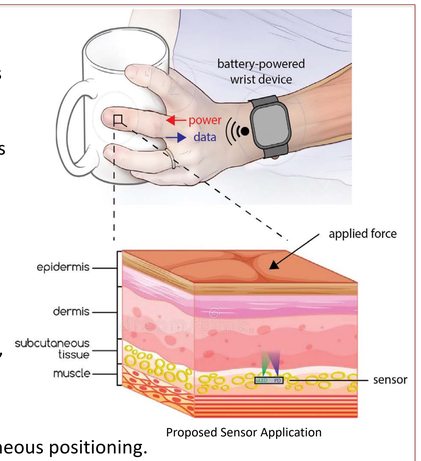
Imaging Photoplethysmography to Determine Pressure Induced Changes in Cutaneous Vascularization

Alexander Steele[1], Avin Khera BS[2,3], Andrew Gabros BS[3], Andrew Richardson PhD[3]

[1]Department of Electrical Engineering, University of Notre Dame, Notre Dame, Indiana, [2]Perelman School of Medicine, University of Pennsylvania, Philadelphia, Pennsylvania, [3]Department of Neurosurgery, Penn Medicine, Philadelphia, Pennsylvania

Introduction

- **Background:** Tactile feedback is crucial for controlling movements, especially in the hands, where skin mechanoreceptors are densely concentrated. Restoring functional movements after paralysis through engineered connections between the brain and body (i.e., neuroprostheses) requires conveying a sense of touch. One way to convey this is through the implementation of implantable artificial mechanoreceptors (IAM) within the hand.
- **Limitations of Previous Sensor:** The initial IAM our lab created was a wireless, hermetically sealed device that sensed forces capacitively from a subcutaneous location under the skin. However, its sensitivity is constrained by this subcutaneous positioning.



Proposed Sensor Application

- **Properties of Skin:** Skin color is transiently influenced by forces due to changes in blood volume within the compressed skin capillaries.
- **New Sensor:** To create a highly sensitive tactile sensor for neuroprostheses, we have proposed an innovative miniature subcutaneous device capable of optically interrogating the blood volume in the overlying dermis.
- **Spatiotemporal Properties Study:** Designing an effective sensor, requires understanding the spatiotemporal properties of blood volume changes in response to tactile forces.
- **iPPG for Circulation Imaging**: In facilitating the development of the new tactile sensor, we present imaging photoplethysmography (iPPG) as a technique capable of obtaining high field-of-view images of the underlying circulation in the hand.

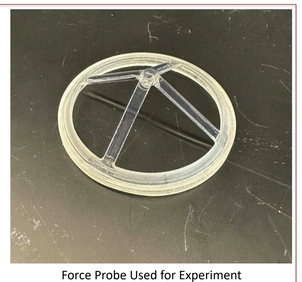
Research Methodologies

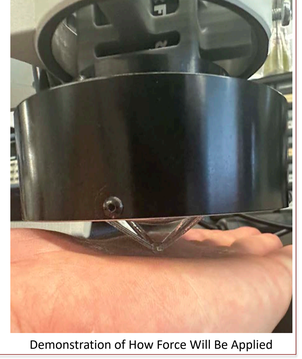
I. Testing Setup:
- Microscope stand repurposed to hold camera system
- Hand placed palm up underneath camera against table for stability

II. Force Probe:
- 3D-printed clear probe mounted to the end of the lens
- Used to apply forces directly to the hand, while still allowing for clear imaging
- Hemispherical tip (diameter = 5mm), measuring 16 mm from the lens

III. Recording Techniques:
- Utilized the application Spinnaker SDK (SpinView GUI) to record 20 second clips of the hand with direct force being applied from probe
- Videos would be recorded with direct contact between the hand and the force probe

IV. Processing Techniques Used on Video:
- Spatial and temporal normalization
- The Plane-Orthogonal-to-Skin (POS) method
- A frequency filter with a bandwidth of 0.0095-0.145Hz, encompassing physiologic bands of endothelial, myogenic, and neurogenic activity

