A Wireless, Battery-Free Photoplethysmography-Based Implantable Force Sensor

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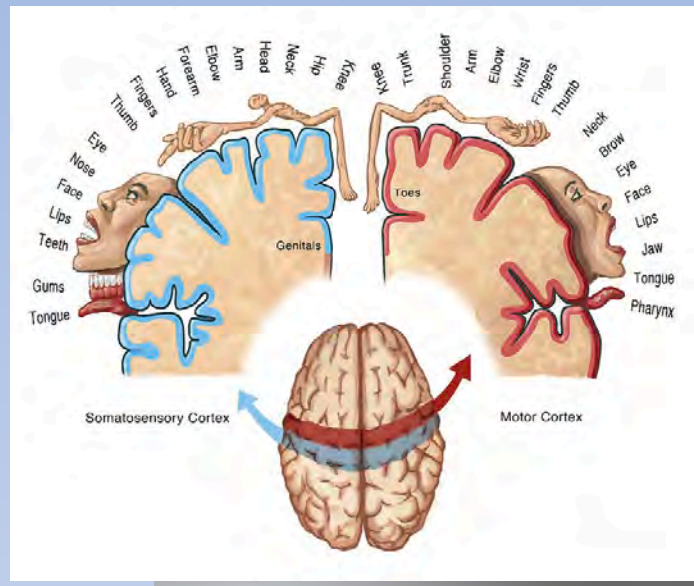
Implantable Force Sensors: Motivation

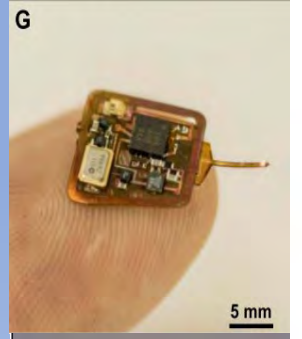
- 300,000 Americans currently suffering from spinal cord injuries[1]
- Limb Reanimation – a “solved challenge”
  - Brain Controlled Functional Electric Stimulation (BC-FES)
  - No sense of touch!
- Somatosensation: source of tactile information
- Restoring somatosensation:
  - Sensor-embedded tactile gloves[2]
  - Sensorized robotic limbs[3]

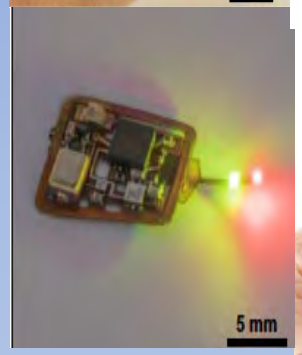
Better solution: implant!

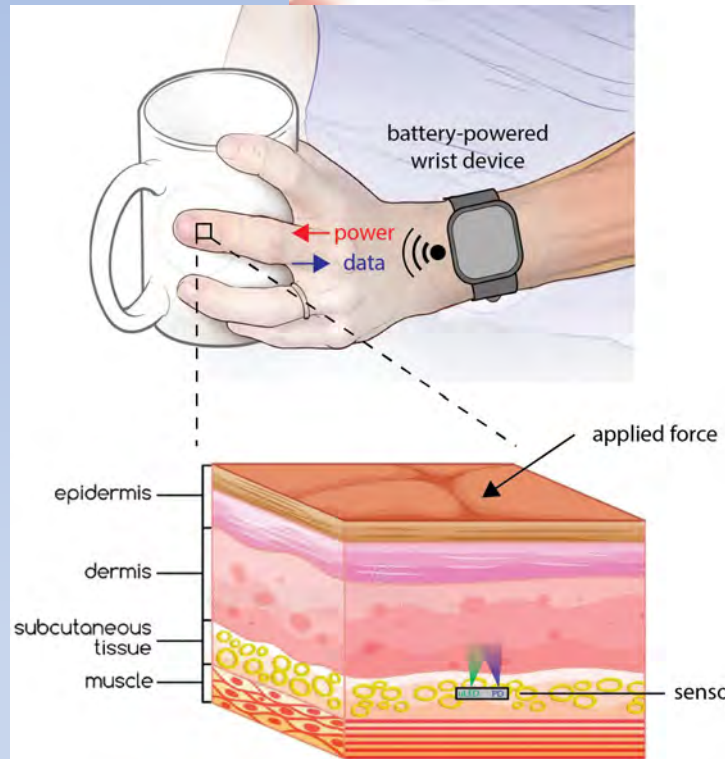


Photoplethysmography (PPG)

