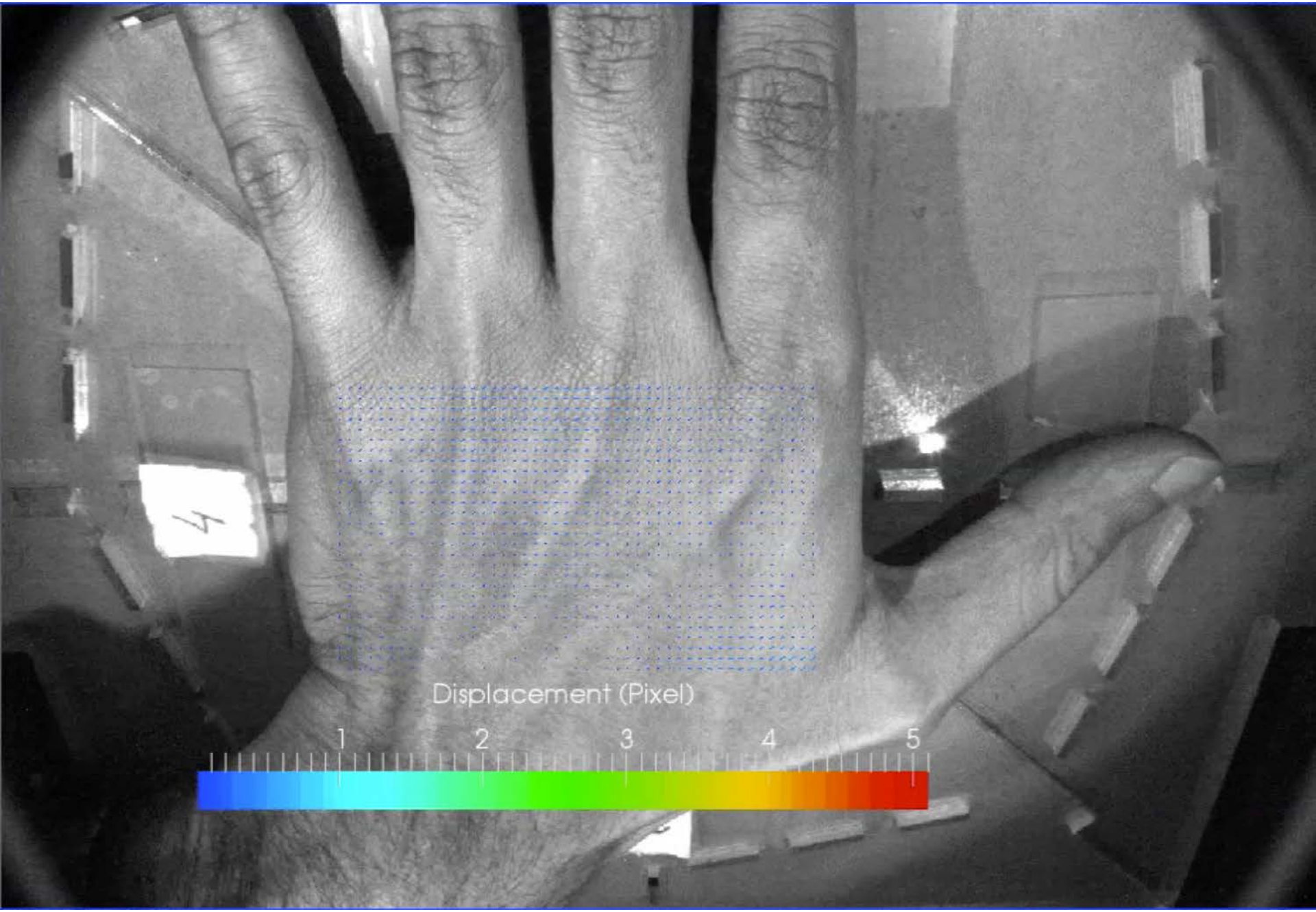
Needle free jet drug delivery

Massachusetts Institute of Technology

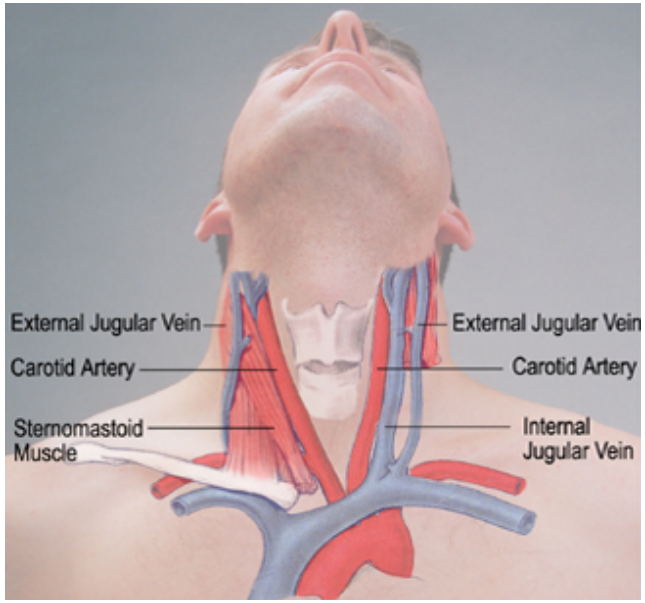


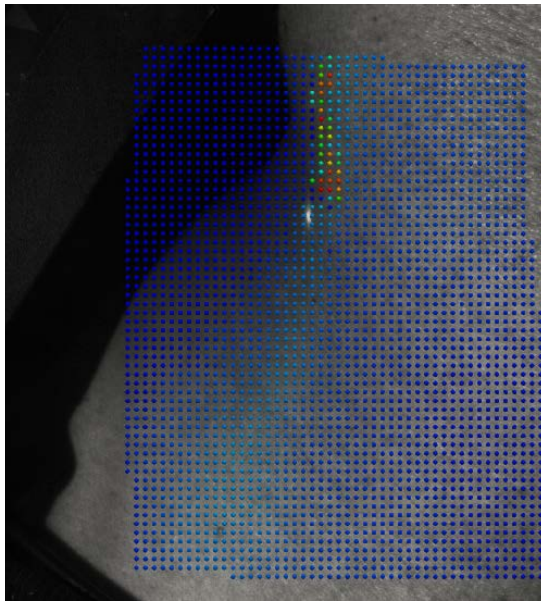


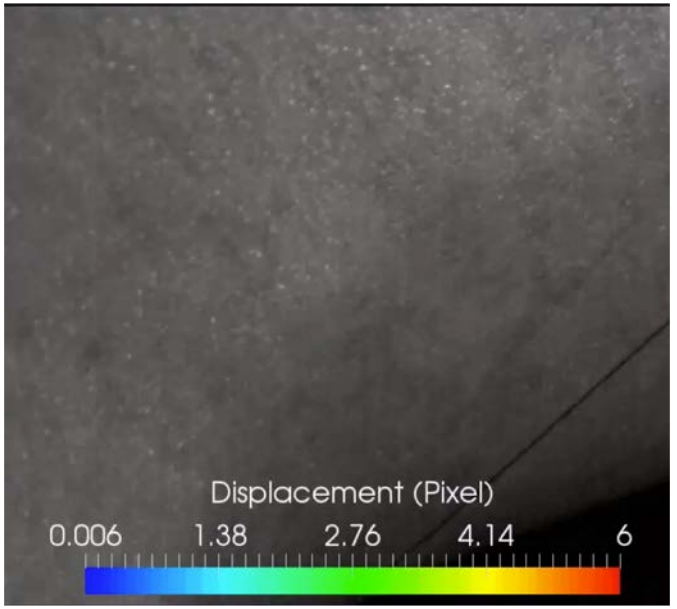


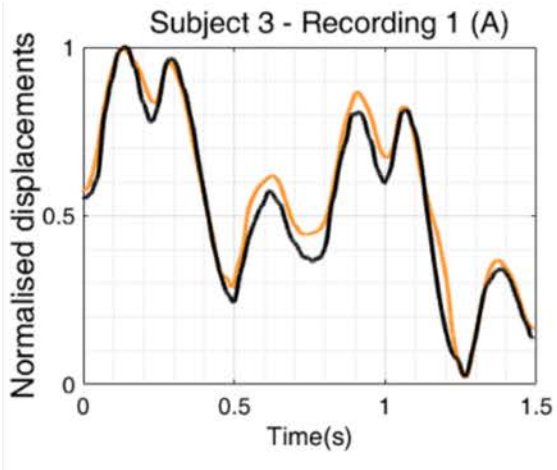

Displacement (Pixel)
1
2
3
4
5

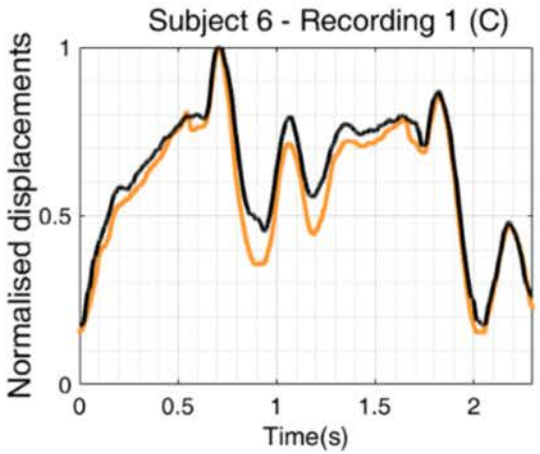
Estimation of Pulse waveforms

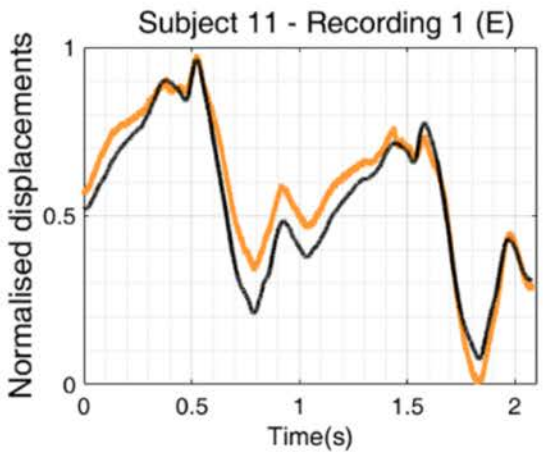








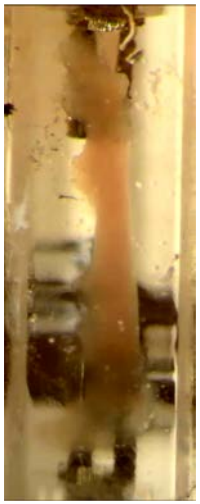




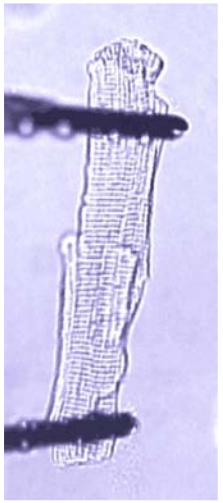
Measured using a laser displacement sensor
Measured using our method

A dynamometer for the heart

10 mm



1 mm



0.1 mm

Andrew J. Taberner

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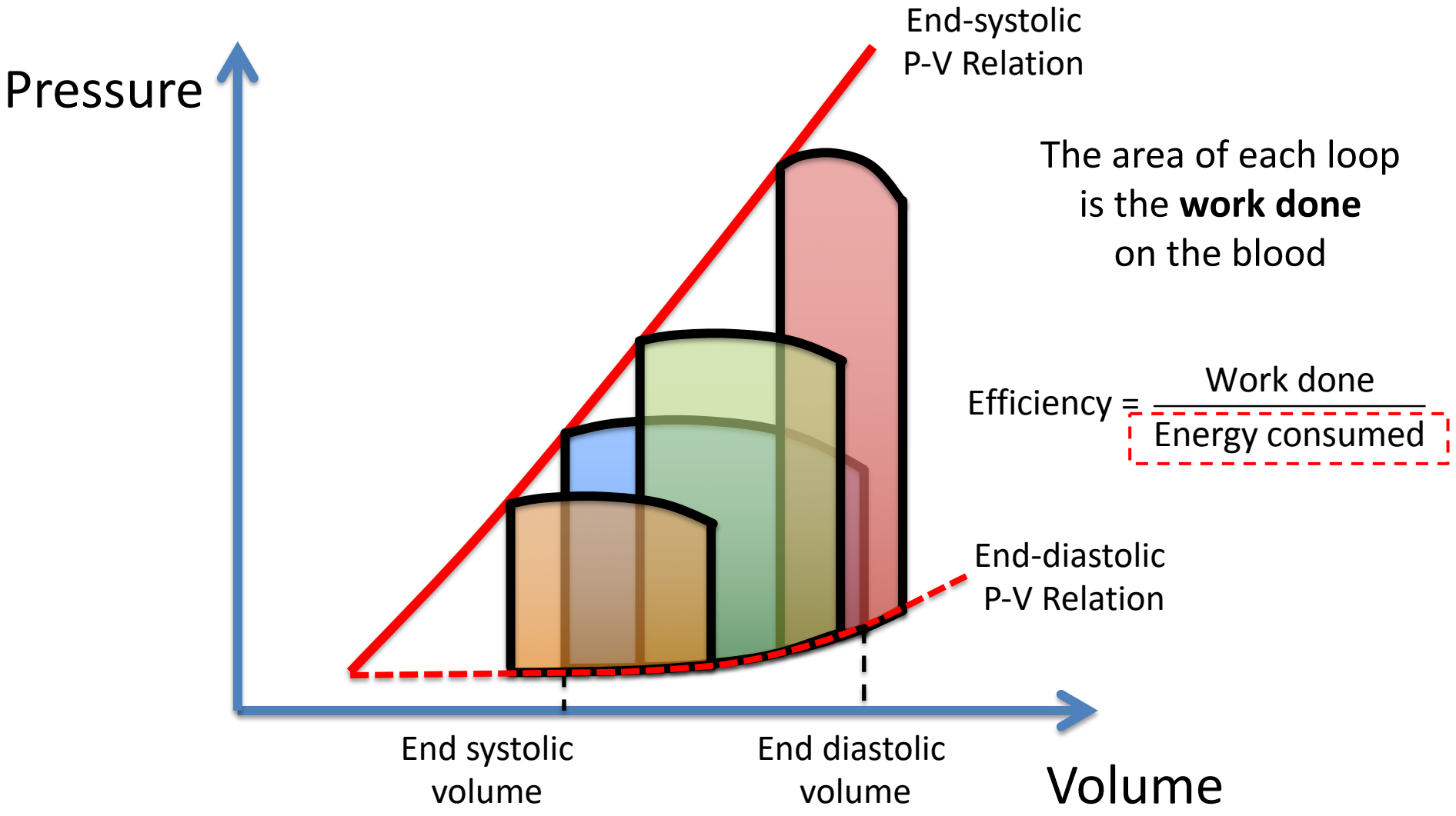
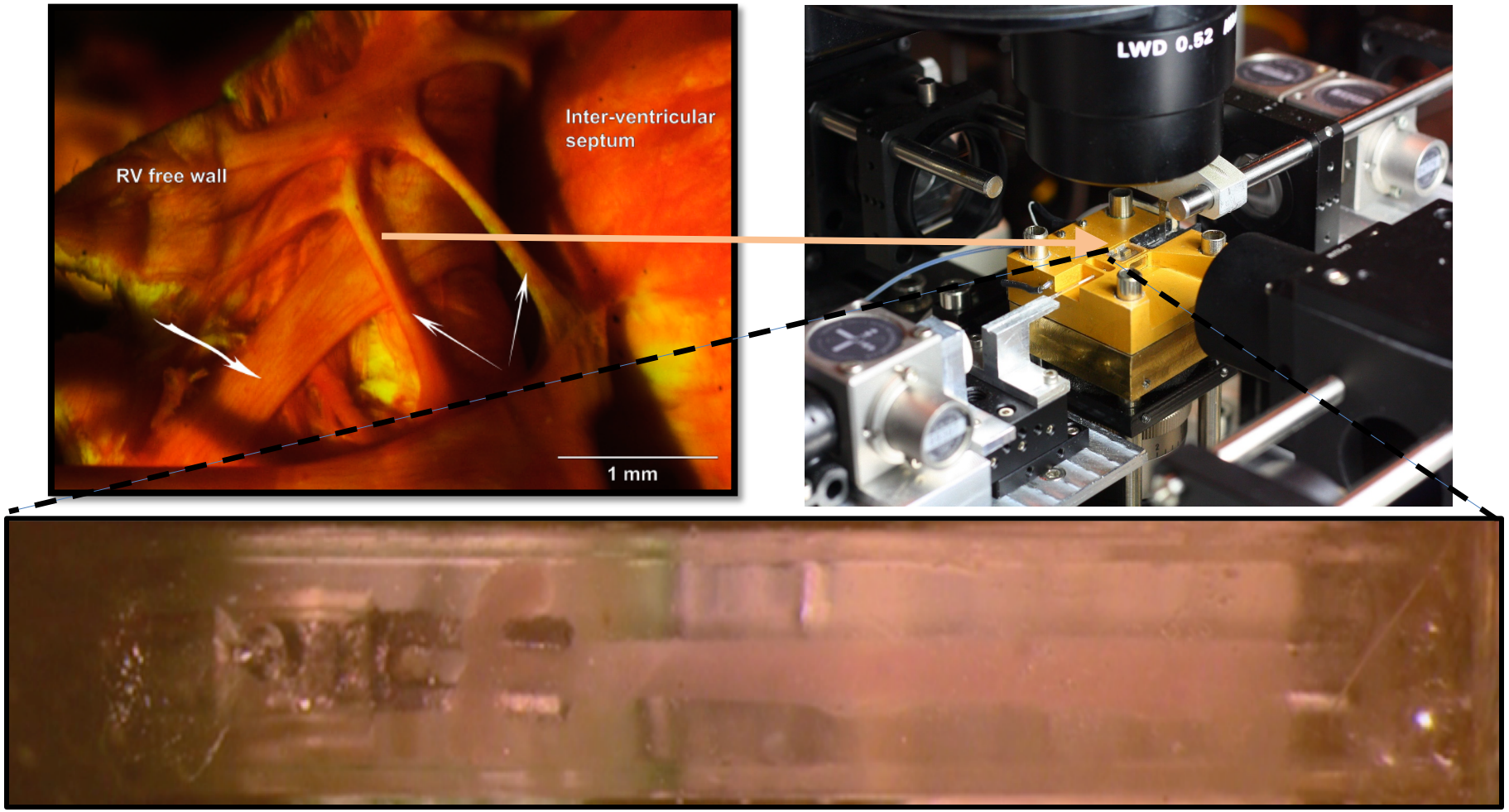
The ventricular ejection cycle



What to measure or control

- Inputs
  - Fuel consumption (Adenosine triphosphate/oxygen), electrical stimulation
- Loads
  - Mechanical impedance, work done, temperature, drugs
- Outputs
  - Pressure, flow rate, heart rate
- Properties
  - Stiffness, geometry, efficiency

