Smart Sleeve: Wearable Soft Sensors for Limb Volume Estimation

Northeastern University
College of Engineering

Claire Vanderpot, *REU Student, North Shore Community College*
Kristen L. Dorsey, PhD, *ECE and PTRMS Departments, Northeastern University*

Northeastern University
Michael B. Silevitch and Claire J. Duggan Center for STEM Education

Abstract

We aim to develop a wearable, **full-arm sleeve integrated with soft, flexible sensors** and a wireless microcontroller to estimate limb volume through circumference measurements.

Ultimately, this smart wearable will enable **remote, objective monitoring** of edema progression and offer **more accurate data to guide treatment** decisions and support at-home care.

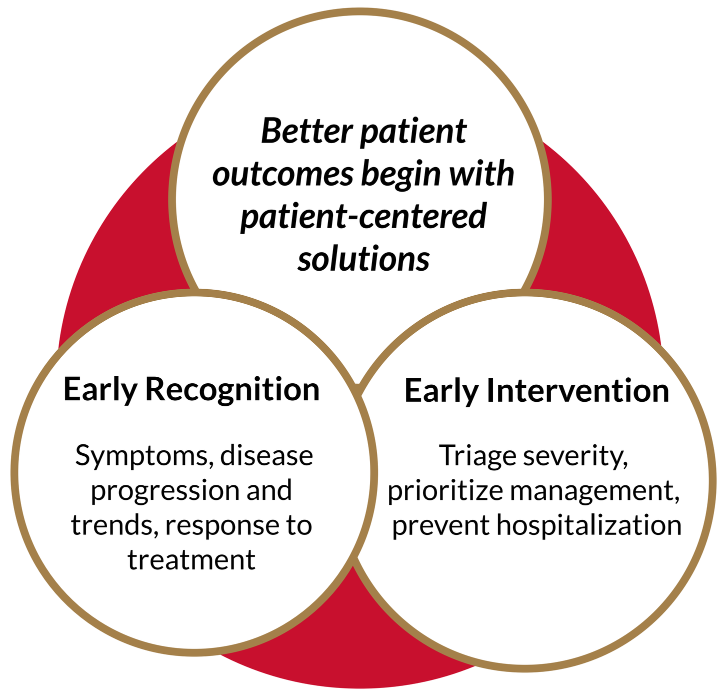
Introduction

Edema, or swelling, is a benchmark clinical indicator in many acute and chronic conditions. Abnormal accumulation of fluid can **damage surrounding tissues** resulting in **pain and limited mobility** for patients.

Figure 1. Stages of Lymphedema in the Upper Limb

Current monitoring methods require in-person assessments and utilize cloth measuring tapes. These measurements can be **inaccurate, infrequent and difficult to reproduce at home**.

The integration of remote monitoring devices can aid in the **early detection and intervention** of disease progression, promoting better patient outcomes.



Research, Design and System Integration

Capacitance Sensors

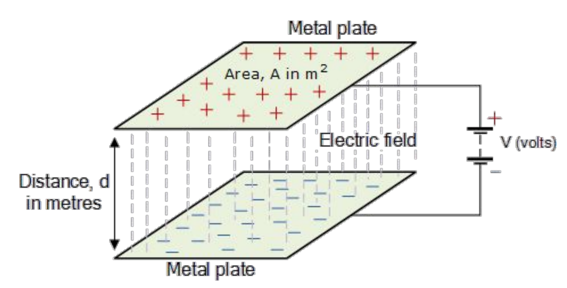


Figure 2. The principle of capacitance, C.

Capacitors

Store electrical energy between two conductive plates separated by an insulating layer (dielectric). [1]

Stretch ⟶ **Change in capacitance**

$$C = \varepsilon \frac{A}{d}$$

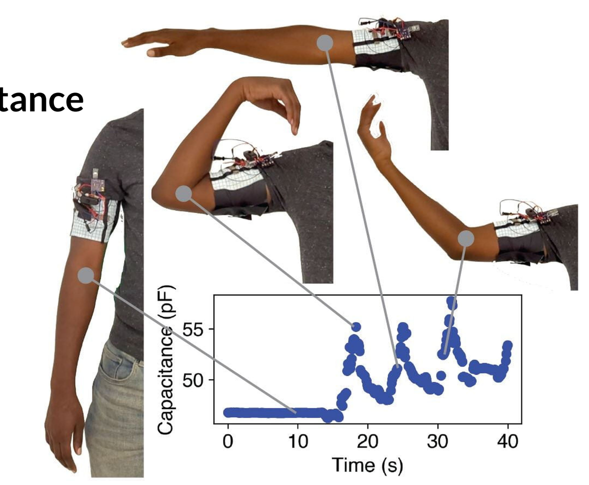


Figure 3. From paper *Wireless Capacitive Measurement Board for Wearable or Proprioceptive Applications*, person wearing a capacitive strain sensor sleeve moves their arm to increase capacitance as the biceps muscle is contracted. [3]