- Sensor motivation: blood drains from fingertip when forces are applied
- Photoplethysmography: optical sensing of blood volume changes in microvasculature
  - Medical application – pulse oximeters
- Implantable PPG sensors developed for cardiac applications[4]
  - Limited force sensing attempts![5]
- Alternatives?
  - Capacitive sensors - large, excessive circuitry[6]



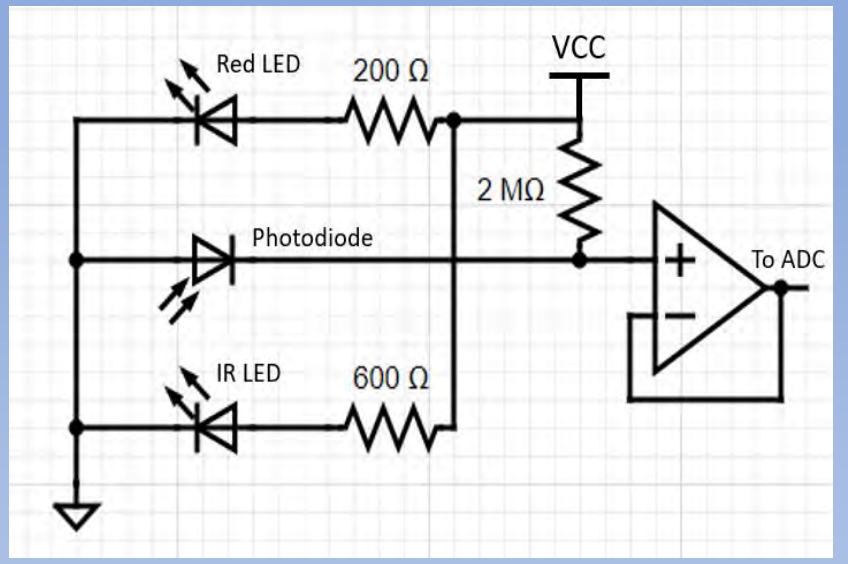