Isolated ‘Trabecula’ Measurements



Parameters to measure or control

Mechanical

Length

Force

Stiffness $= \frac{\Delta F}{\Delta L}$

Metabolic

Heat rate

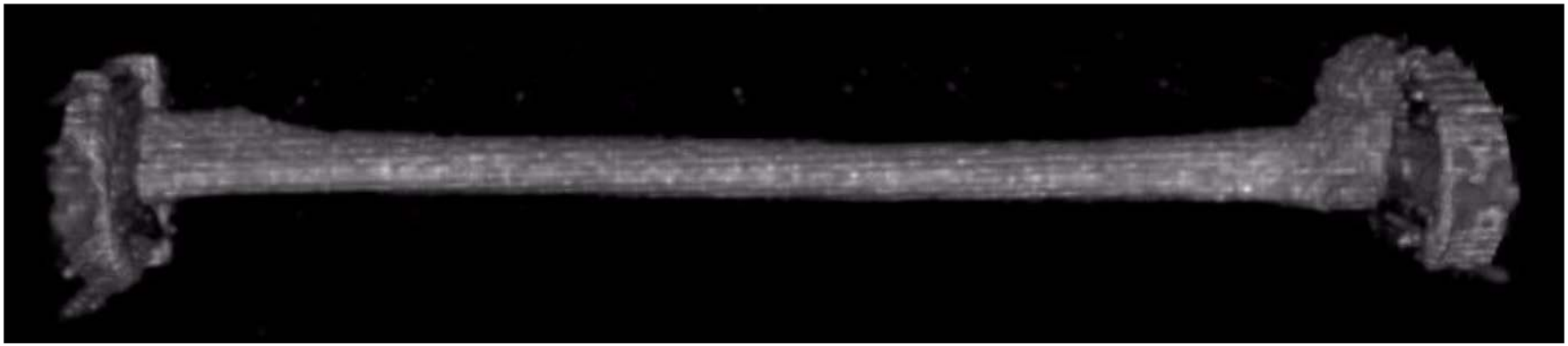
Oxygen consumption

$[Ca^{2+}]_i$

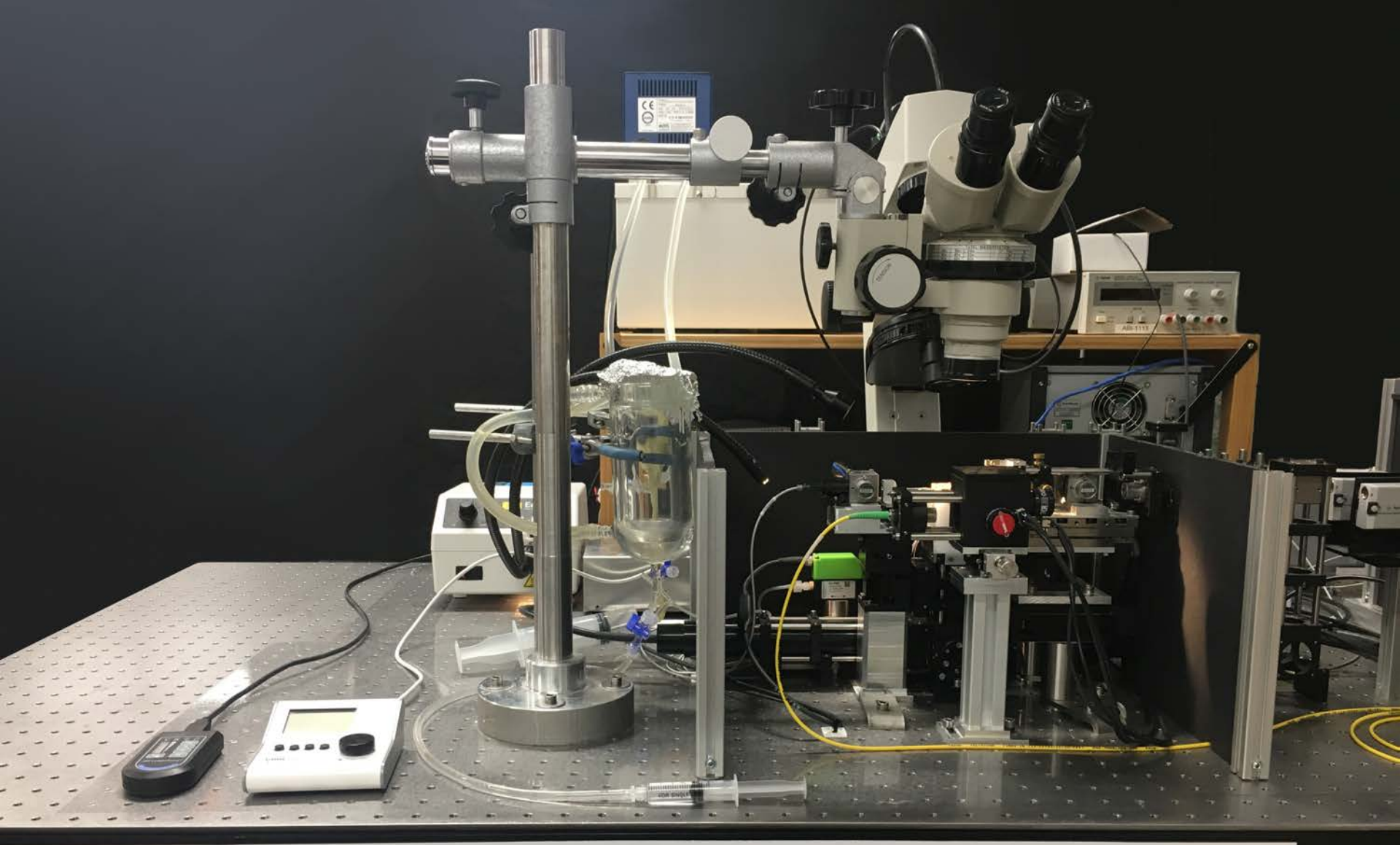
Geometric

Sarcomere length

Shape



1 mm



CARDIOMYOMETER

CTED, AND
D BY

Andrew Taberner · Poul Nielsen · Callum Johnston · Alex Anderson · Ming Cheuk
Bryan Ruddy · Stephen Olding · June-Chiew Han · Denis Loiselle · Marie Ward
Jarrah Dowrick · Amy Garrett

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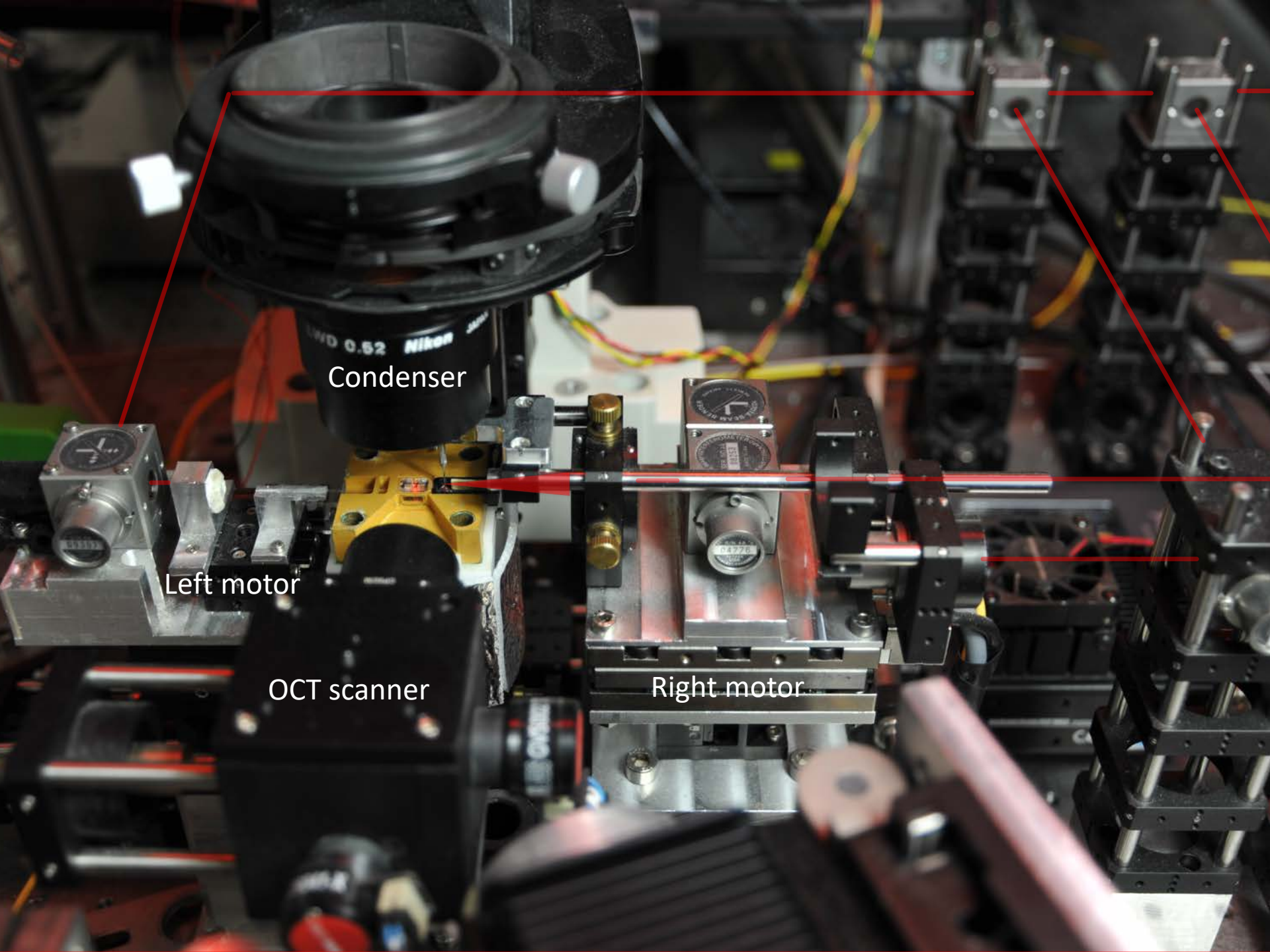
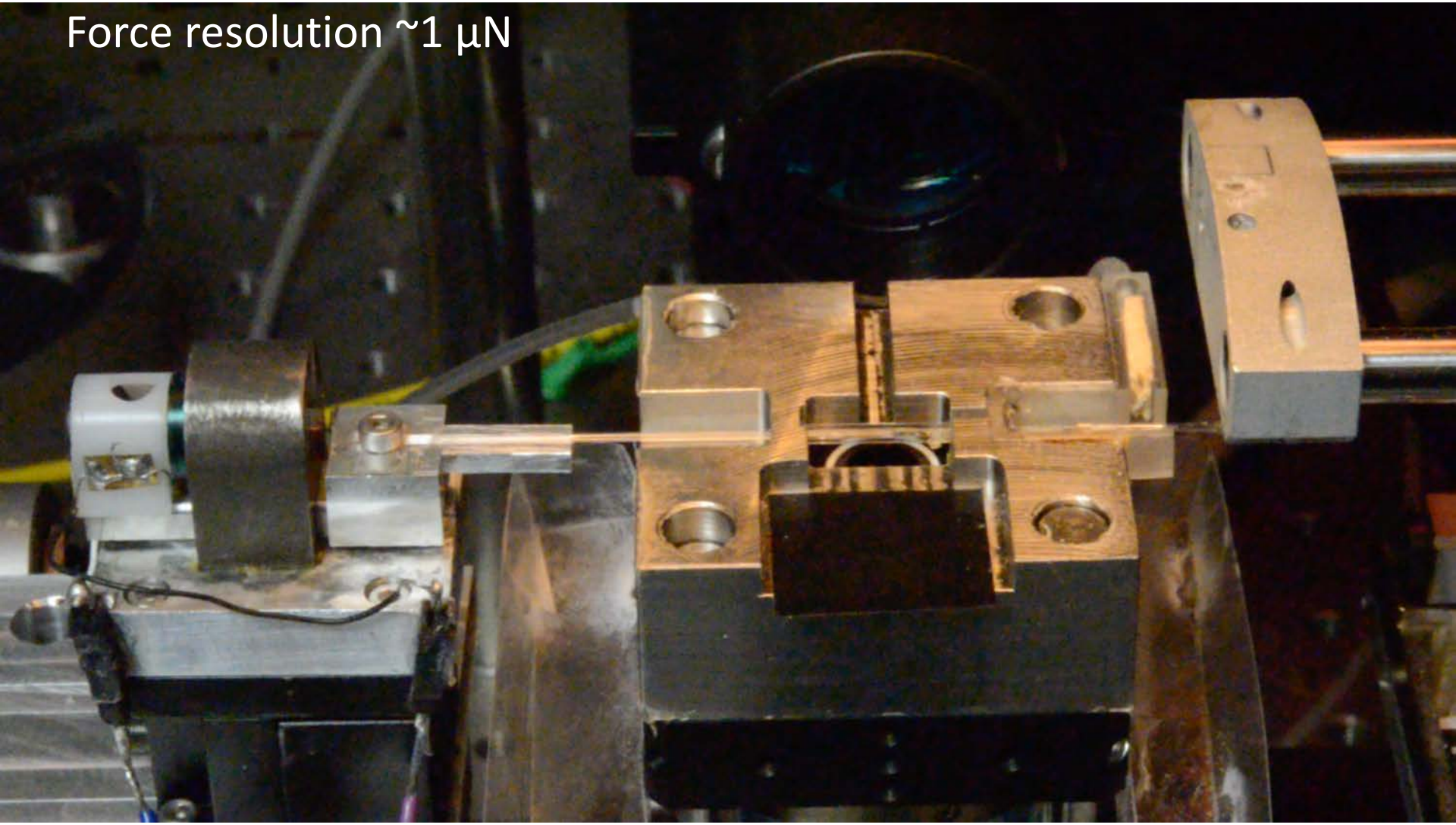
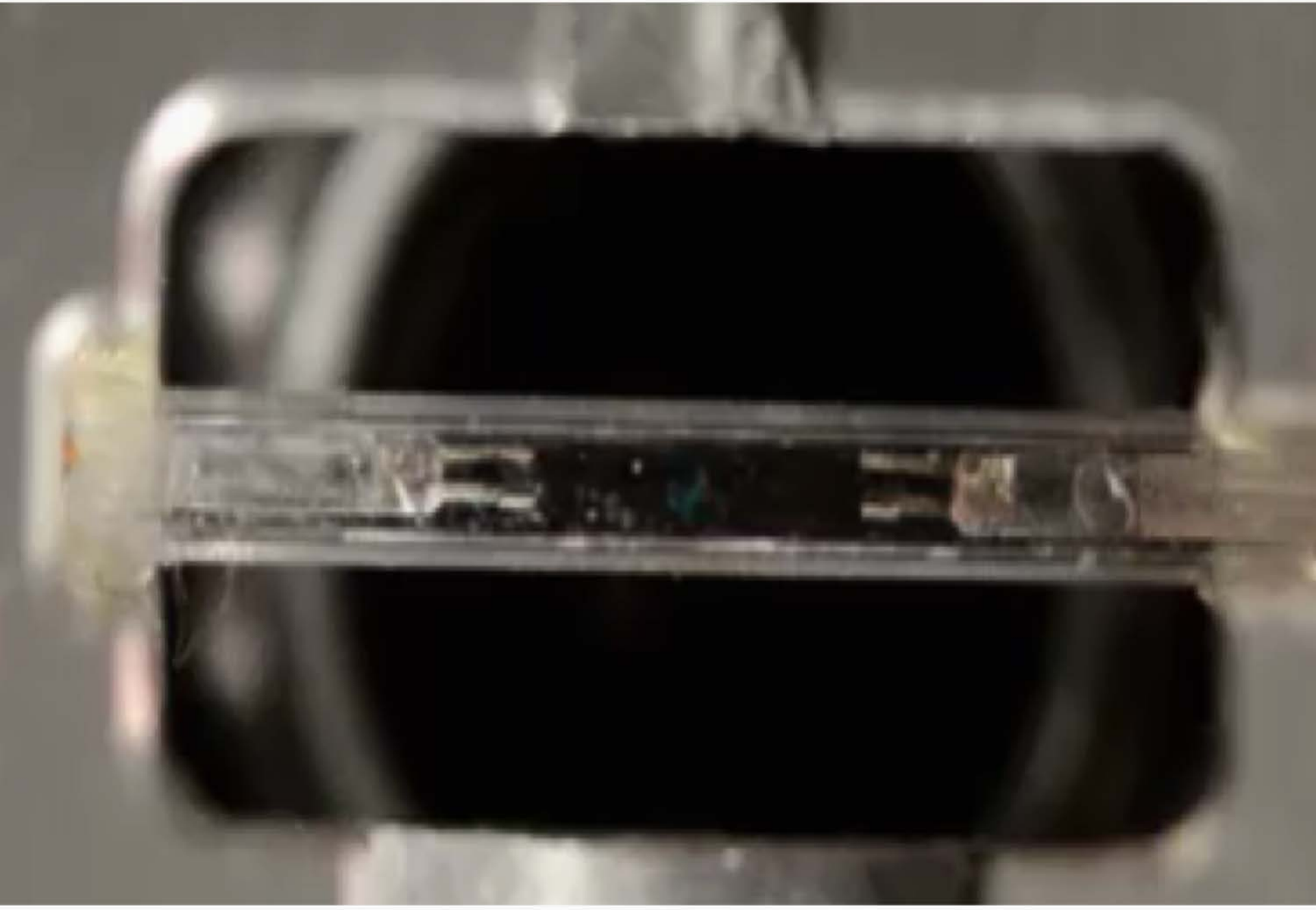
MASSEY FUNDI
MIT
Heart Foundation
hrc

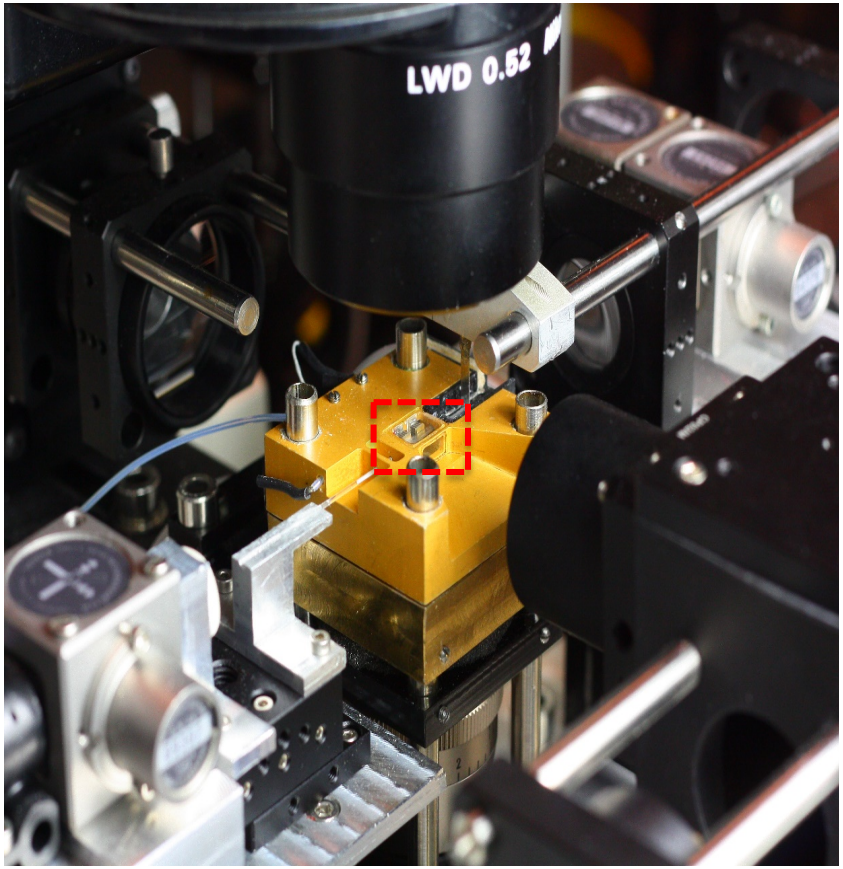

Condenser
Left motor
OCT scanner
Right motor

Force resolution ~1 μN





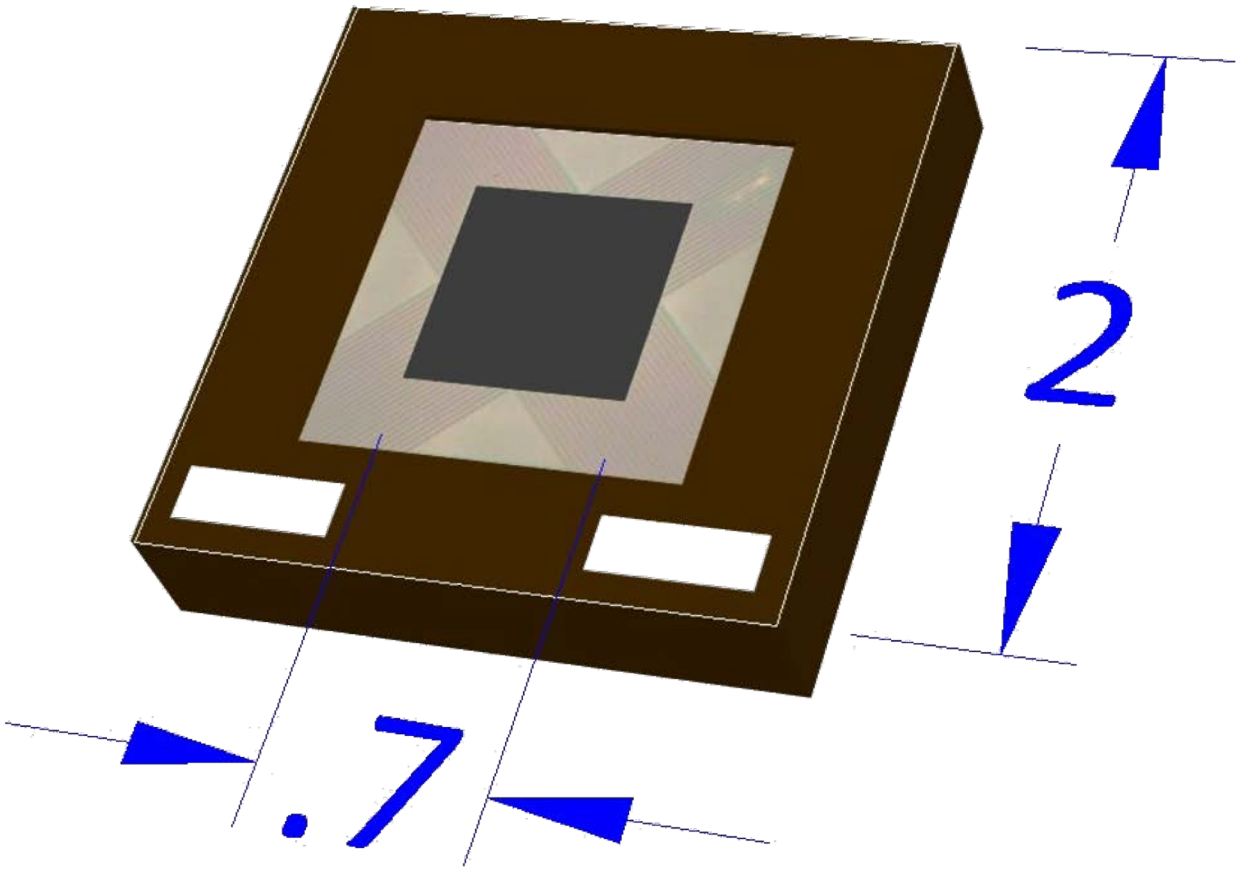
Cardiac Myometer



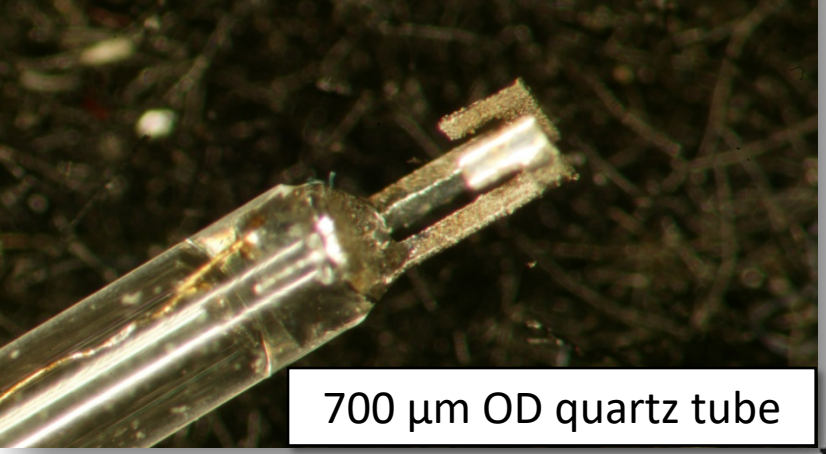
- Force/Length
  - Laser Interferometer with custom voice-coil motors
  - FPGA-based control algorithm
- Heat rate