Bend Labs 1-Axis Sensor

Figure 4. Bend Labs soft capacitive sensor

How it meets our needs:

Flexible and durable

Water- and weather-resistant

Low power consumption

I²C interface [4]

PCB & MCU

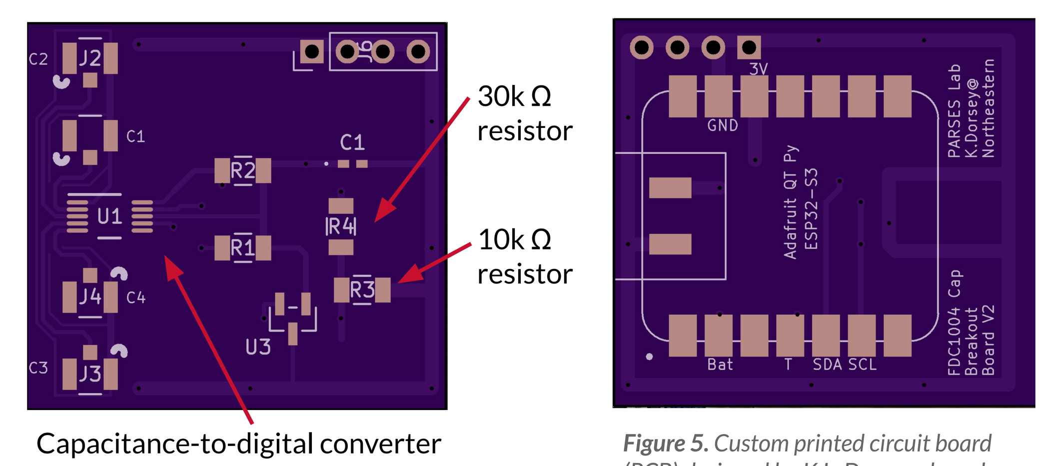
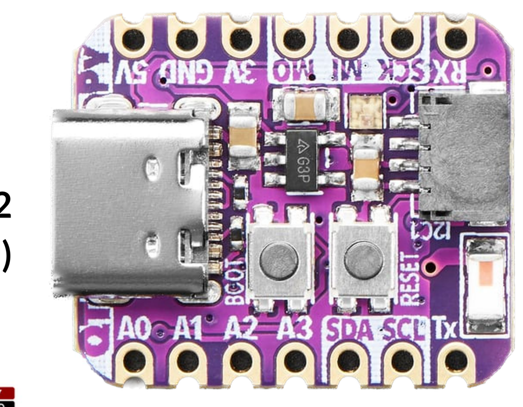


Figure 5. Custom printed circuit board (PCB) designed by K.L. Dorsey, shared within PARSES lab document center.

Adafruit QT Py ESP32 Microcontroller (MCU)



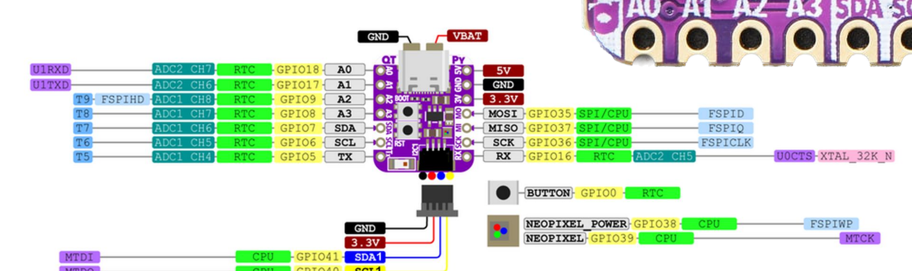


Figure 6. Adafruit QT Py ESP32 microcontroller (MCU) and its pin out diagram.[5] The MCU is soldered to the PCB for use with the smart sleeve system.