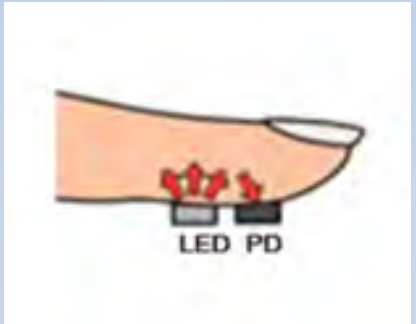


Proof-of-Concept Prototype

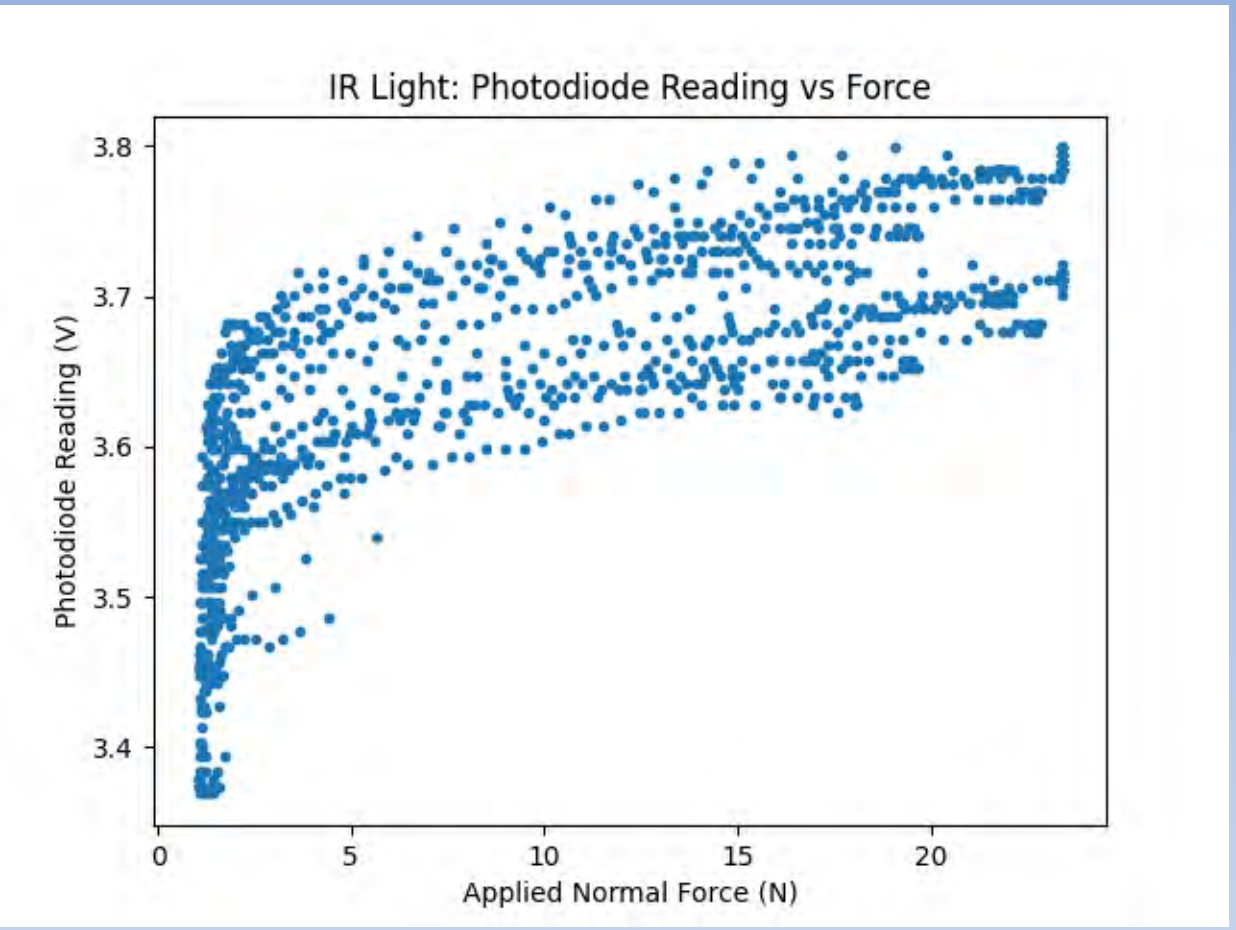
- Simple protoboard construction:
  - Red, IR LED equidistant from photodiode
  - Resistive amplifier circuit
  - Arduino ADC for data collection

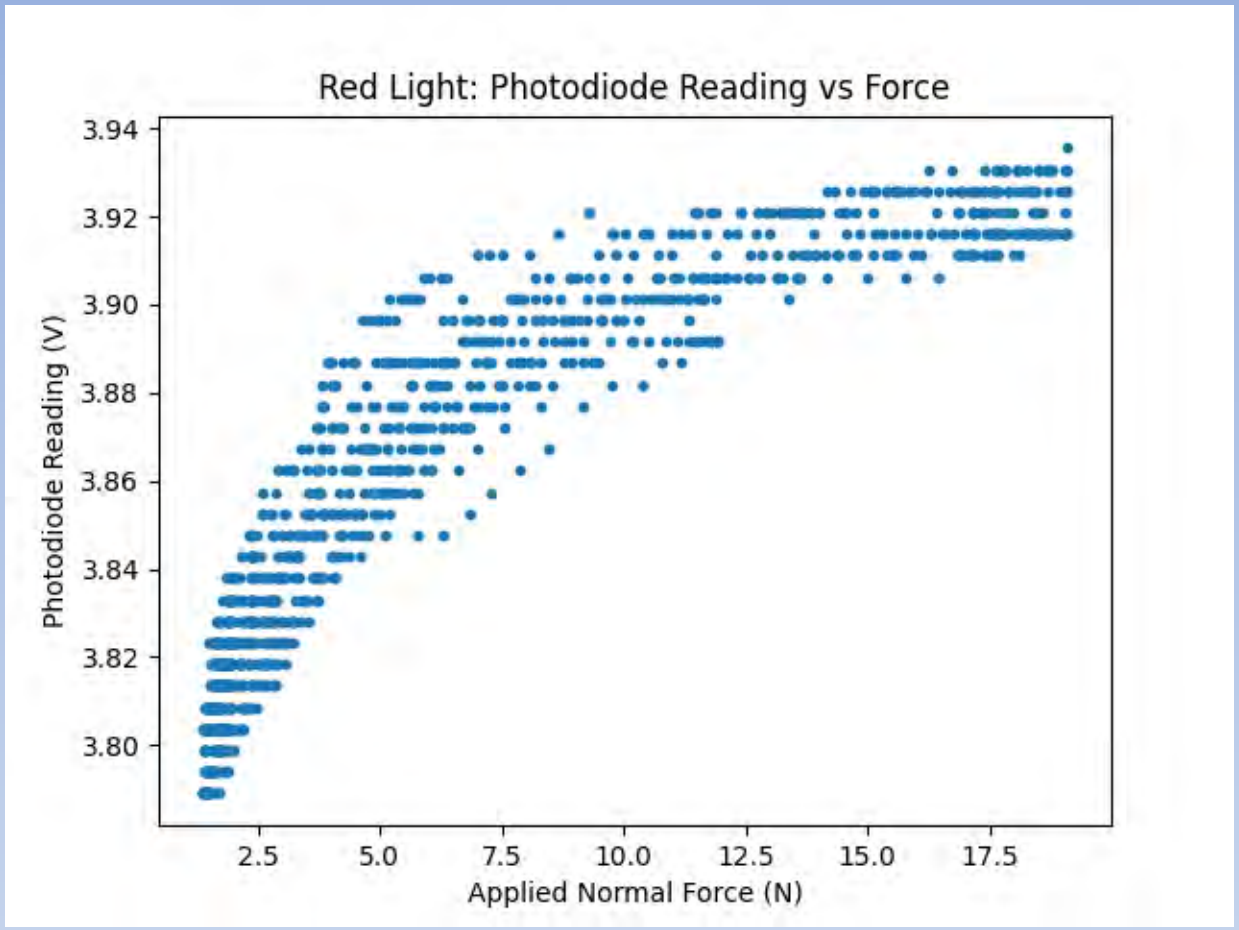
- Operation:
  - Press thumb against LEDs, PD
  - Load cell measures ground-truth force