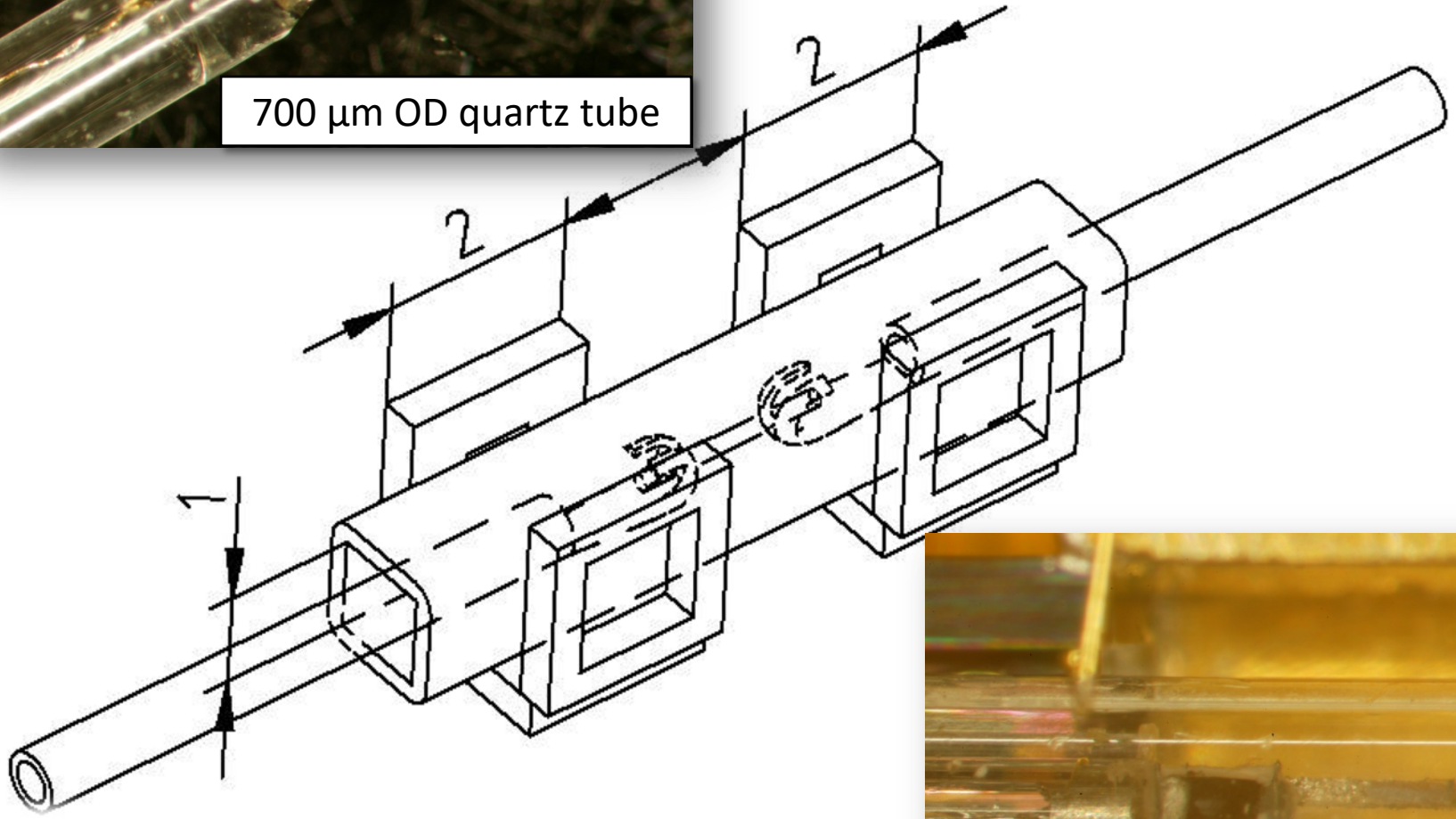
HL PlanarTechnik Infra-red thermopile-based bolometer

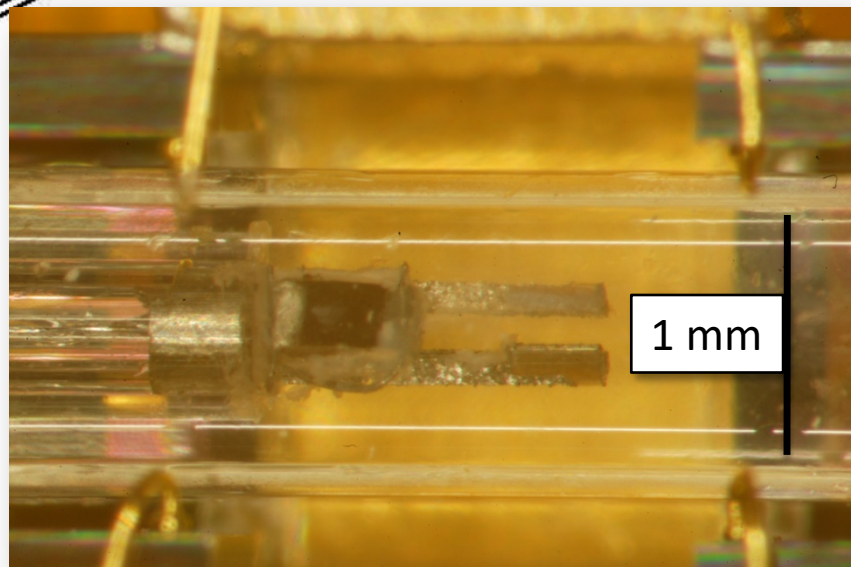
In-ear thermometer
www.braun.com

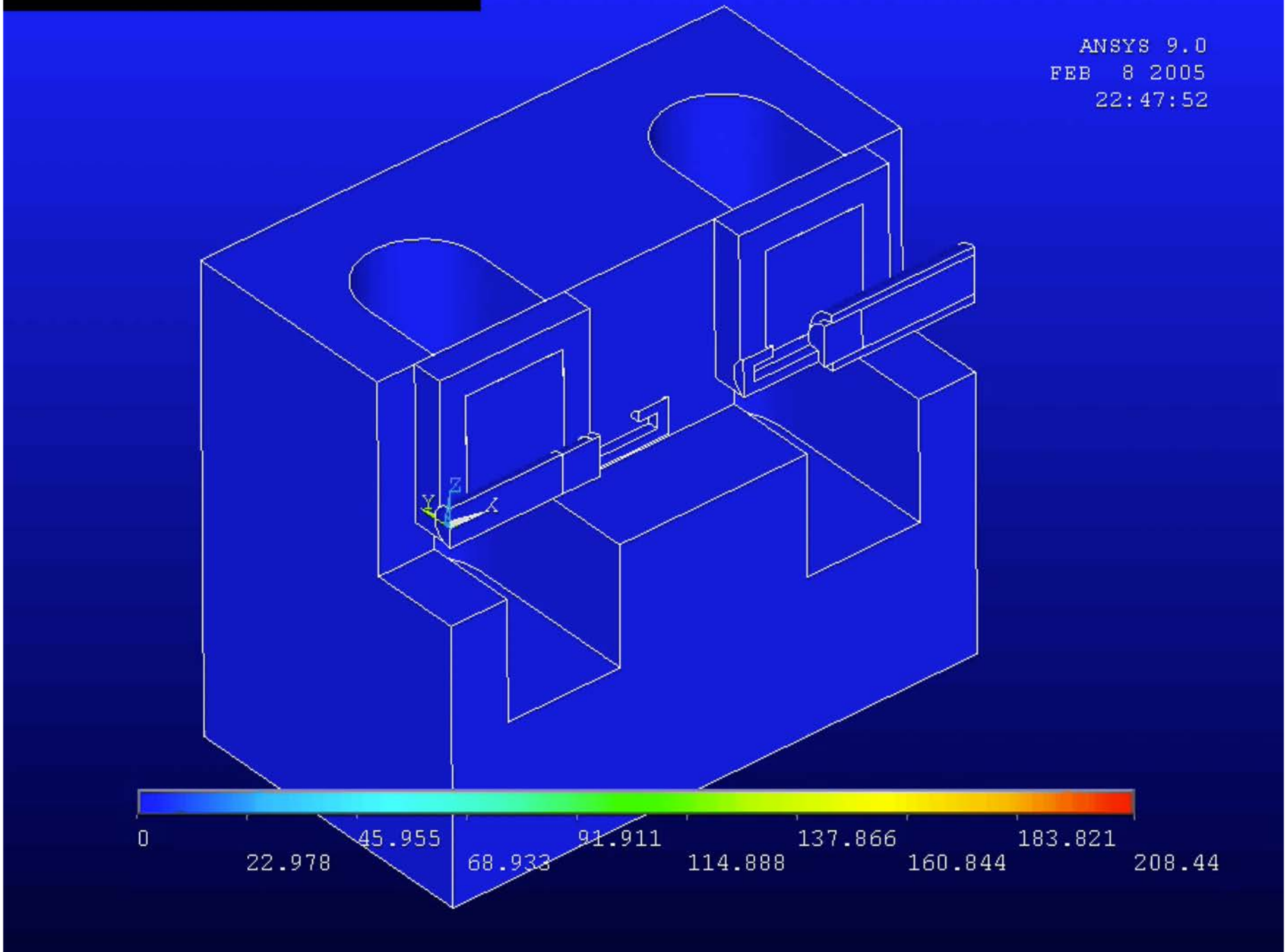


Dimensions in mm


700 µm OD quartz tube


2
2
1


1 mm


ANSYS 9.0
FEB 8 2005
22:47:52
0
22.978
45.955
68.933
91.911
114.888
137.866
160.844
183.821
208.44

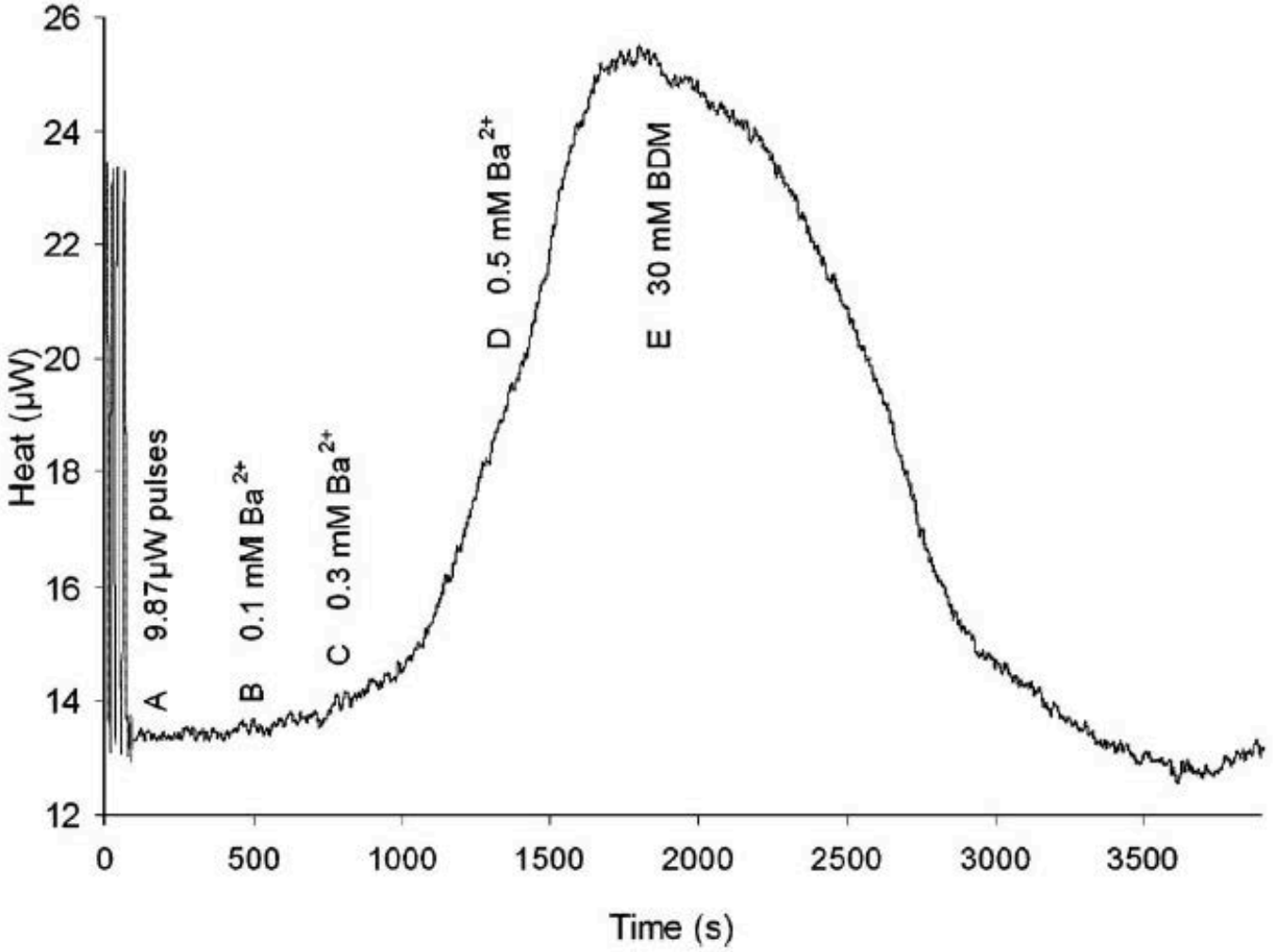
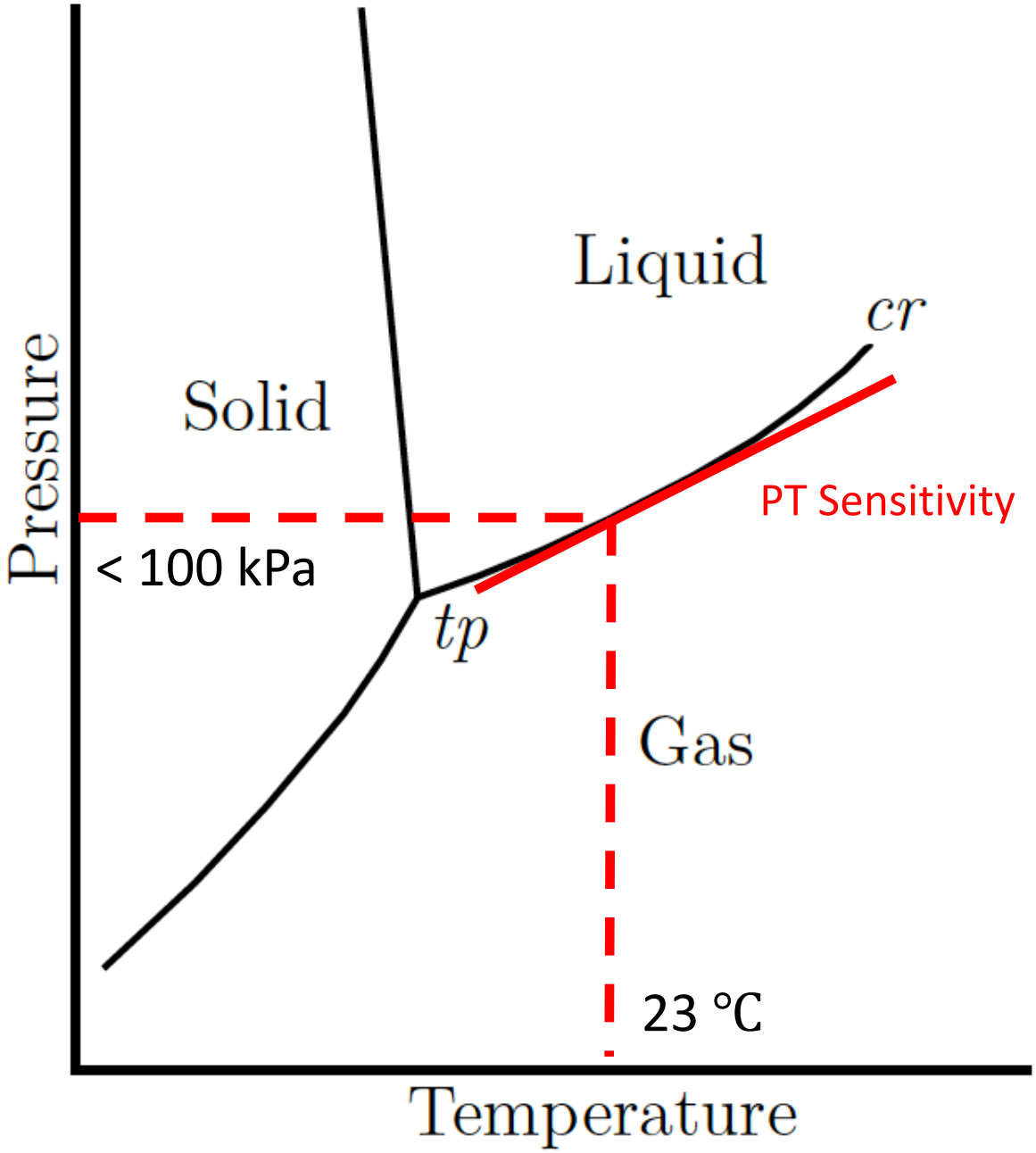


