Session 21

CANTILEVER FORCE SENSORS
**MicroElectroMechanical Systems**

- Sensors and Actuators
  - Strain gauges, Pressure Sensors, Accelerometers Micromirrors, BioMEMS, etc.
  - Combined electrical, mechanical, optical, material, fluid, chemical, and/or biological systems
Horizontal Cantilever

- Micromachined device to measure individual focal adhesions
- Dynamic measurements of traction forces during cell migration
Fabrication

- Phosphorous-doped Glass
  - Deposit
  - Lithography
  - Etching
- Poly-Silicon #1
  - Deposit
  - Lithography
  - Etching
- Spin-on-Glass
  - Deposit
  - Lithography
  - Etching
- Poly-Silicon #2
  - Plasma deposit
  - Lithography
  - Etching
- Etch-Release
Measurement

- Cells pull in the front and retract in the rear
- Retraction force at rear releases adhesions
Microposts to Measure Cell Forces

\[ F = \left( \frac{3\pi Ed^4}{64L^3} \right) \delta \]

- **F**: Traction Force
- **δ**: Displacement
- **E**: PDMS Modulus of Elasticity
- **d**: Post Diameter (3 μm)
- **L**: Post Length (5-11 μm)

PDMS microposts

Deflection Measurements

Immunofluorescence
*(tridecafluoro-1,1,2,2-tetrahydrooctyl)-1-trichlorosilane*
Biofunctionalizing the Posts

0.2% (w/v) Pluronics® F127 difunctional block copolymer surfactant

PDMS stamp

Ink with ECM

ECM Adsorbed

Activate with UV-Ozone

Stamp

Protein Transfer

Block*

Non-adhesive

Seed Cells

* 0.2% (w/v) Pluronics® F127 difunctional block copolymer surfactant
Focal Adhesions and Force

- Positive correlation of FA and local force
Spread Area and Force

- Contact area, i.e. cell spreading, promotes larger traction forces
- Constitutively active RhoA mutant causes large forces at low contact area
Hexagonal Packed Posts

- Closer spacing between smaller posts
- Positive correlation between stiffness and force

du Roure, et al. (2005) PNAS, 102:2390
**Stiffness vs. Spreading**

**Micro-Contact Printing**  
(Cell Spread Area)

**Micropost Dimensions**  
(Substrate Stiffness)

<table>
<thead>
<tr>
<th>Array</th>
<th>L (μm)</th>
<th>d (μm)</th>
<th>k (nN/μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.96 ± 0.36</td>
<td>2.14 ± 0.03</td>
<td>10.7 ± 2.3</td>
</tr>
<tr>
<td>2</td>
<td>7.44 ± 0.28</td>
<td>2.04 ± 0.06</td>
<td>15.5 ± 3.6</td>
</tr>
<tr>
<td>3</td>
<td>7.19 ± 0.22</td>
<td>2.22 ± 0.10</td>
<td>24.1 ± 6.3</td>
</tr>
<tr>
<td>4</td>
<td>7.45 ± 0.20</td>
<td>2.42 ± 0.05</td>
<td>30.5 ± 6.2</td>
</tr>
<tr>
<td>5</td>
<td>6.70 ± 0.13</td>
<td>2.50 ± 0.07</td>
<td>47.8 ± 10</td>
</tr>
</tbody>
</table>

\[ F = \frac{3\pi Ed^4}{64L^3} \delta \]
Muscle Posts


During development, myocardial stiffness coincides with increased contractile performance.

<table>
<thead>
<tr>
<th>Stiffness</th>
<th>E (kPa)</th>
<th>G (kPa), $\nu \approx 0.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prenatal</td>
<td>12 ± 4</td>
<td>≈ 4</td>
</tr>
<tr>
<td>Neonatal</td>
<td>39 ± 7</td>
<td>≈ 13</td>
</tr>
</tbody>
</table>

Values adapted from Jacot et al. *J. Biomech.* 2010
Twitch Power increases with Stiffness

- Fast line scanning for velocity, power.

![Graph showing velocity, force, and power responses to different stiffness levels.]
Multicellular Measurements

- Force correlates with cell growth

Nelson, et al. (2005) PNAS, 102(33):11594
Bowties to Measure “Tugging” Force

For graphs: *, p < 0.05 (Student-t test)

Shear Flow Mechanotransduction

Cell-Cell Junctions Under Flow

Nanoposts

- High resolution force measurements

830 nm dia, 3.3 μm tall
16 nN/μm

830 nm dia, 3.0 μm tall
28 nN/μm

670 nm dia, 3.3 μm tall
8 nN/μm