Prototype - Results



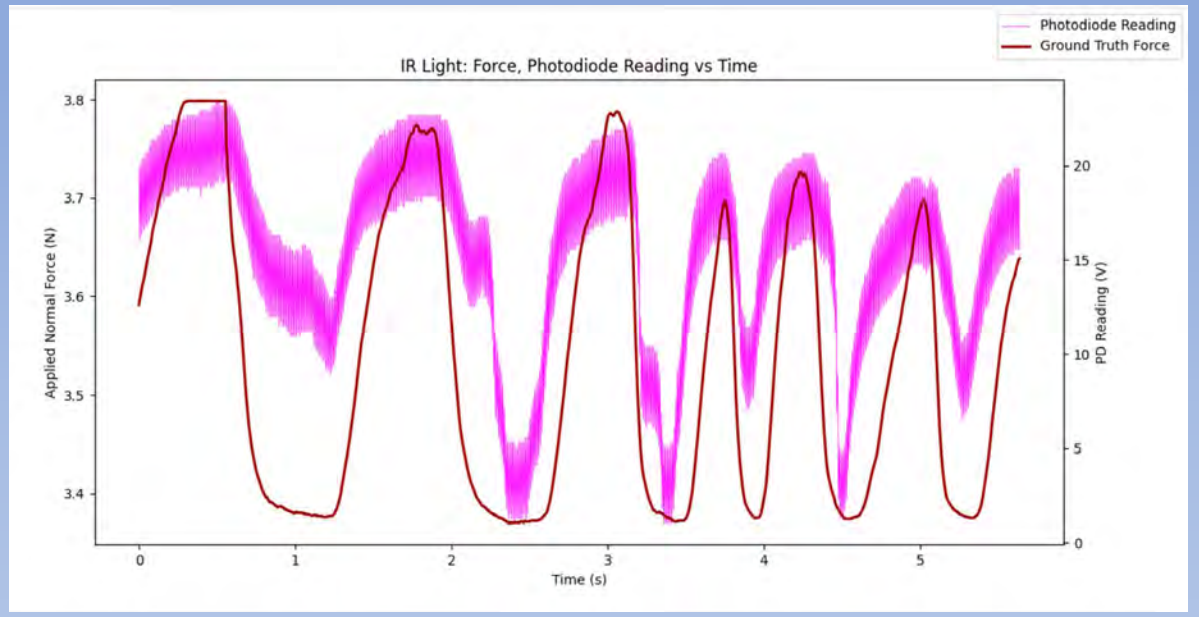


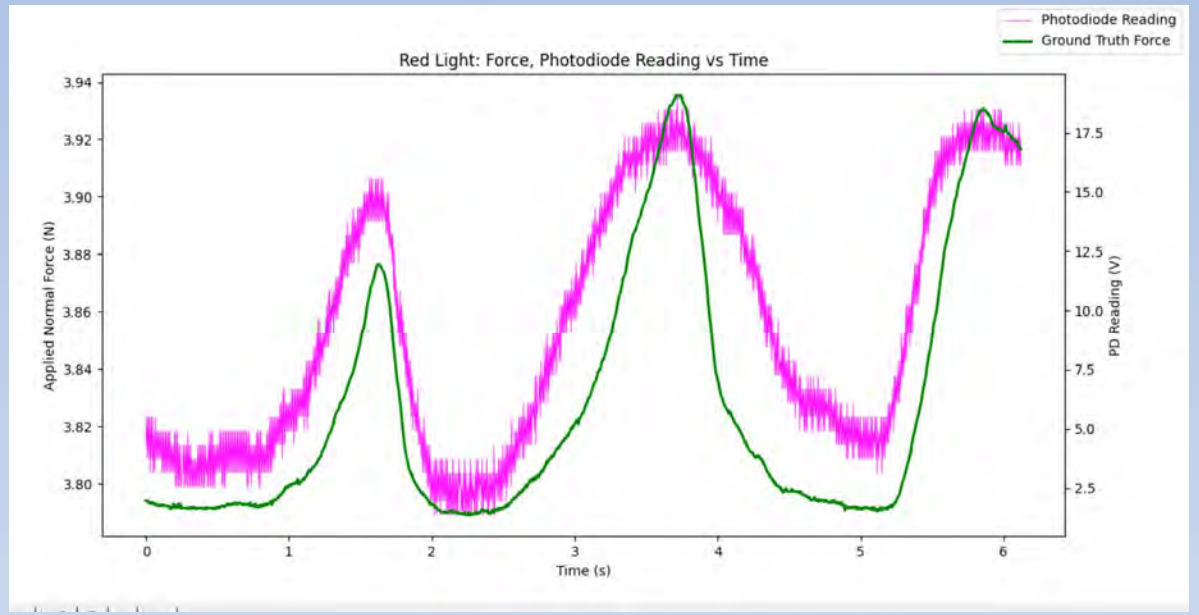
Monotonic relationship between sensor output and applied force!