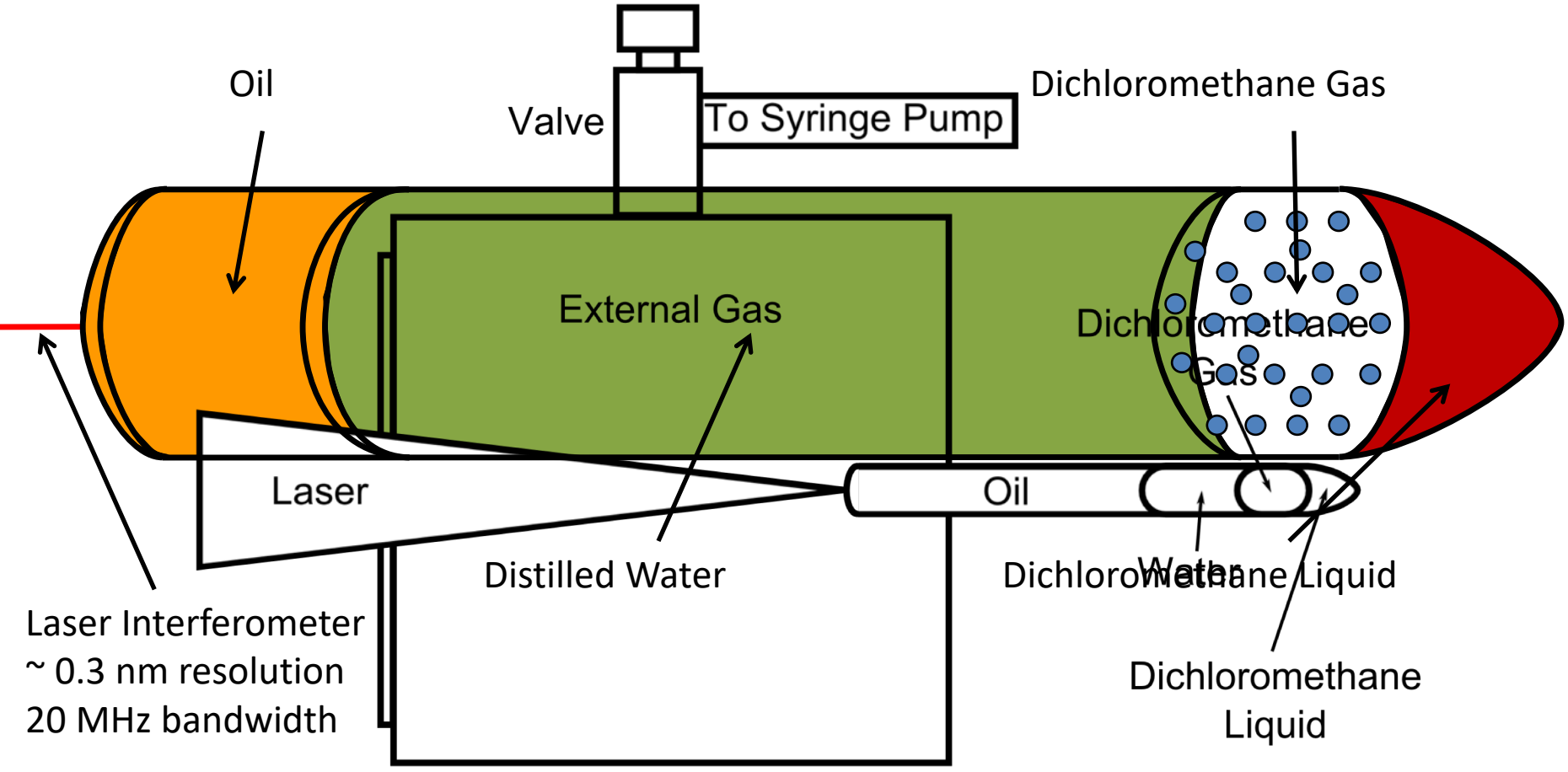
FIG. 8. Heat output of a cardiac trabecula in response to a Ba^{2+} contracture eventually terminated by the introduction of BDM.

Heat rate?


Liquid
cr
Solid
Pressure
PT Sensitivity
< 100 kPa
tp
Gas
23 °C
Temperature

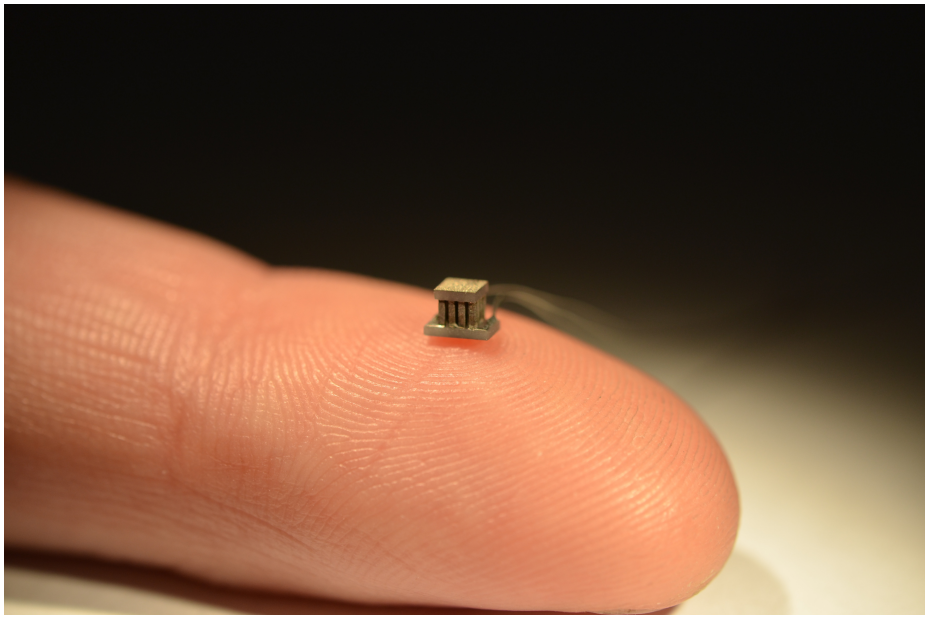
Substance	PT Sensitivity ($\mathrm{kPa \cdot K^{-1}}$)
Acetone	1.32
Carbon Disulfide	1.82
Chloroform	1.14
Dichloromethane	2.30
Methanol	0.88
Methyl Acetate	1.28
Water	0.19

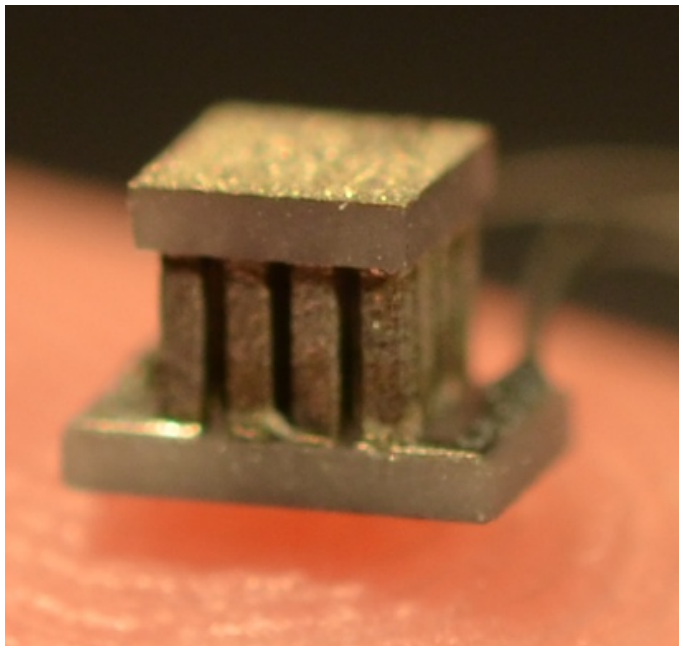
Vapour Pressure Thermometry



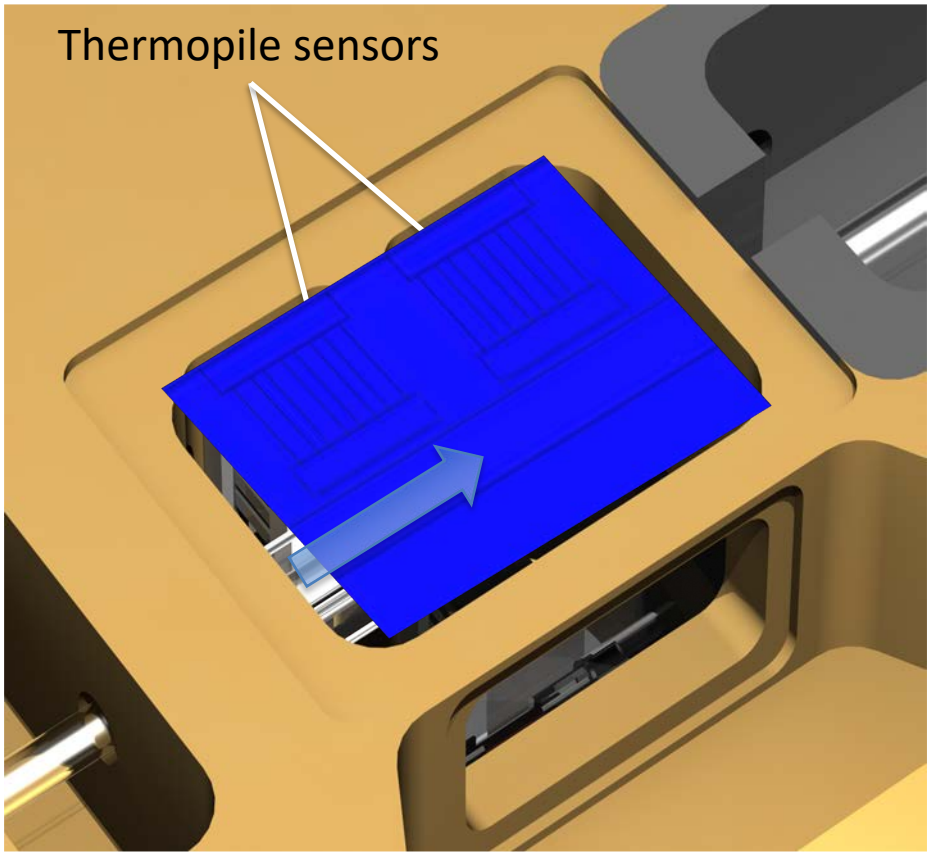
Vapour Pressure Thermometry?

- Range: ~0.5 K
- Resolution: 16.1 µK/√Hz – highest for vapour pressure sensor
- Modest reproducibility between sensors
- Expensive, and not very practical!

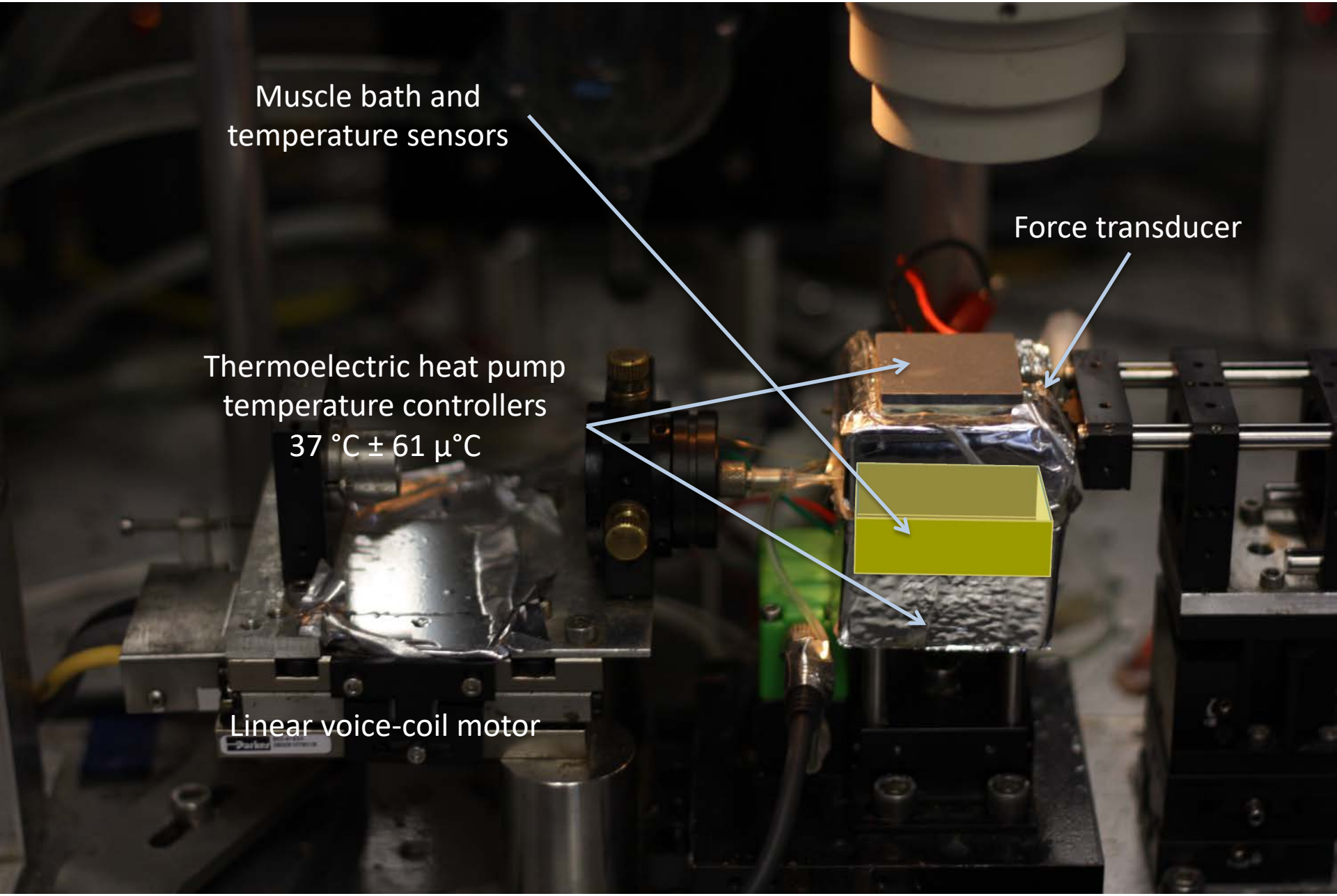


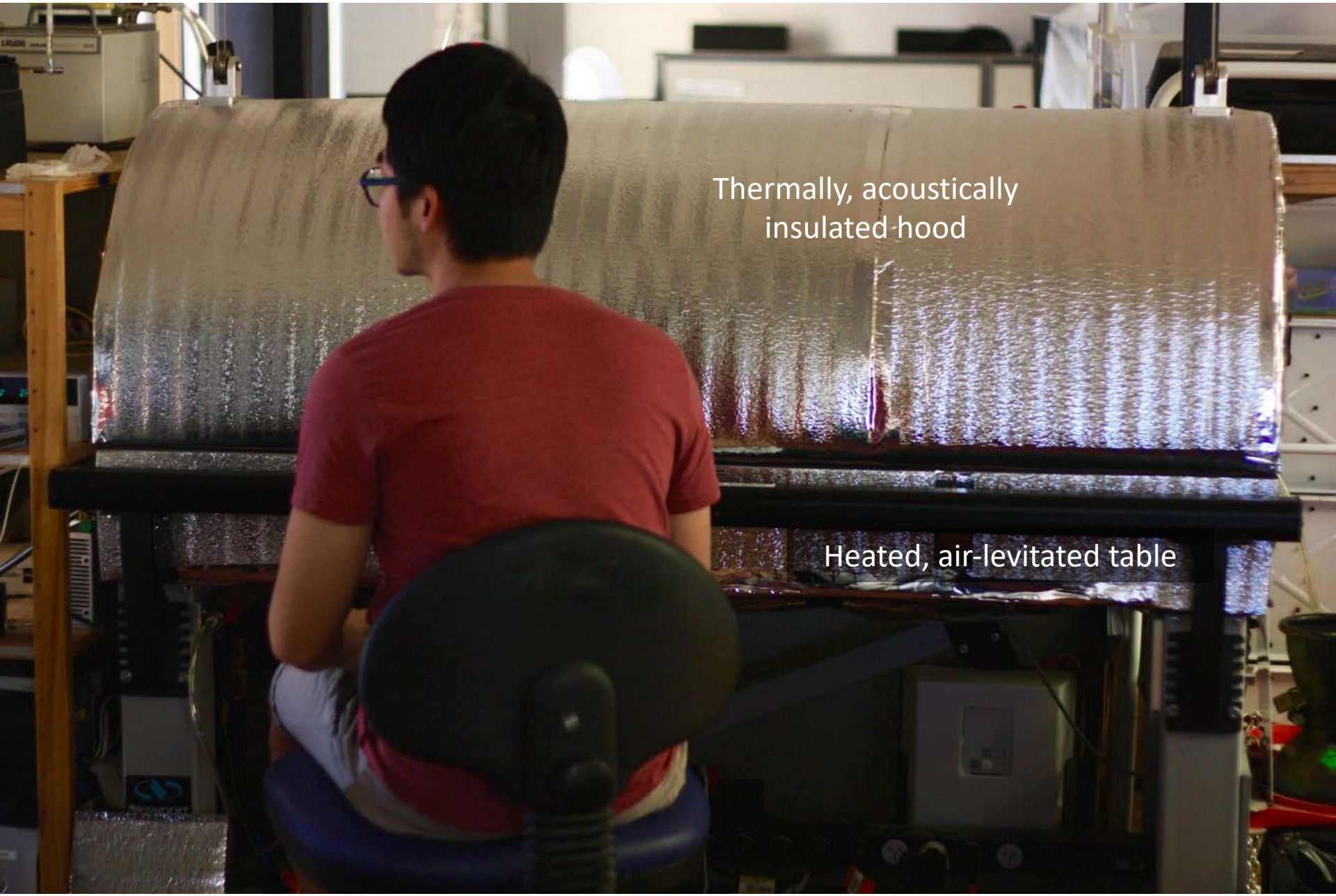


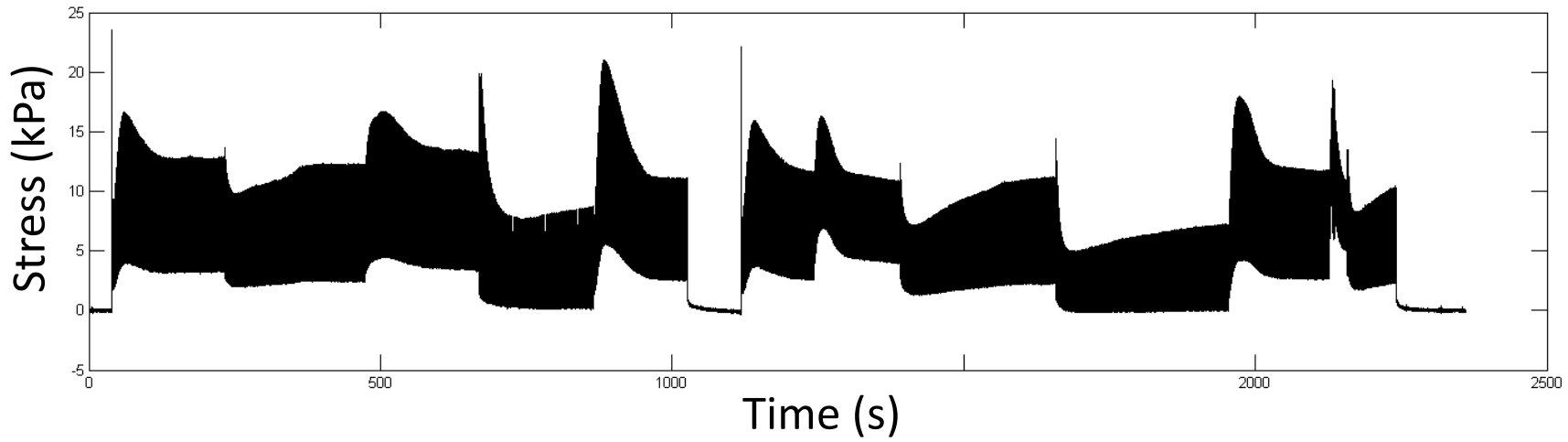
~3 µW, 1 mK
Sensitivity: 300 mV/W
Heat rate resolution: 10.8 nW
Time constant: ~15 s