Power: Battery Monitoring

Lithium Ion Battery

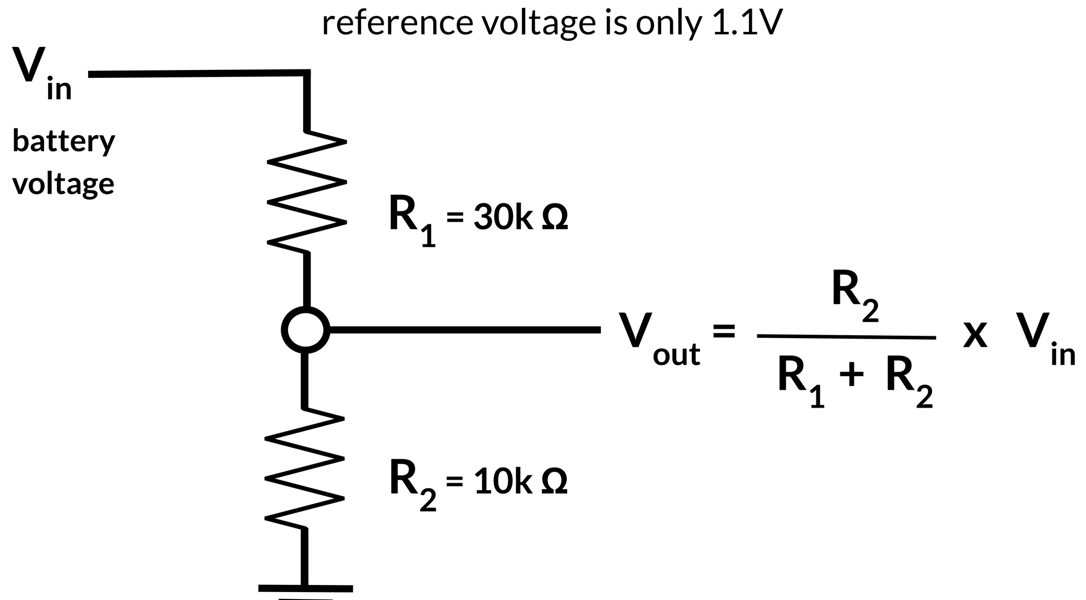
Tested with 3.7V – 4.2V batteries

Low power consumption system

Minimum safe voltage ~ 3.0V

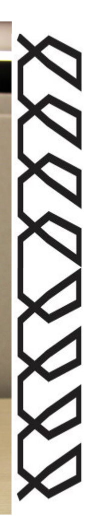
Must monitor to prevent over-discharging[6]

Voltage Divider: Required for reading battery voltage because MCU's reference voltage is only 1.1V



$$V_{out} = \frac{R_2}{R_1 + R_2} \times V_{in}$$

Prototype Fabrication



Brother Sewing Machine

Stitch #3

Stitch #21 (shown left)

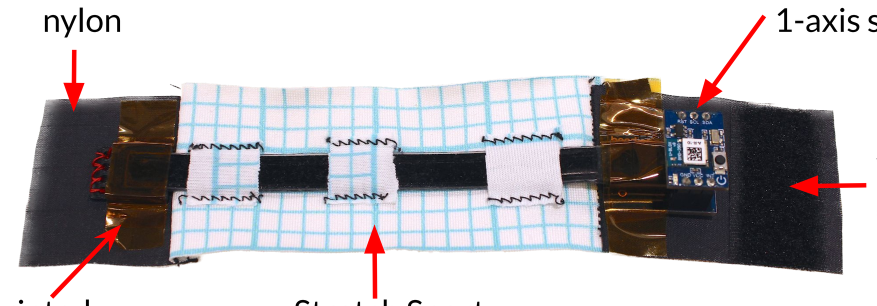


Figure 7. First hardware-integrated band.

Results

Final hardware integration is the next step before user testing can begin.

Key test question:

How does the sleeve perform from one wear to the next?

Figure 8. A "proof of concept" prototype.

Discussion

User testing and data collection are required to correlate capacitance readings to circumference measurements and ultimately limb volume calculations.

Durability, reliability and ease of use of the sleeve are key to ensuring the system meets patient and provider needs. **Further material testing and analysis** is recommended. Ideally, subjective data is collected on **user experience.**

dFMEA: Design Failure Mode and Effect Analysis: A critical step in product development to evaluate all possible points of failure in the system and rating the severity of their impact.

Example: The system's ability to accommodate patients with more severe edema → sensors must have wide stretch tolerance.

References

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