Prototype - Results

- Photodiode reading tracks applied force

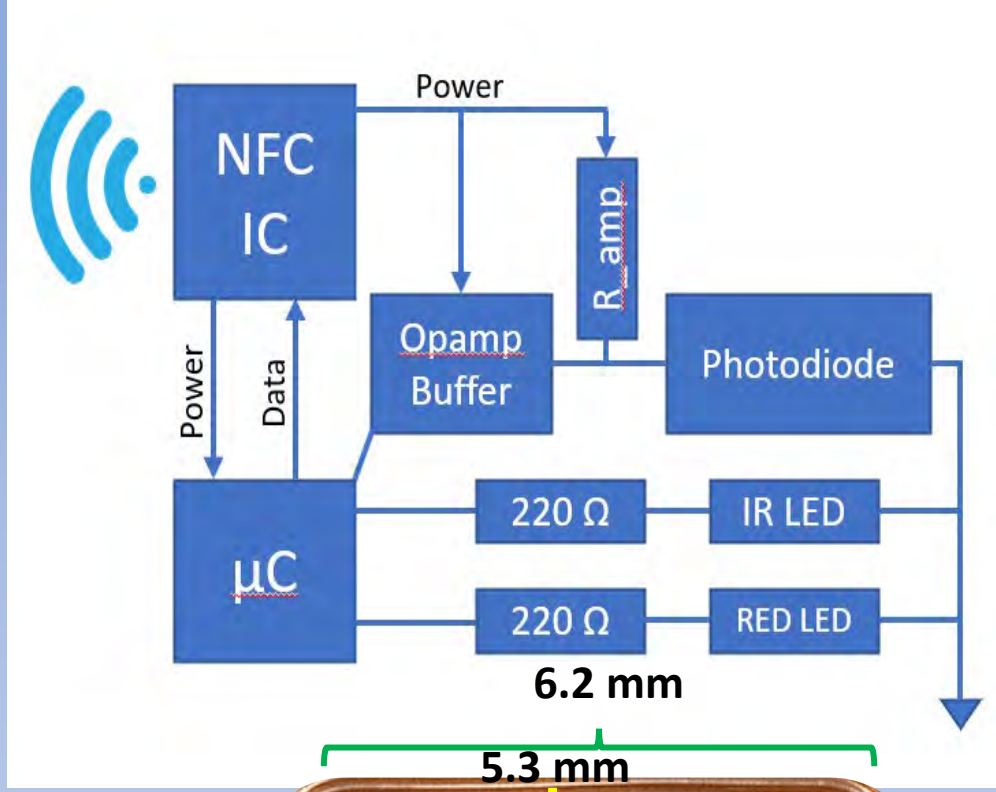
- PPG is a viable option for force sensing!