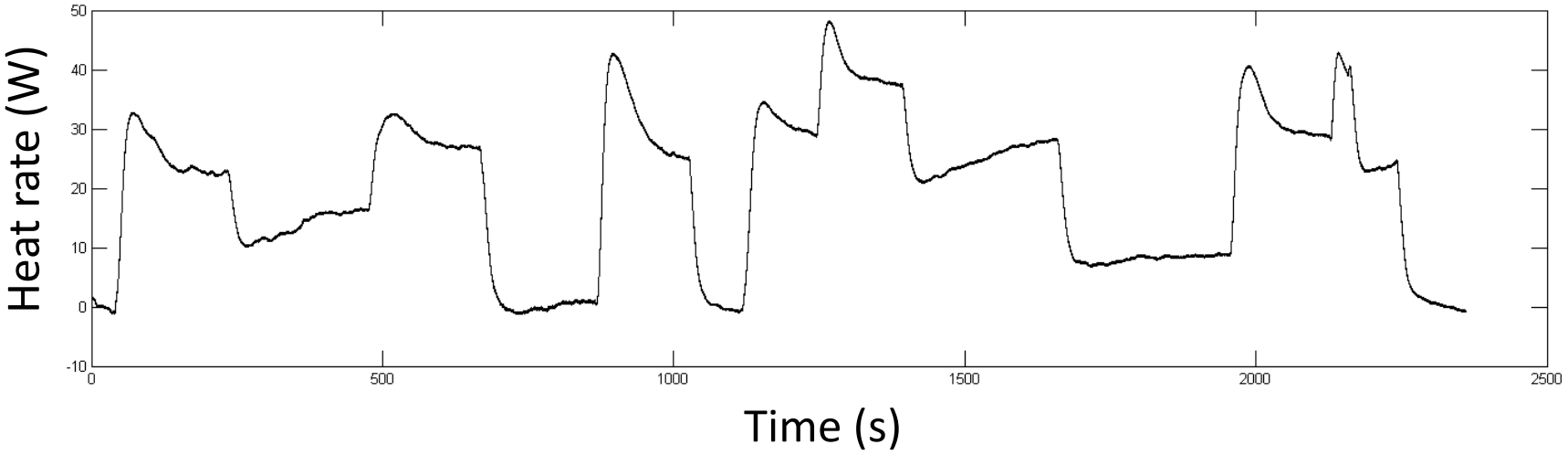


- Force/Length
  - — Laser Interferometer
- Heat rate
  - — Flow through calorimetry

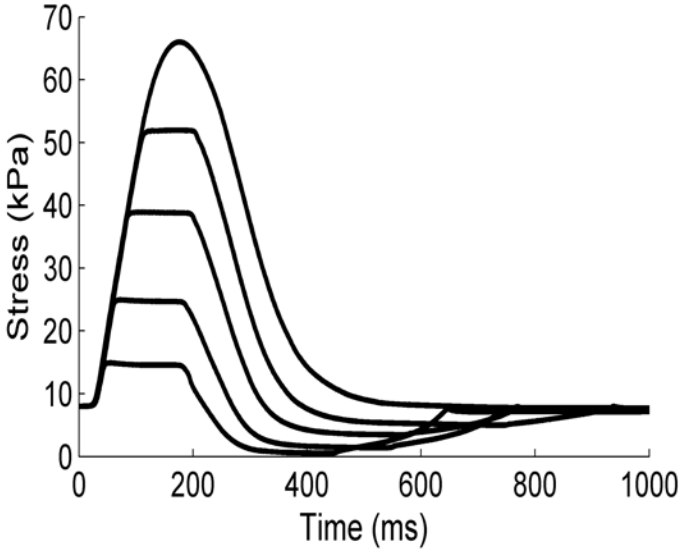

Muscle bath and
temperature sensors
Force transducer
Thermoelectric heat pump
temperature controllers
37 °C ± 61 µ°C
Linear voice-coil motor

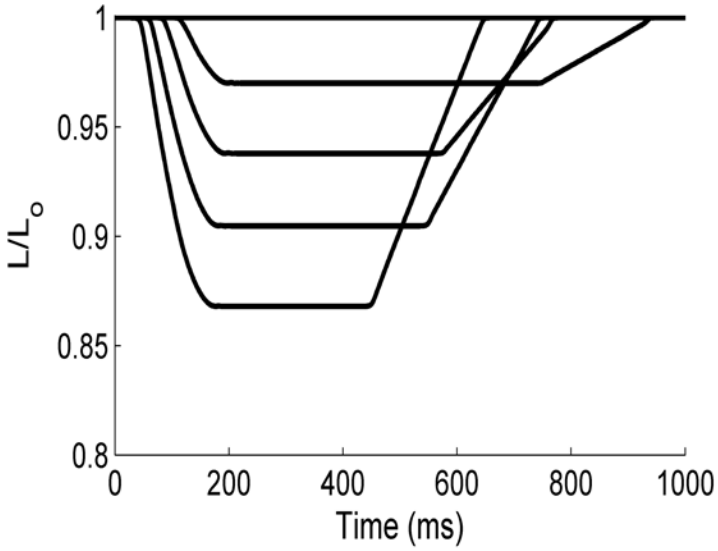

Thermally, acoustically
insulated hood
Heated, air-levitated table

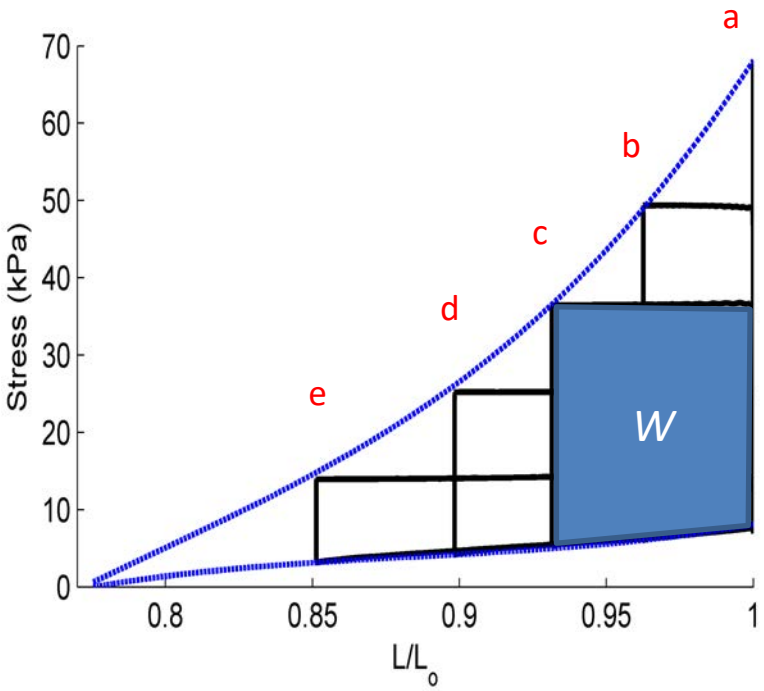

Stress (kPa)
25
20
15
10
5
0
-5
0
500
1000
2000
2500
Time (s)

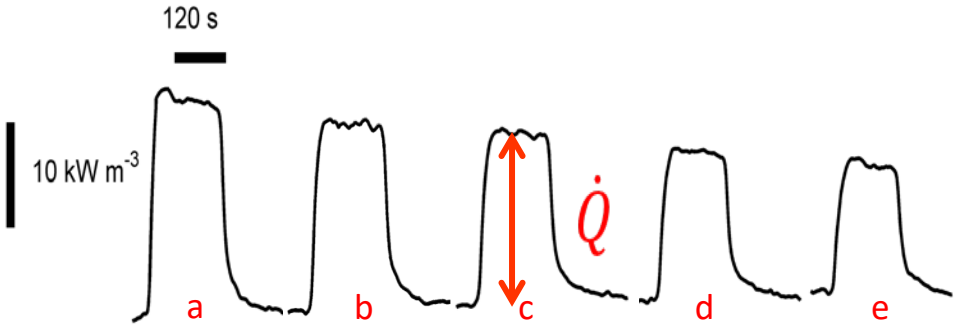

Heat rate (W)
50
40
30
20
10
0
-10
0
500
1000
1500
2000
2500
Time (s)

At room temperature (23 °C)



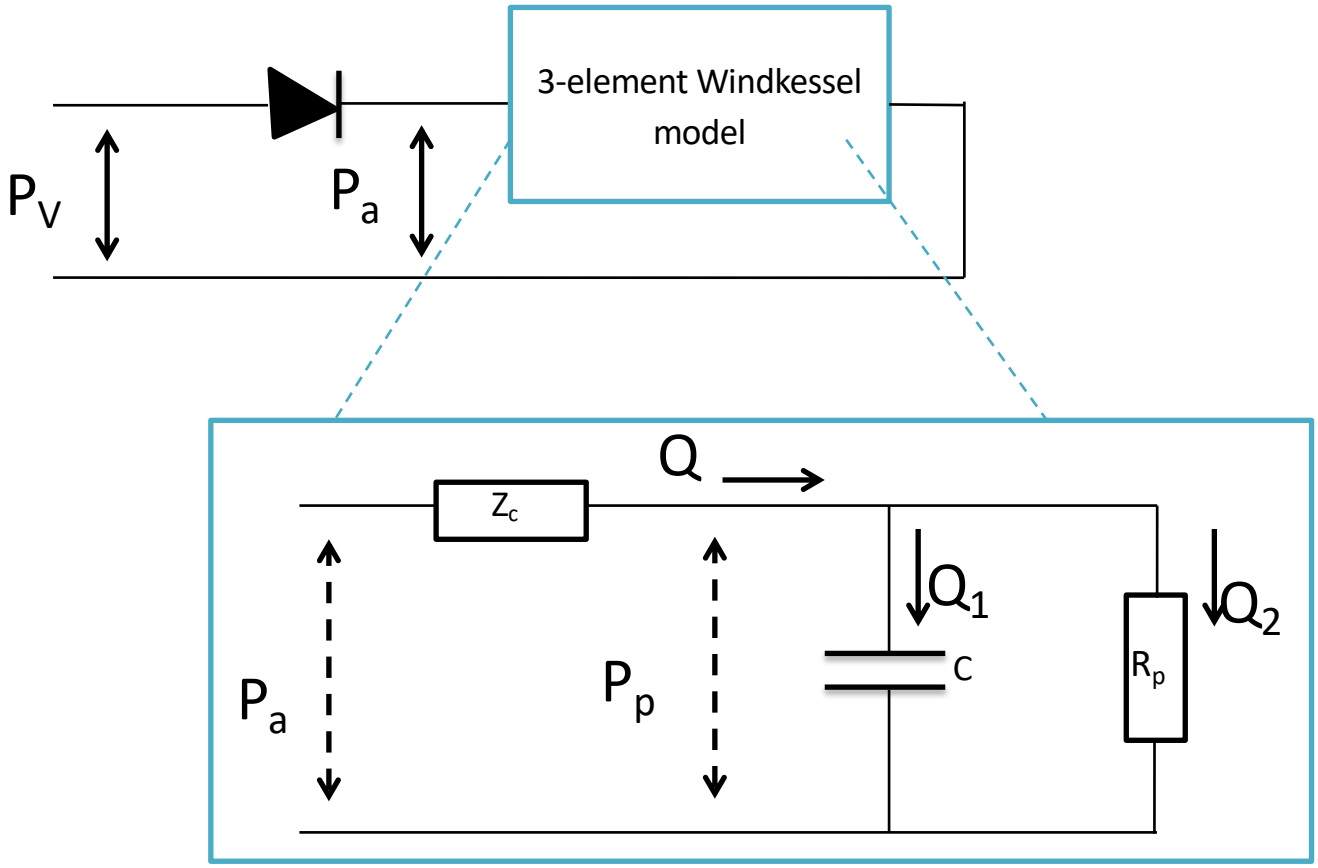


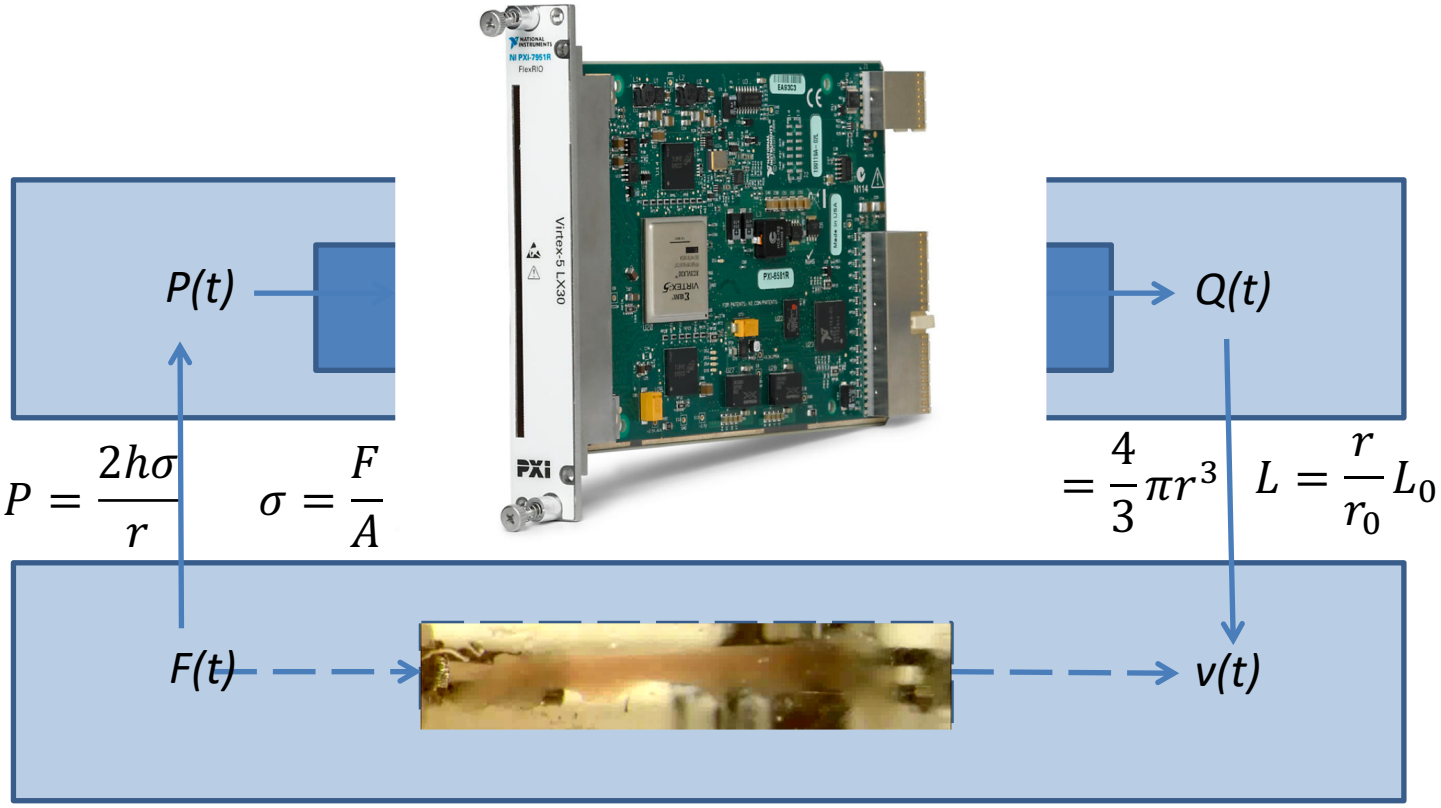


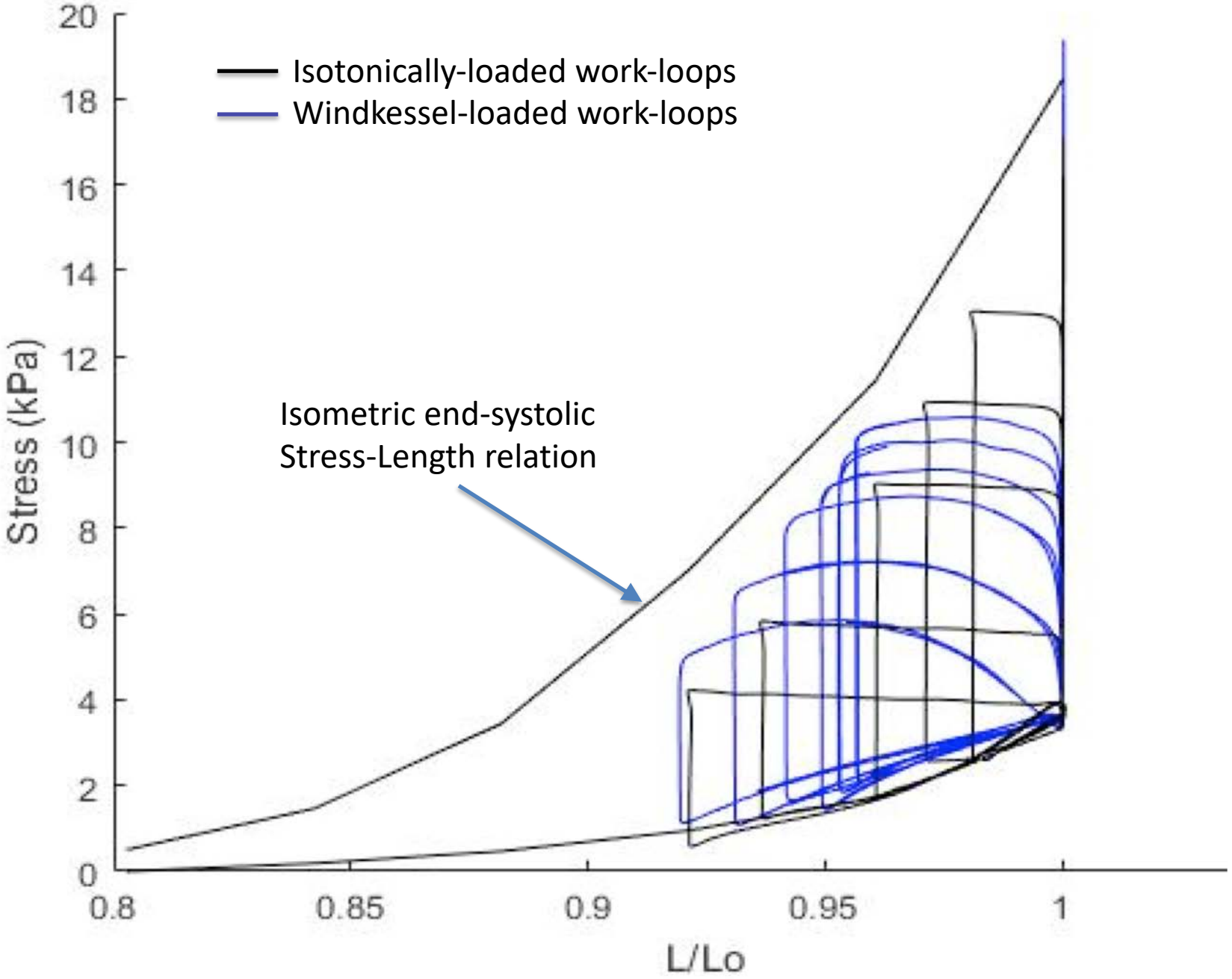


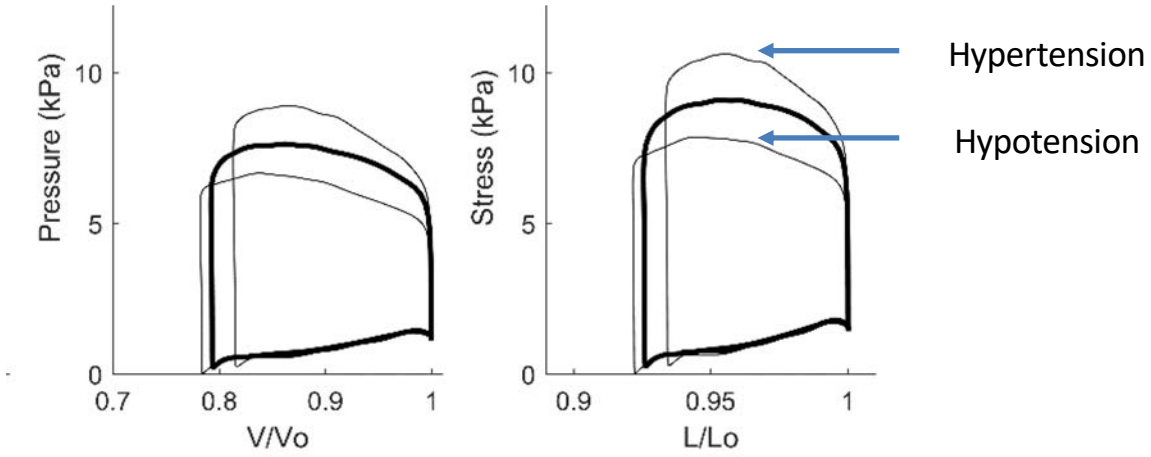
$$\varepsilon = \frac{W}{Q + W}$$

Modelling trabecula load




P(t)
Q(t)
$P = \frac{2h\sigma}{r}$
$\sigma = \frac{F}{A}$
$= \frac{4}{3}\pi r^3$
$L = \frac{r}{r_0} L_0$
F(t)
v(t)
Virtex-5 LX30
PXI