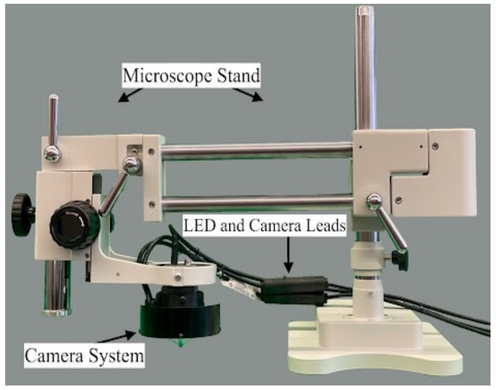

Force Probe Used for Experiment


Demonstration of How Force Will Be Applied

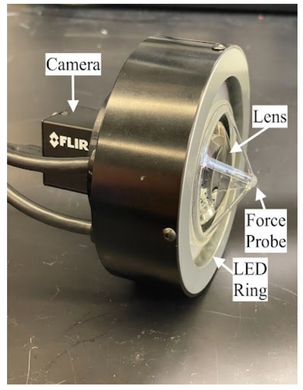
Camera Setup

Camera Specs:
- 3.2 Megapixel RGB camera (Blackfly BFS-U3-32S4C-C, Teledyne FLIR, Wilsonville, OR)
- Resolution 2048x1536
- 3.5mm Lens (Max aperture F2, Edmund Optics, Barrington, NJ)
- LED ring (RL5604 WHITE, Advanced Illumination, Rochester, VT)

Entire Camera Setup

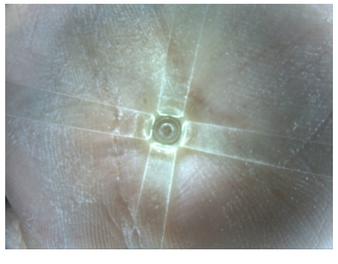


Camera System

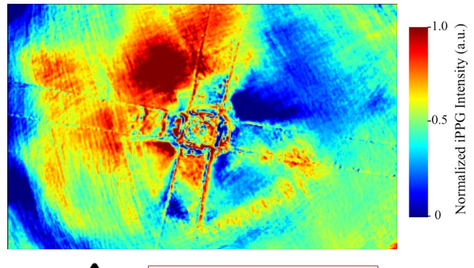


Mapping Cutaneous Blood Volume (CBV)

Before


Frame at ~ 5 seconds of original video with the probe moving to the left and downward on hand

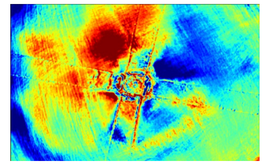
After



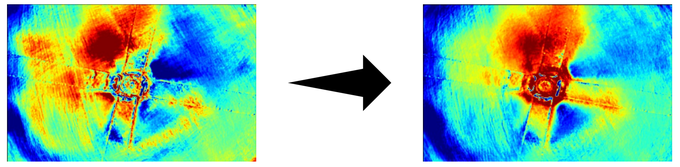
Frame at ~ 5 seconds (same time point) with a mapped normalized iPPG cutaneous blood volume

- **Original:**
  - 20 second video clip of hand
  - Force probe applied direct pressure to hand during entire 20 seconds
  - 1920x1080 Resolution
  - Started from center of the palm, moving medially to the level of the 5th digit, then translating distally to the MCP joint
- **Post Processing:**
  - Novel images of microcirculation at near-DC bandwidths
  - No significant noise
  - 1920x1080 Resolution
  - Mapping the normalized iPPG cutaneous blood volume in hand (0-1)
  - Lower blood volume: Blue
  - Higher blood volume: Red

Discoveries



- **Description:**
  - Probe moving to left and downwards across hand at ~1cm/sec
  - Left trail of blue as a result of shear forces
- **Analysis:**
  - Reduced CBV as lagging adaptive vasodilatory mechanisms follow behind the moving point of compression
  - Mechanisms: Endothelial metabolic activity and myogenic control



- **Description:**
  - Transition from frame 75 to 175
  - Probe has become static in later frame
  - Rush of blood appears in red at the point of contact after 1 second
- **Analysis:**
  - Perfusion originated from the microcirculation of surrounding tissue
  - Pressure-induced vasodilation (PIV)
  - Due to myogenic control, distal arterioles increased blood flow to capillaries following compression

Conclusion & Next Steps

- **Conclusion:**
  - We successfully visualized pressure-induced changes in microcirculation perfusion
  - Observed phenomena were influenced by previously documented autoregulation methods
- **Next Steps:**
  - Observe effects of several different conditions of force using new testing apparatus
    - I. Specific points on hand
    - II. Controlled amounts of force and type (Shear, Direct)


Model of New Testing Apparatus With XYZ-Force Stage Controlling Force

References & Acknowledgements

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