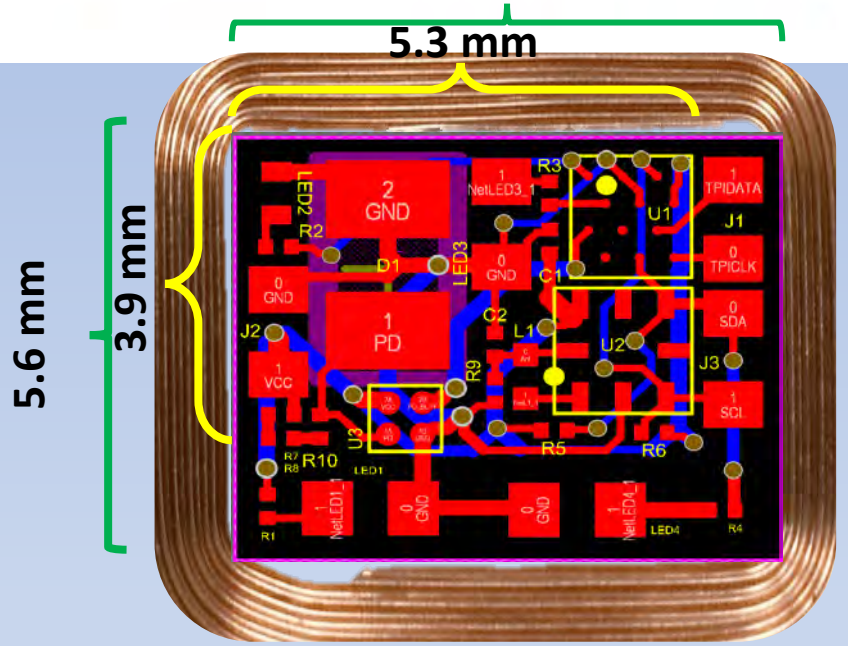




Implantable Sensor

- New Features:
  - Wireless data transmission
  - RF energy harvesting
- PCB size: 5.6mm x 6.2mm
  - Electronics footprint: 3.9mm x 5.3mm
- Software: AVR assembly language