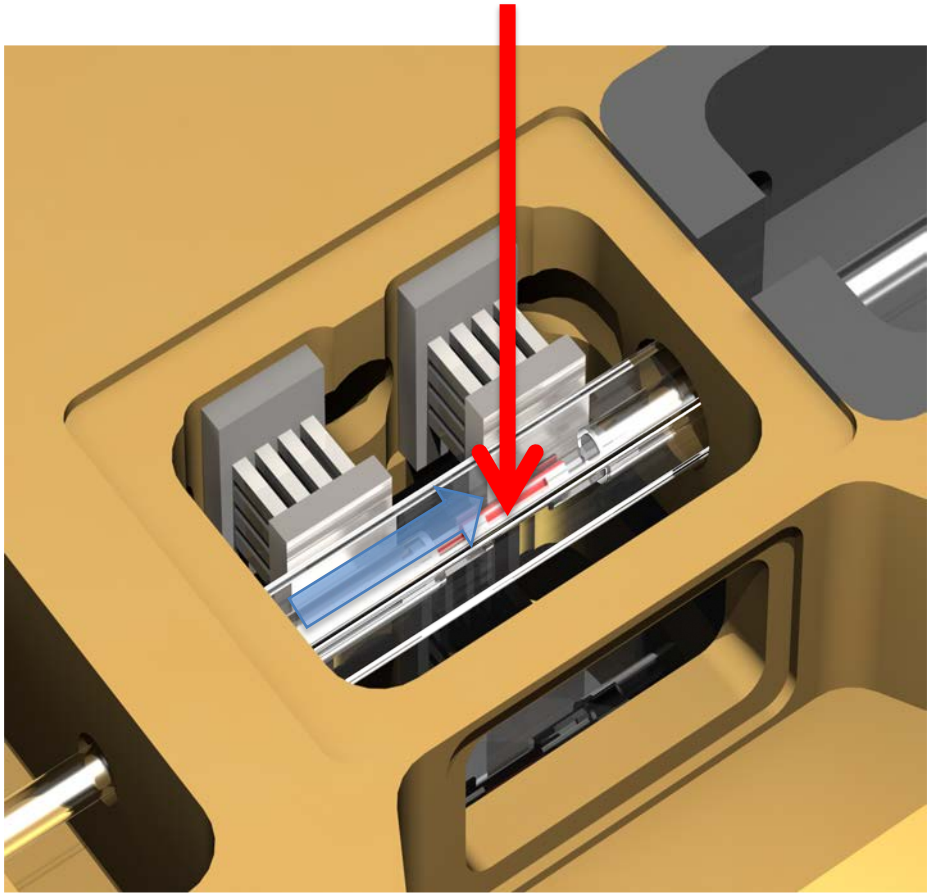

Isotonically-loaded work-loops
Windkessel-loaded work-loops
Isometric end-systolic
Stress-Length relation
Stress (kPa)
L/Lo
0
2
4
6
8
10
12
14
16
18
20
0.8
0.85
0.9
0.95
1


Pressure (kPa)
10
5
0
0.7
0.8
0.9
1
V/Vo
Stress (kPa)
10
5
0
0.9
0.95
1
L/Lo
Hypertension
Hypotension

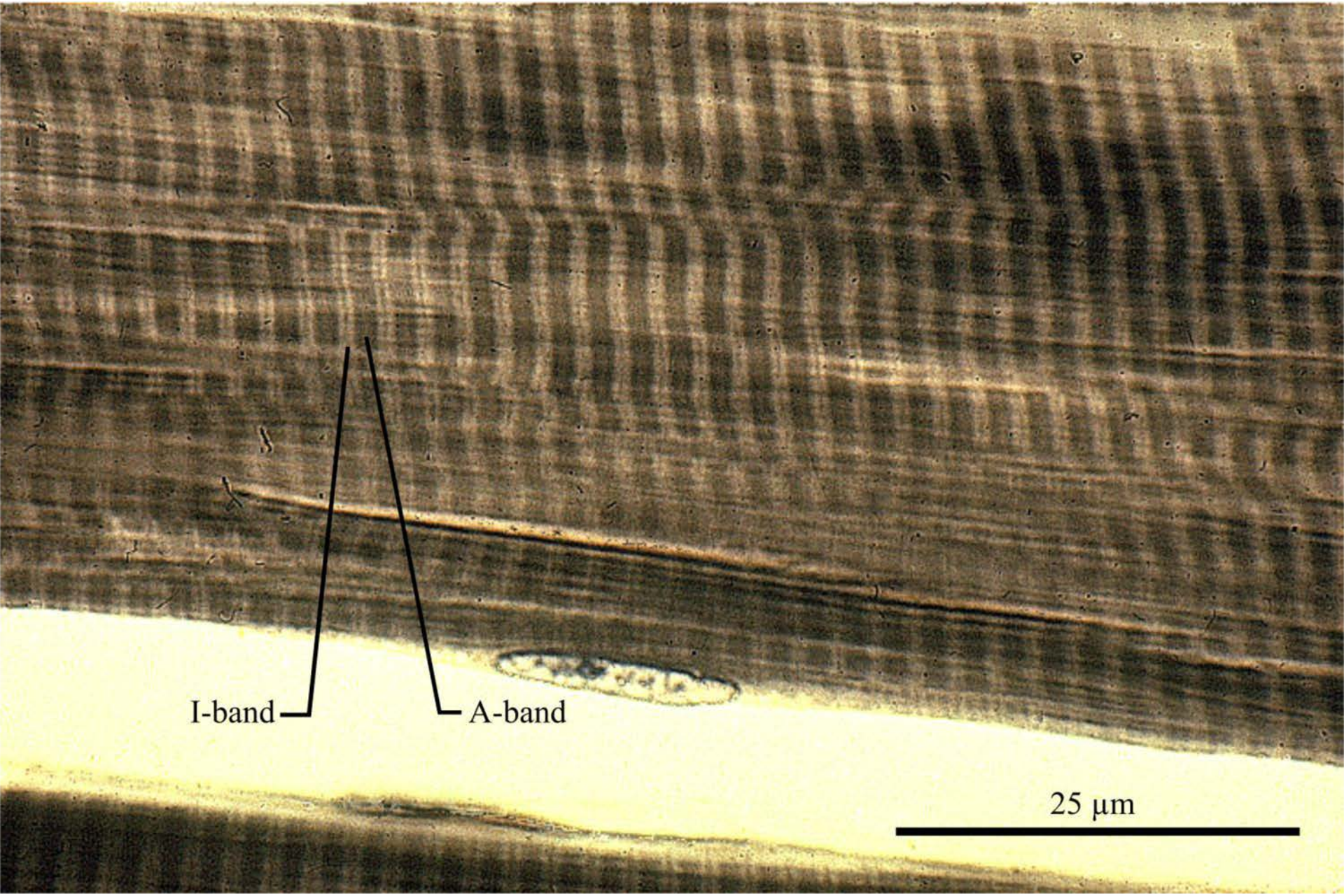
Mechano-energetic studies

- Is there a difference in efficiency between muscle from left and right ventricles?
- Can fish-oil dietary supplements increase the efficiency of your heart?
- What effect does diabetes, hypertension, hypertrophy, or salt-sensitivity have on heart efficiency?

Temperature change: 1 mK
Heat rate resolution: 10.8 nW
Time constant: ~15 s

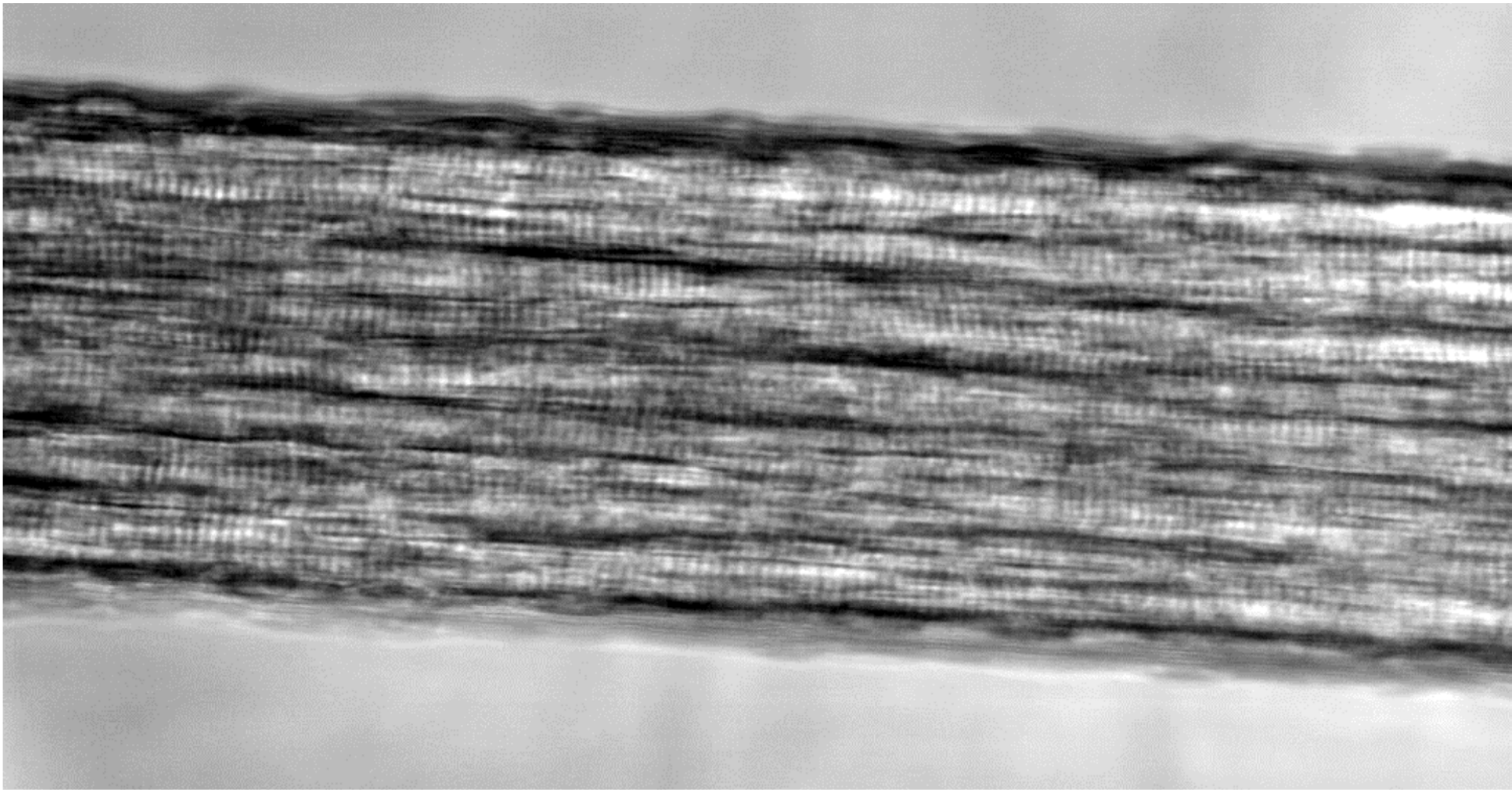


- Force/Length
  - — Laser Interferometer
- Heat
  - — Flow through calorimetry
- Sarcomere Length
  - — Bright-field Microscopy

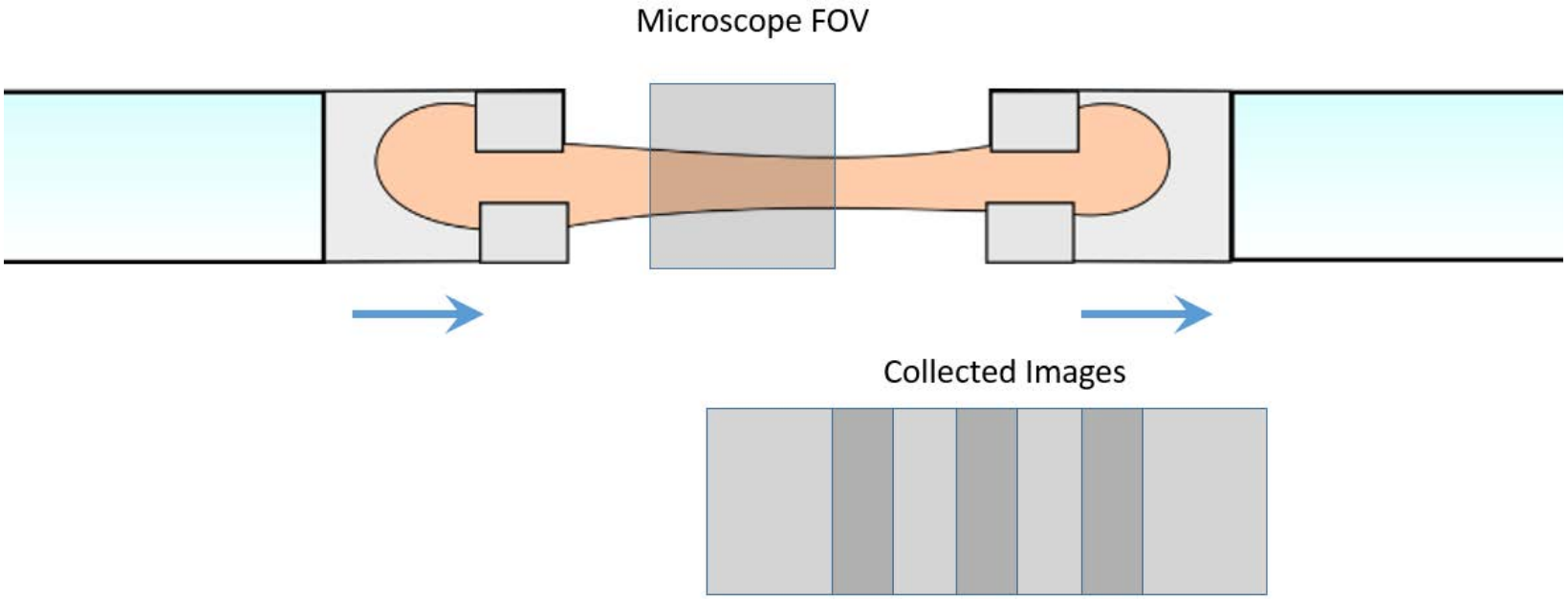


R. C. Wagner and F. E. Hossler, "MUSCLE -- Sarcomeres, High Magnification," vol. 326059 bytes, cmushm.gif, Ed., ed: University of Delaware, 1998.