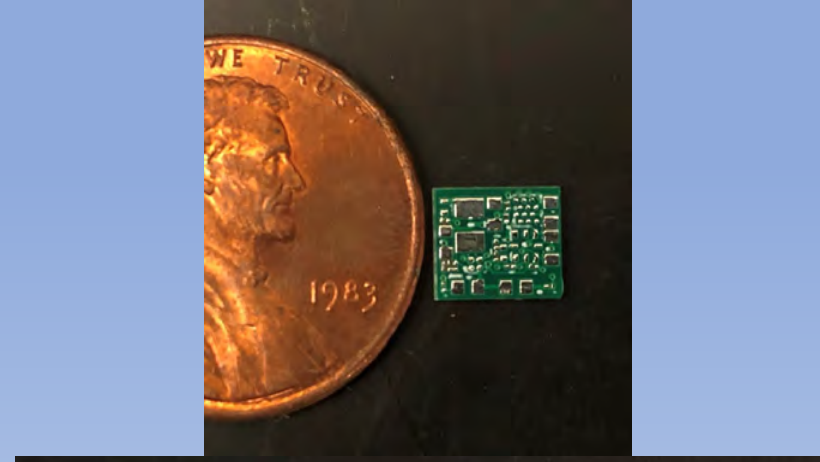


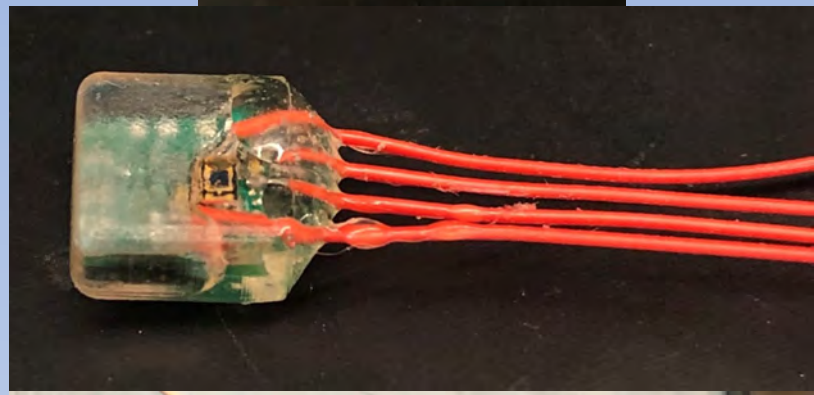


In Vivo Testing

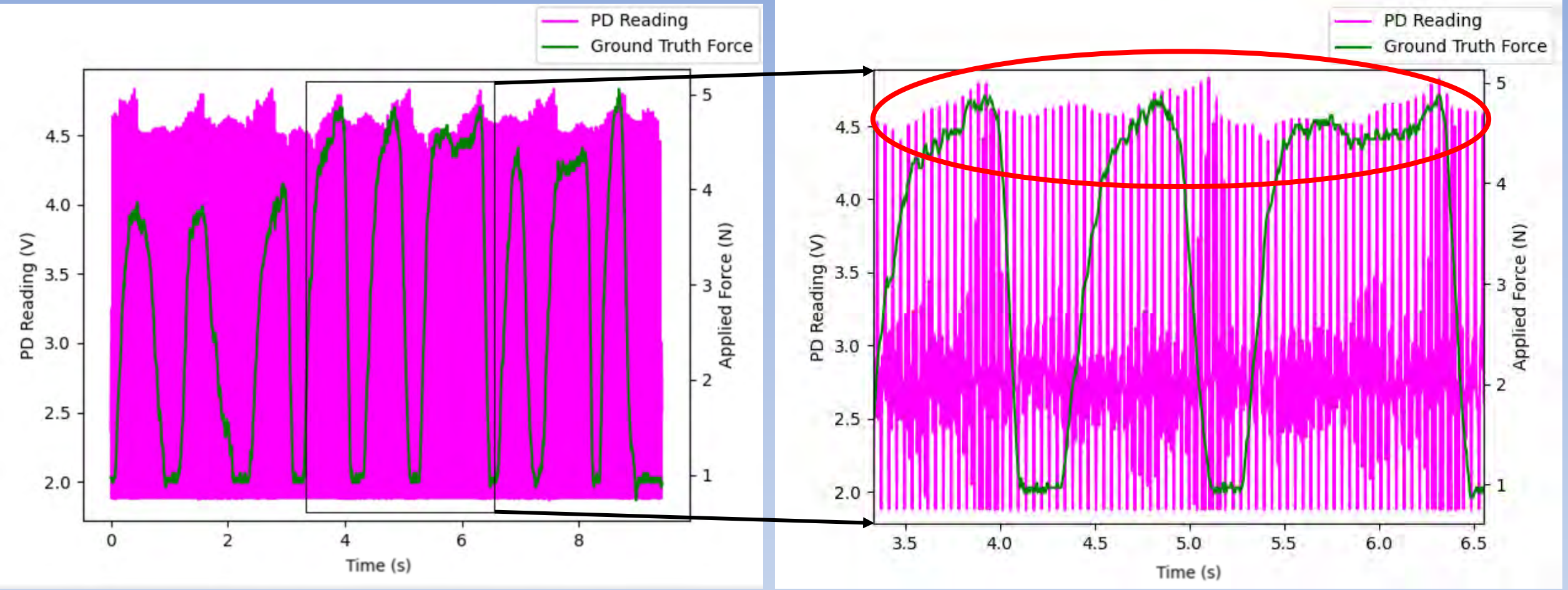
- Simple on-chip implementation:
  - Red + IR LED, Photodiode
  - 3D printed resin case, epoxy seal