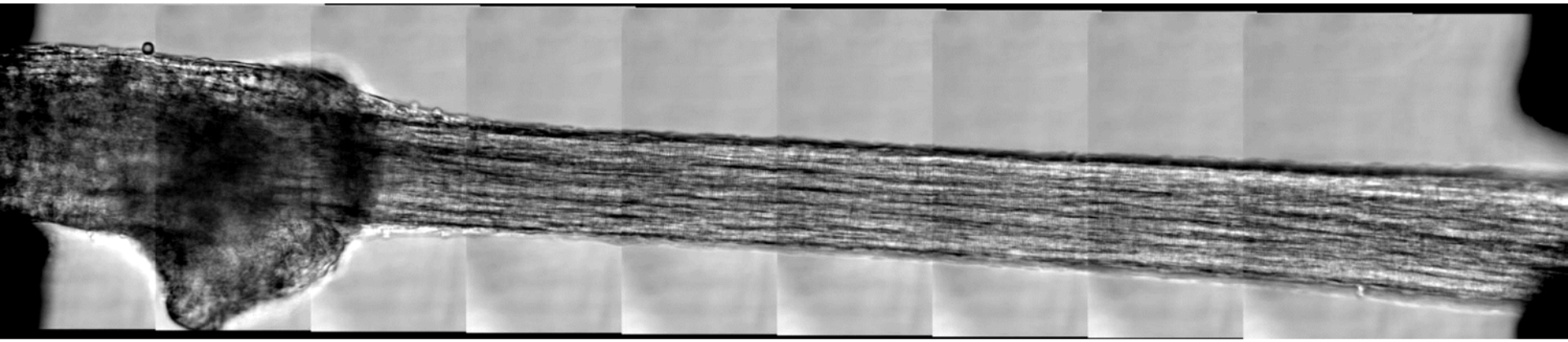
Microscope Data

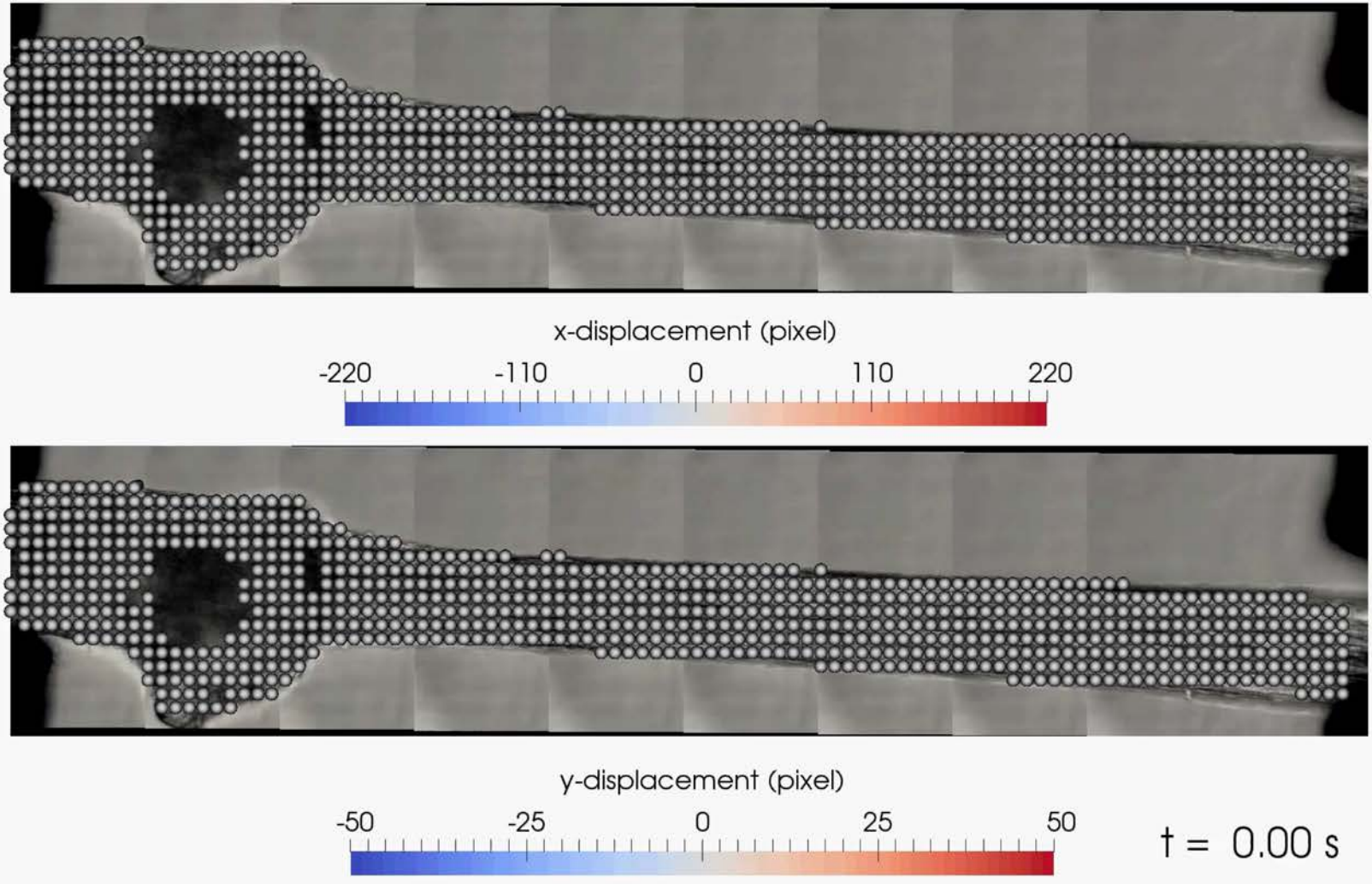


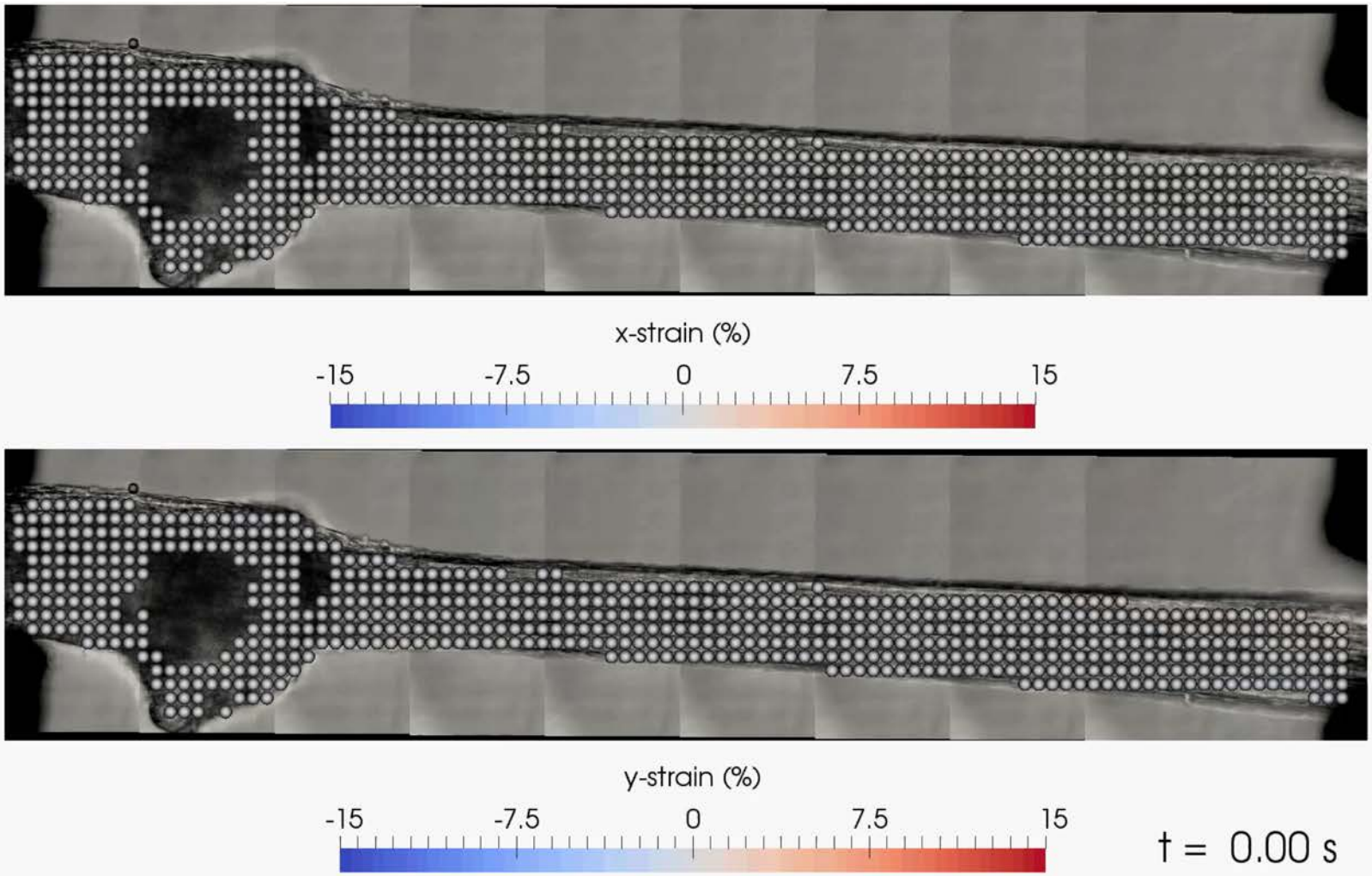
Gated Imaging



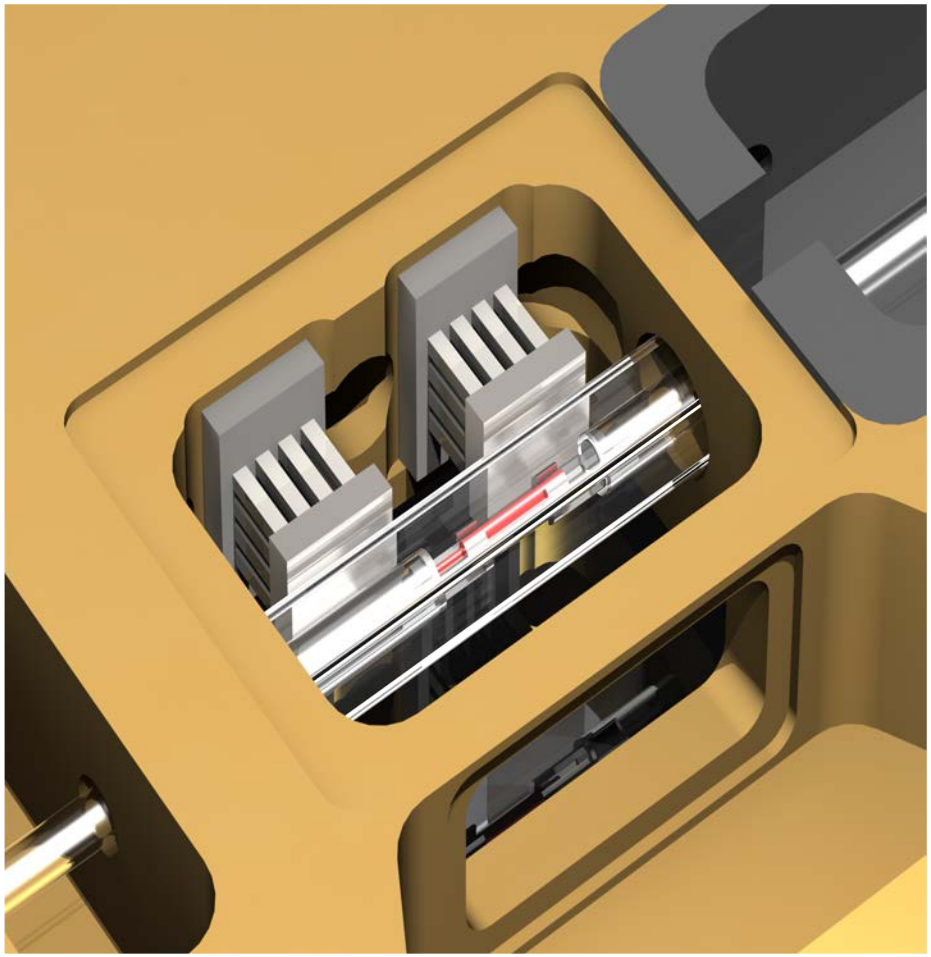
Gated Microscope Data




x-displacement (pixel)
-220
-110
0
110
220
y-displacement (pixel)
-50
-25
0
25
50
t = 0.00 s

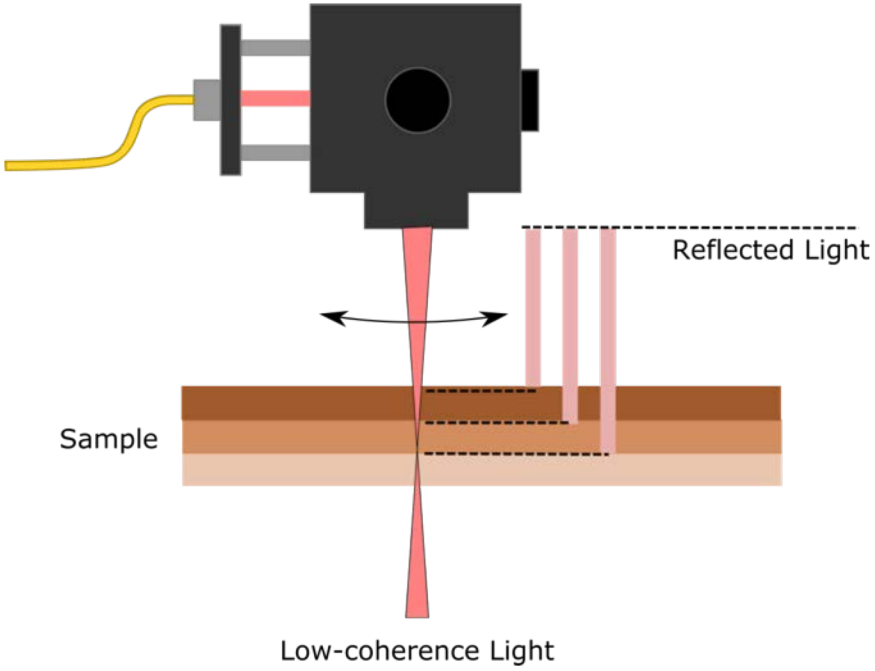

x-strain (%)
-15
-7.5
0
7.5
15
y-strain (%)
-15
-7.5
0
7.5
15
t = 0.00 s

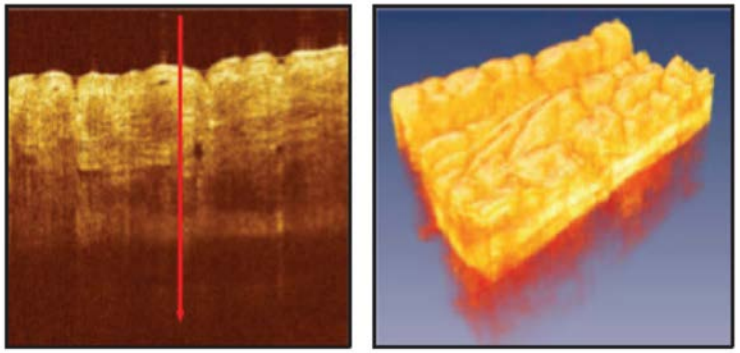
Cardiac Myometer



- Force/Length
  - — Laser Interferometer
- Heat
  - — Flow through calorimetry
- Sarcomere Length
  - — Bright-field Microscopy
  - — Laser Diffraction
- Calcium
  - — Fluorescence
- Oxygen
  - — Fluorescence Quenching
- Geometry
  - — Optical Coherence Tomography

Optical Coherence Tomography

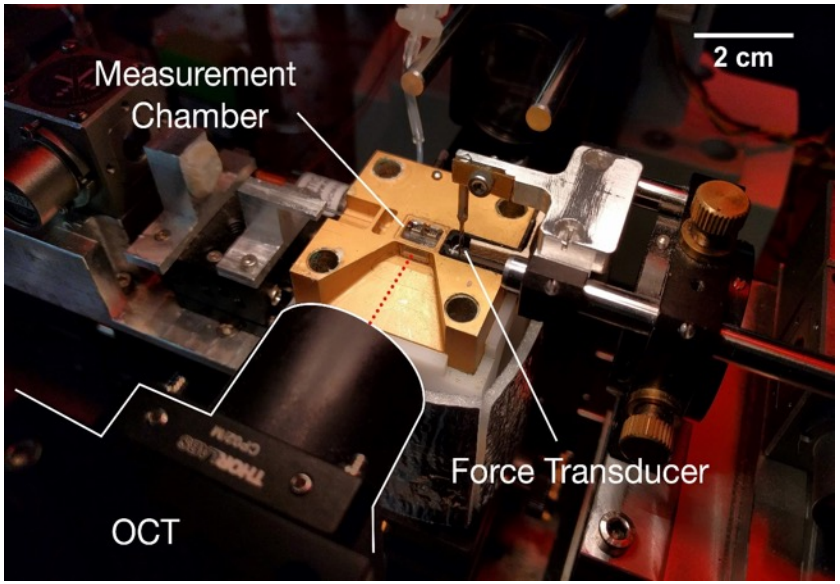




B-Scan

3D Volume

Implementation in Cardiac Myometer



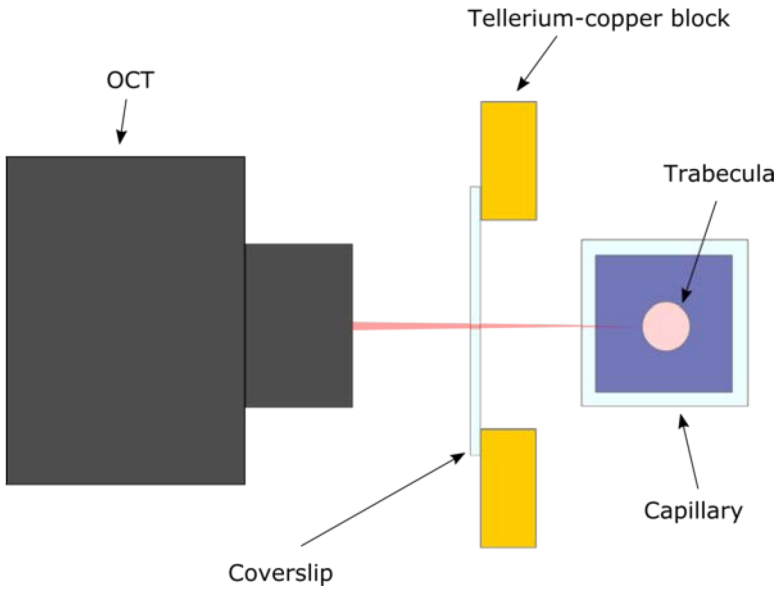
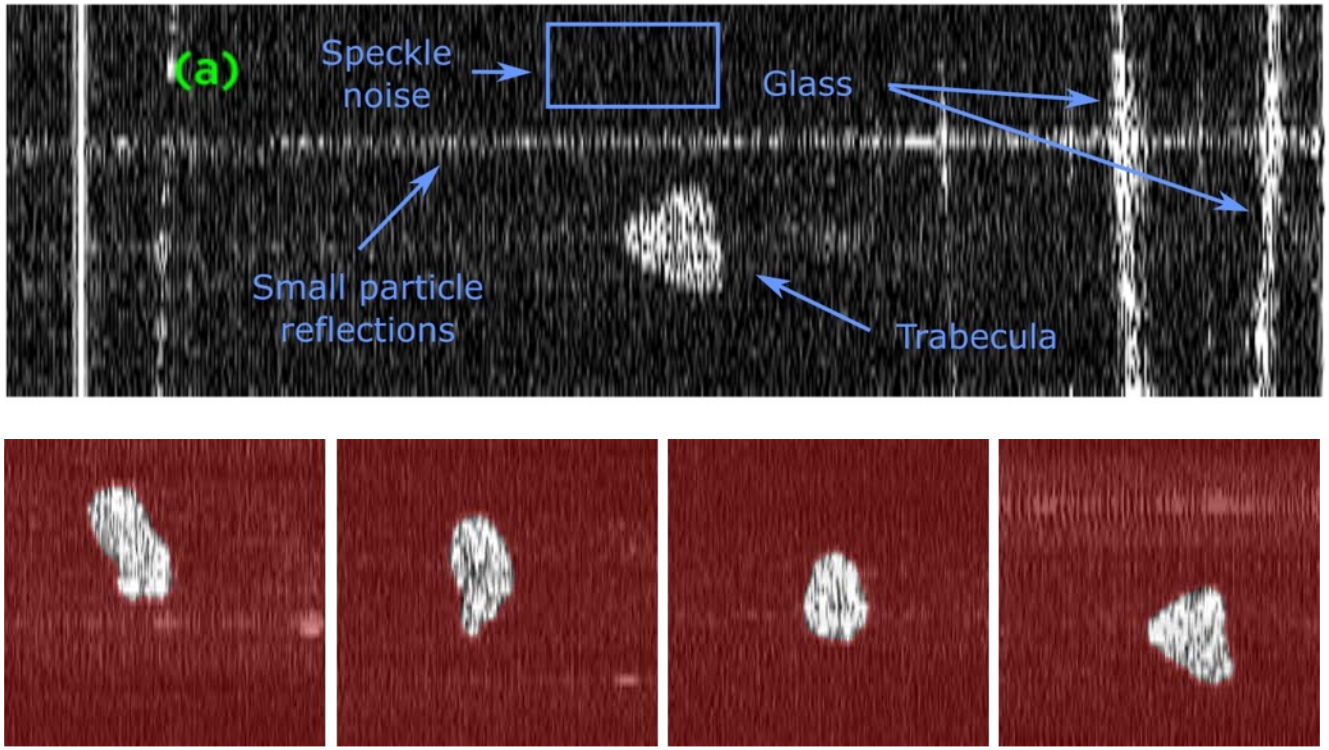
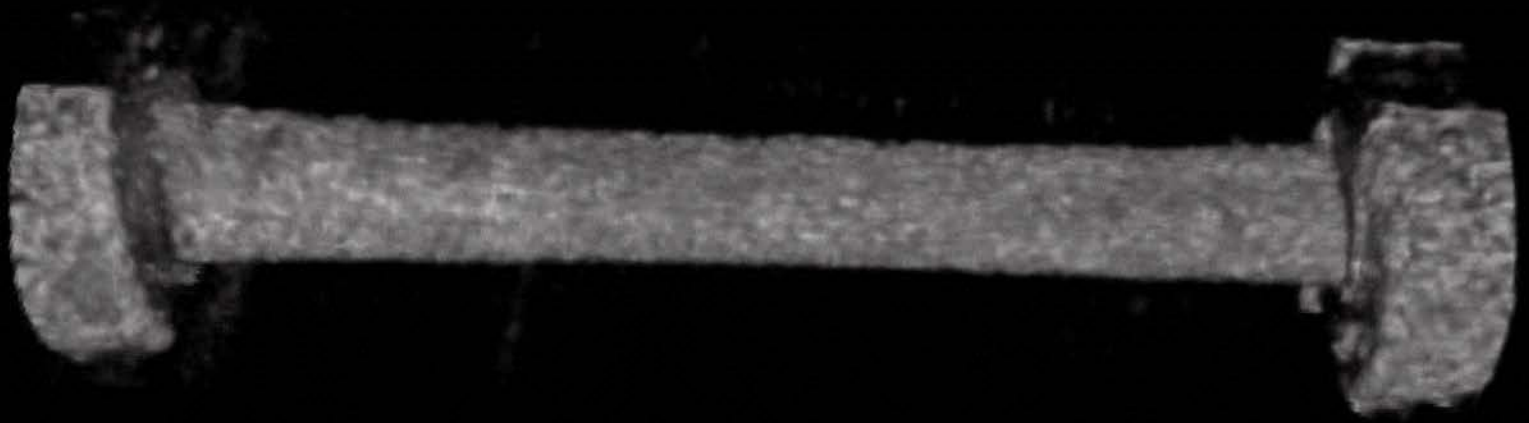


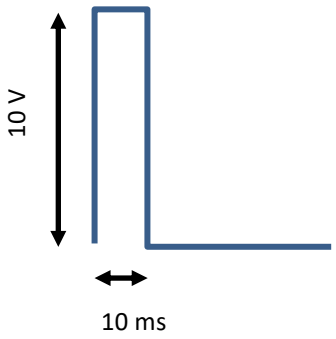
Image Processing: Segmentation

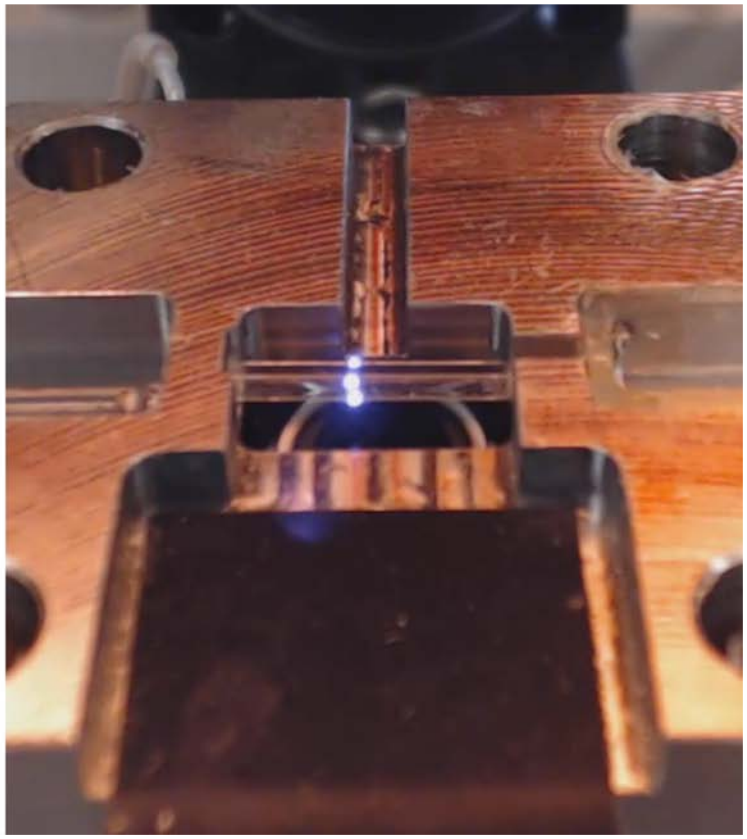




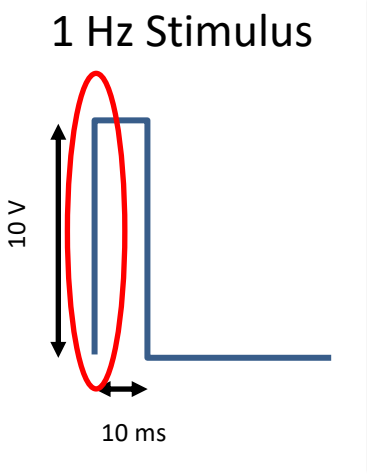
Imaging Contracting Trabeculae using OCT

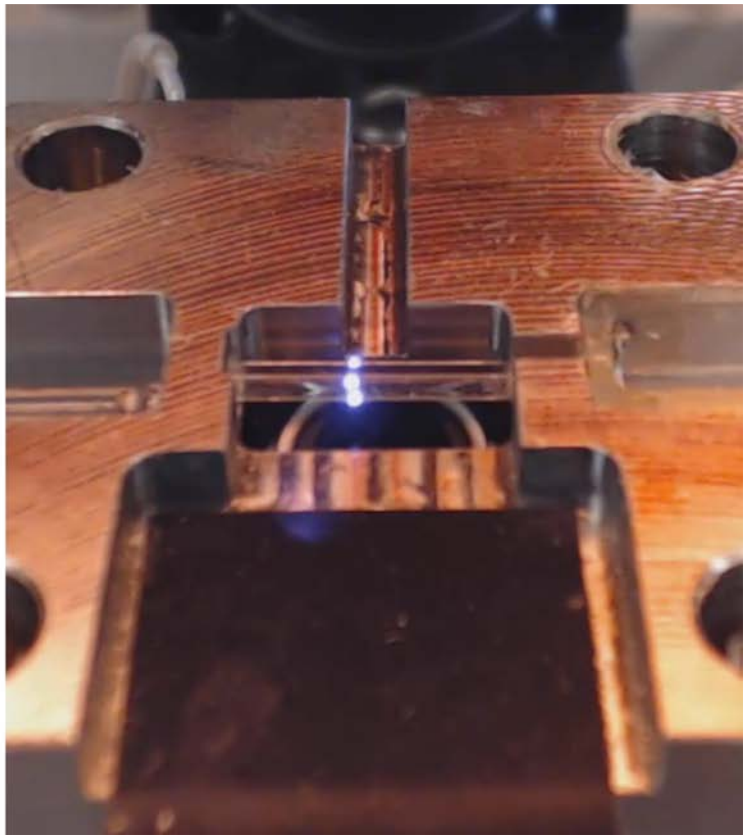
1 Hz Stimulus



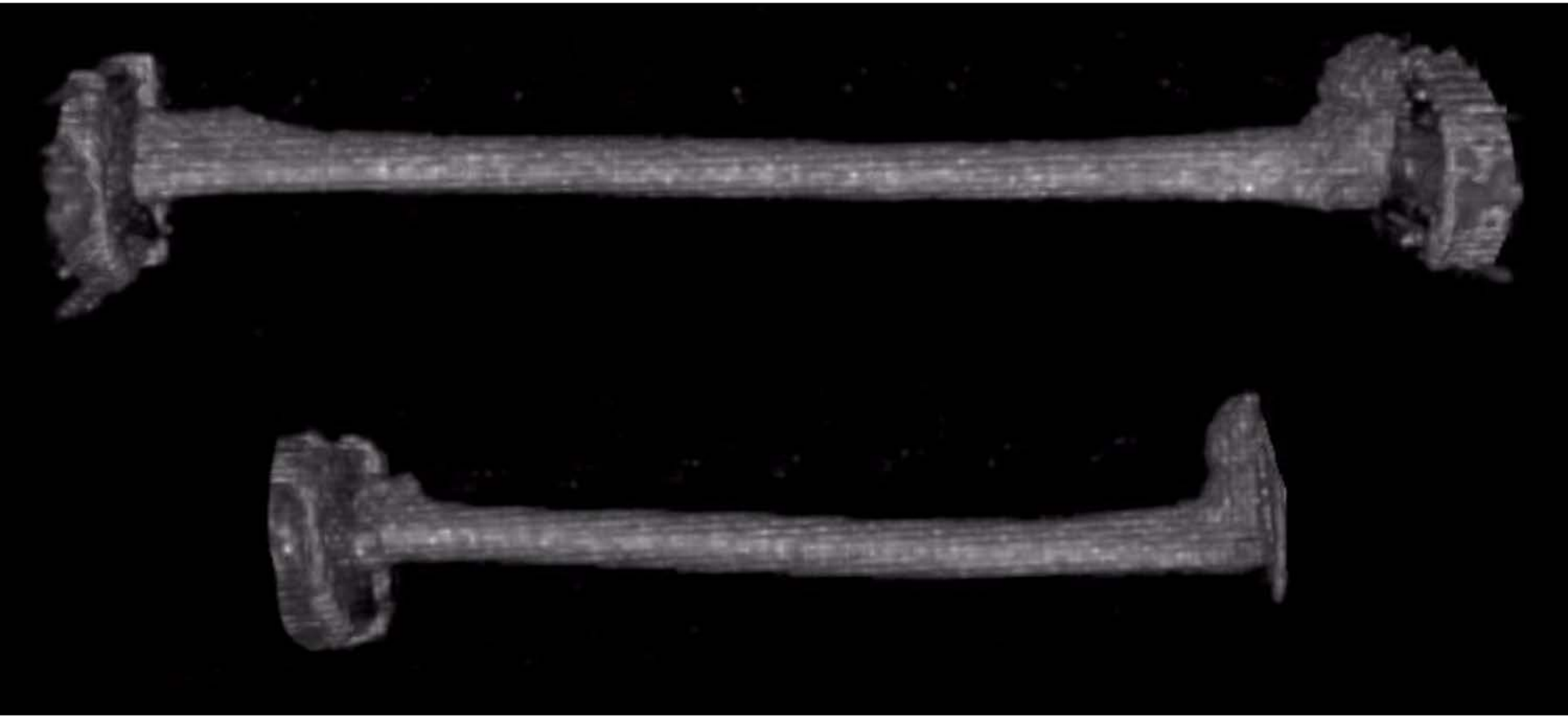


Imaging Contracting Trabeculae using OCT

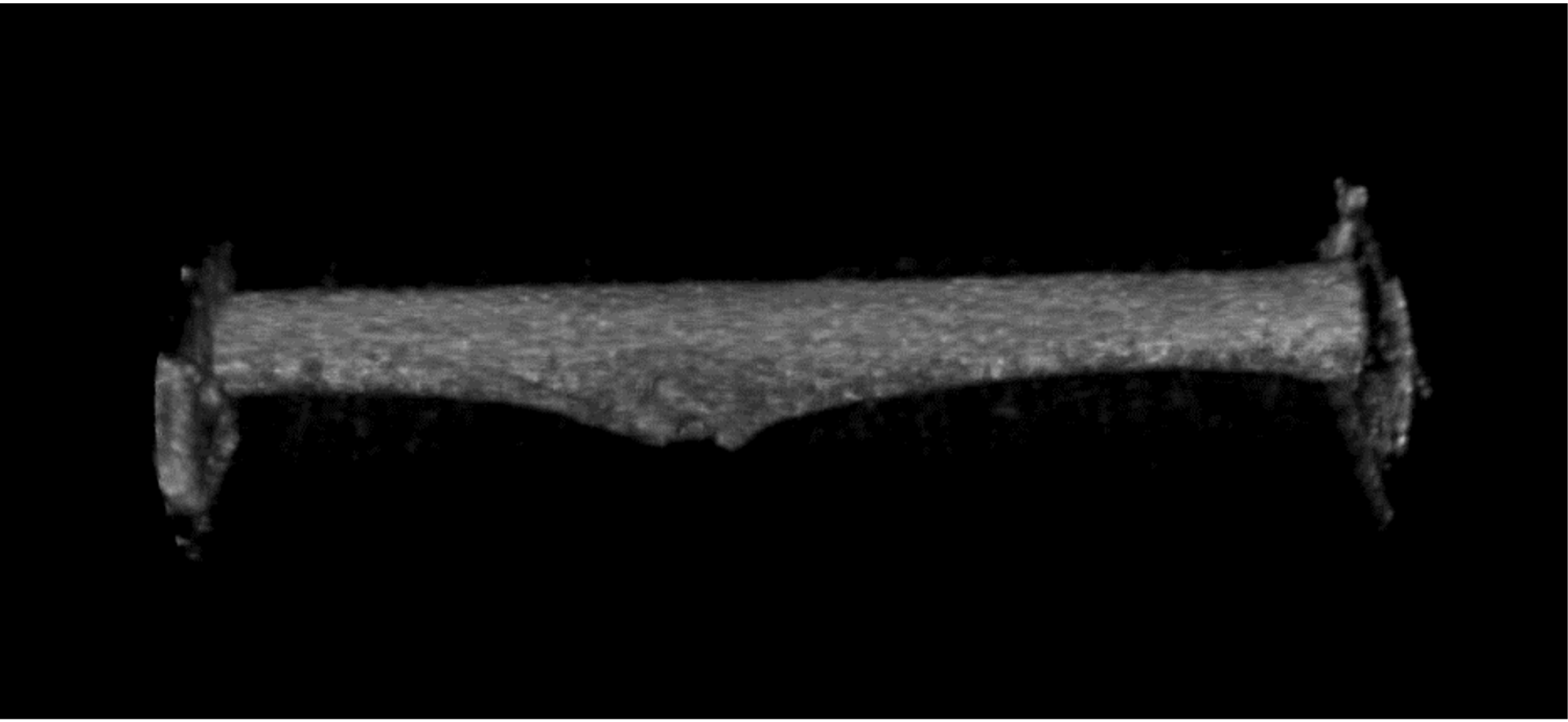




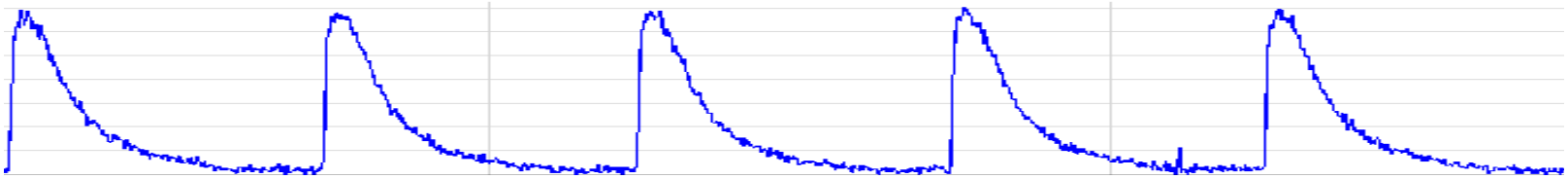
Reconstructed Image



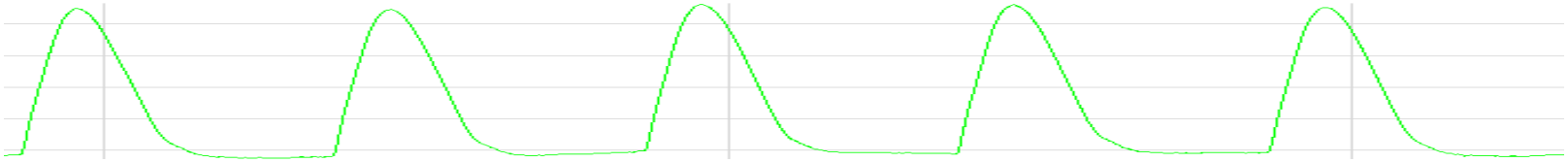
Non-uniform motion



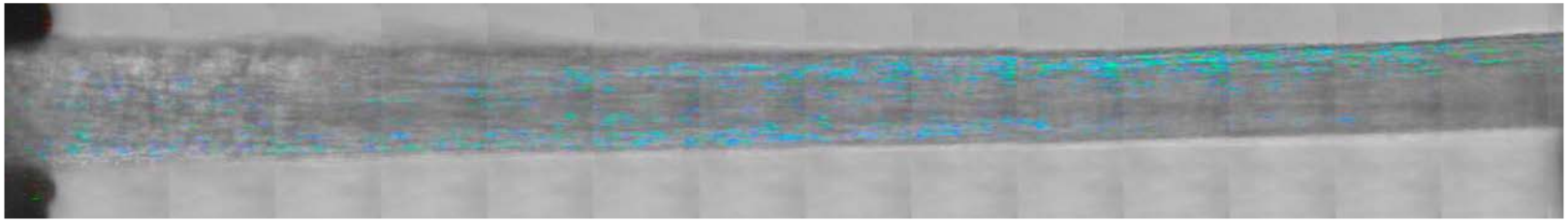
Calcium



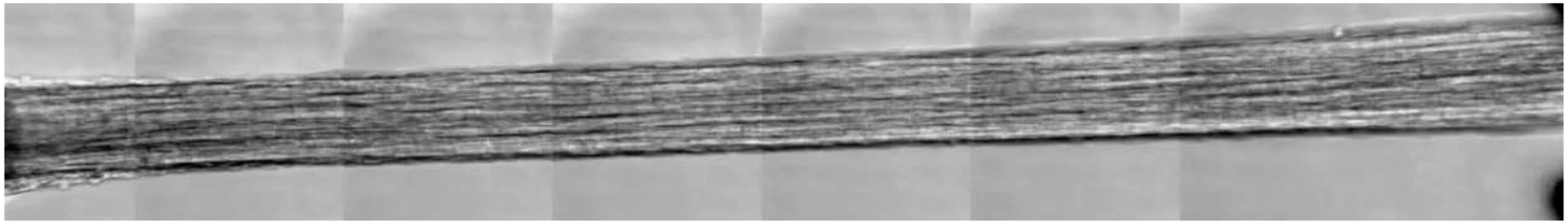
Force



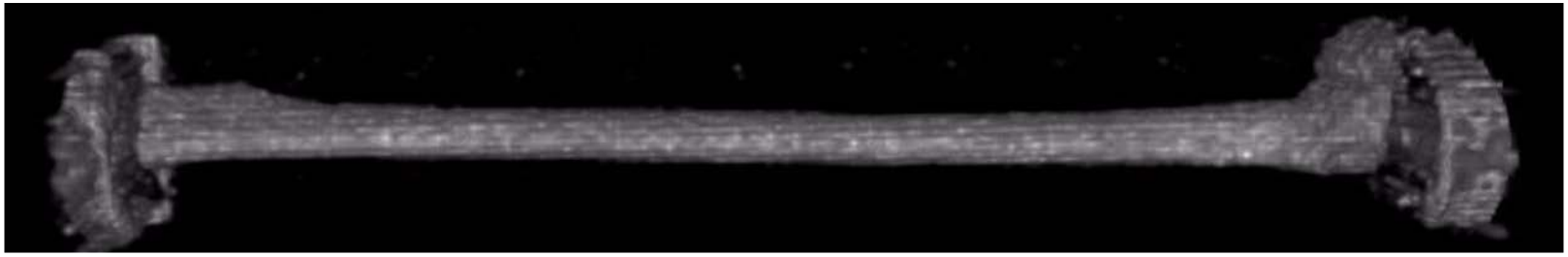
Sarcomere Length



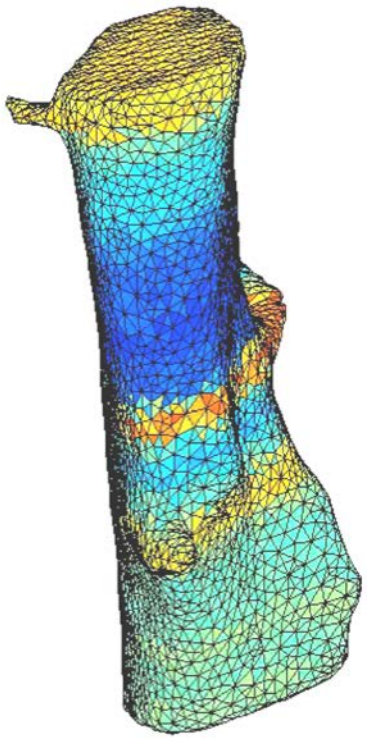
Motion



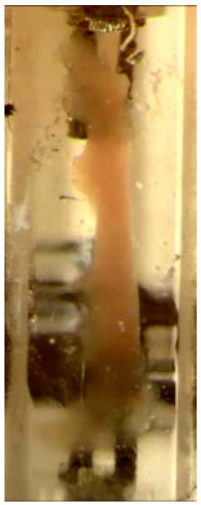
Shape

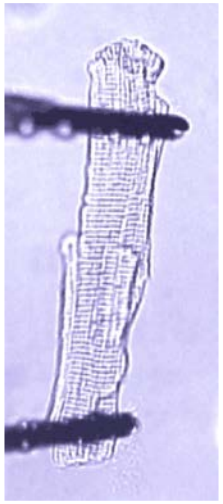


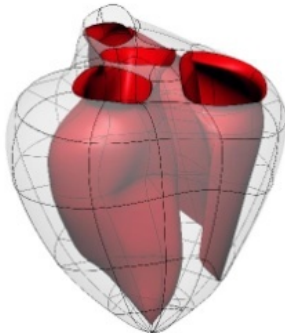
Computational models

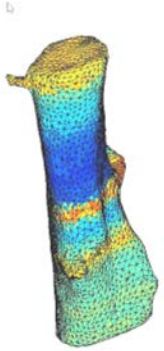


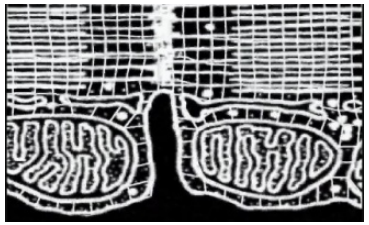
- Normalise measurements to geometric properties
- Compute material properties
- Demonstrate relationships between variables
- Convey multivariate data in 4D
- Embed in higher-scale models











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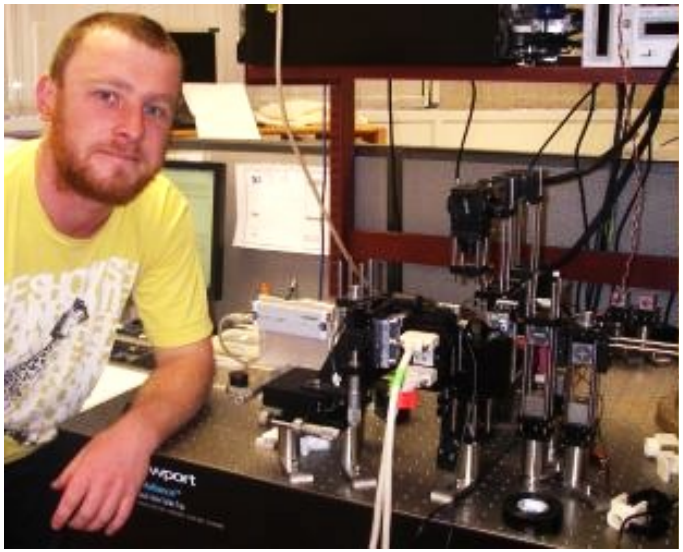
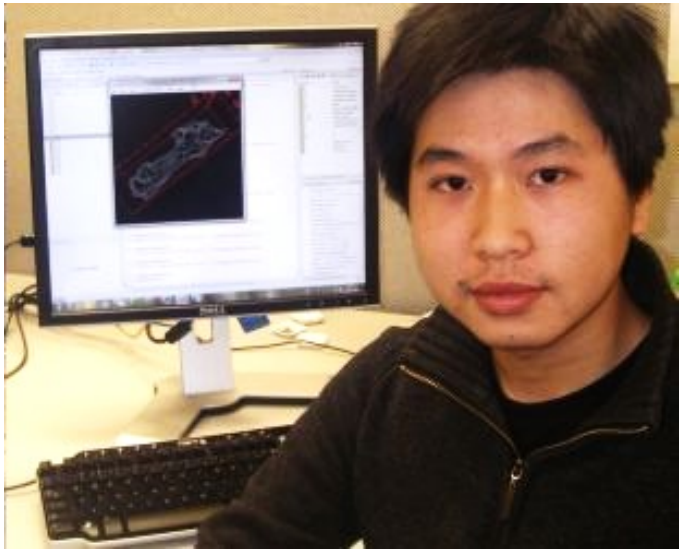


Alex Anderson



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