- Subcutaneously implant sensor in hindlimb of an anesthetized rat





In Vivo Results

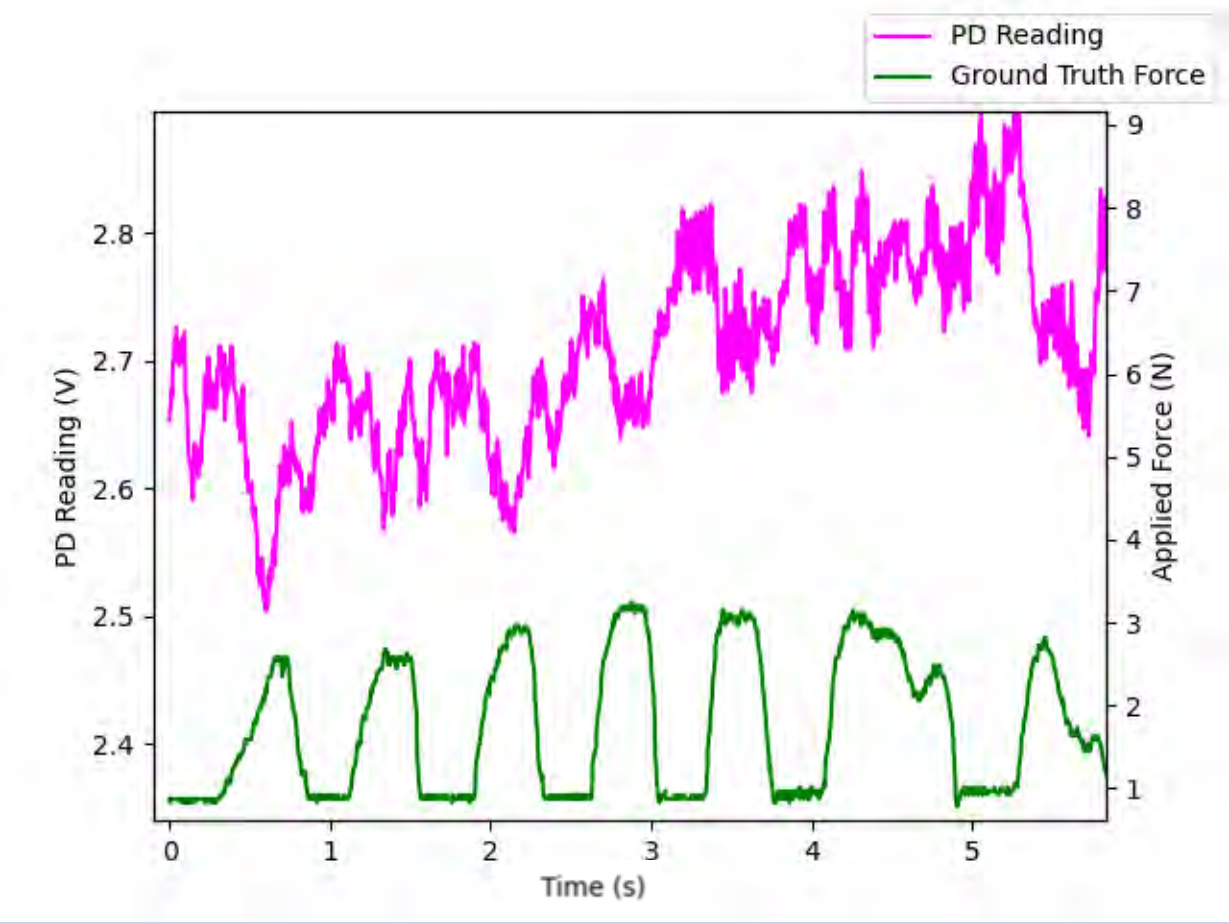


Much noisier signal

Spikes in photodiode signal somewhat track forces

In Vivo - Results

- Filtered data reveals cyclical pattern
  - Physiological processes?
  - No apparent correlation with force



In Vivo – Future Analysis and Considerations

- More analysis needed for *in vivo* results
  - Advanced filtering / signal processing for noise reduction
  - Fourier transforms for frequency analysis?
- Rat may be a poor model for human skin
  - Blood flow differs significantly[6]
- Need to minimize direct LED light entry to photodiode

In summary…

- PPG-based optical sensor is a viable option for force sensing
- First-generation wireless PCB shows promise, but advanced manufacturing techniques may be needed
- Advanced signal processing required to determine if applied force can be reliably inferred from sensor data

Next Steps

- Compare absorption of red and IR light
- Quantify relationship between force and photodiode readings
- PCB iteration, wireless testing, fused silica package

Acknowledgements

- Translational Neuromodulation Lab
  - Dr. Andrew Richardson, Andrew Gabros
- Aflatouini Lab
  - Dr. Firooz Aflatouini, Han Hao
- R01 Sensor Group
  - Dr. Mark Allen, Lin Du
- SUNFEST Coordinators
  - Dr. Sue Ann Bidstrup Allen, Julia Falcon
- NSF Grant No. 1950270

References

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