SweatSense: A Low-Cost Eccrine Sweat Biosensing Technology for Diabetes Diagnosis and Management

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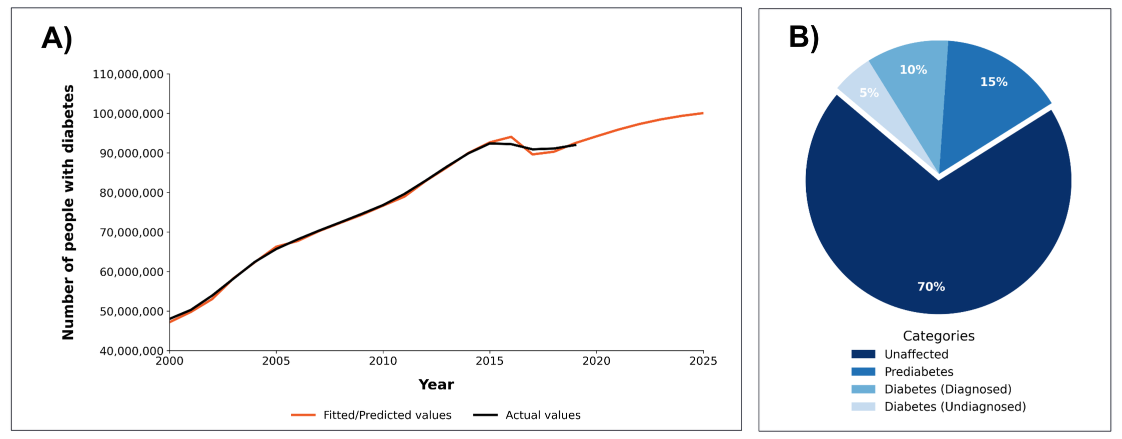
ABSTRACT



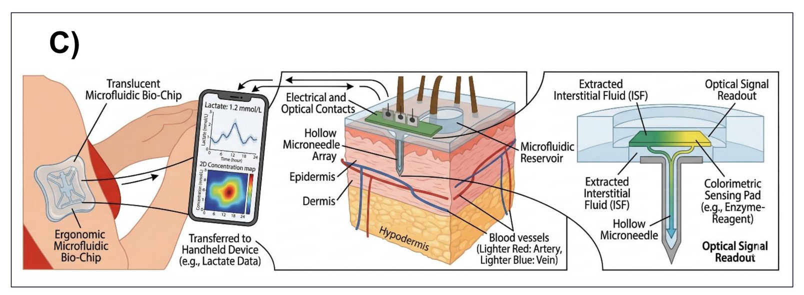


Figure 1. A) ARIM model for global burden of diabetes (2000-2030) [1]. B) Diabetes and prediabetes rates in Canada (2024) [2]. C) Diagram of microfluidic platform for monitoring interstitial fluid [4].

About **30% of Canadians** live with diabetes or prediabetes. This condition can cause serious, even life-threatening complications, with the condition on average reducing life expectancy by **5 – 15 years**. Canada has an aging population, a vulnerable racial demographic, and a trend of physical inactivity that makes diabetes a pressing health crisis.[2] Most modern diabetes monitors use needles to access glucose concentrations of the interstitial fluid, so users can be aware if their metabolic health is at risk of emergency. However, these devices (i.e. Dexcom G7) are **expensive, invasive, and unsuitable** in exercise.[3]

OPERATION CYCLE

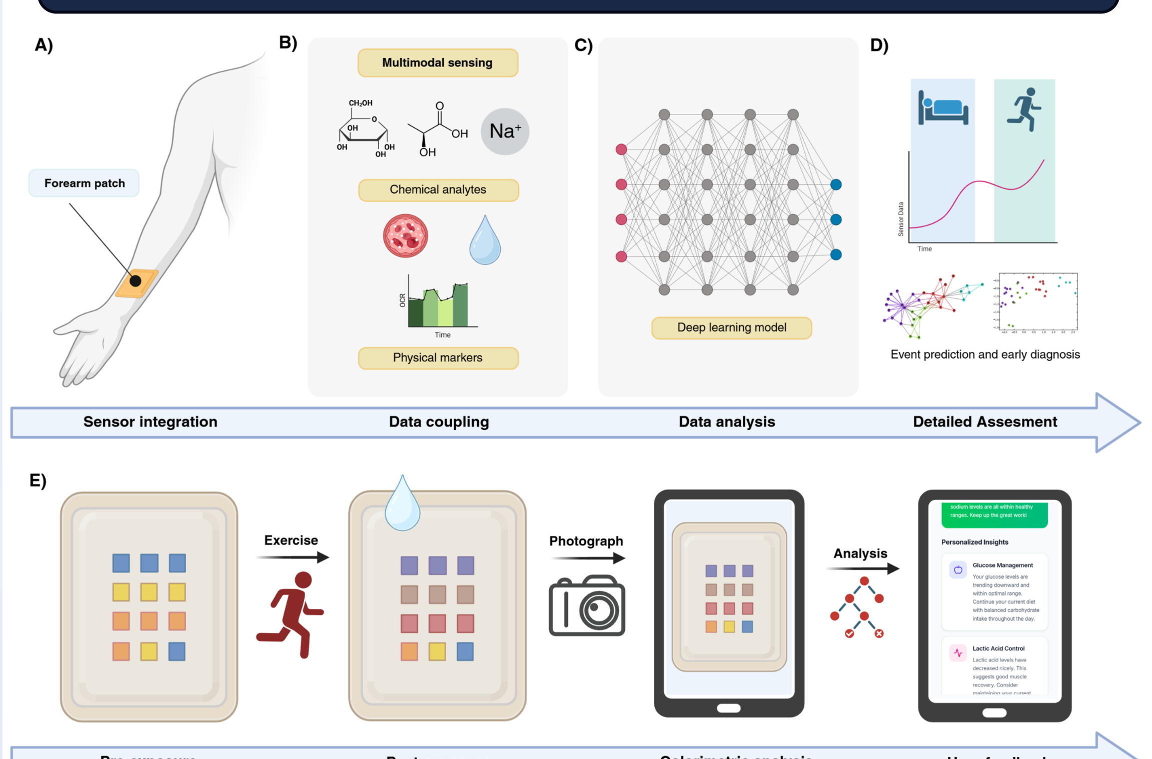


Figure 2. A) Wearable integration location B) Multimodal sensing with multi-analyte and user information. C) Convolutional neural network (CNN) to conduct data analysis. D) Analysis for forecasting events and assisting diagnosis. E) SweatSense Full concept operation.

ENGINEERING OBJECTIVES

Objective	Goal	Rationale
Rapid	Can complete entire operation reliably in under five minutes.	Glucose levels can vary quickly, risking diabetic emergencies.
Non-invasive	Can operate without needle or long-term implantation.	Less discomfort for users and enables more flexibility with usage.
Multi-Analyte	Can perform reliable analysis on several analytes of interest	The detection of several analytes allows for more thorough analysis of health.
Manufacturing Simplicity	Can be operated with minimal power or device components.	Design simplicity enables less intrusion and greater flexible for exercise.
Pricing & Accessibility	Can be produced at a lower cost and accessible to wider users.	Lower costs allow the device to serve as an alternative to expensive CGMs.

ENGINEERING DESIGN

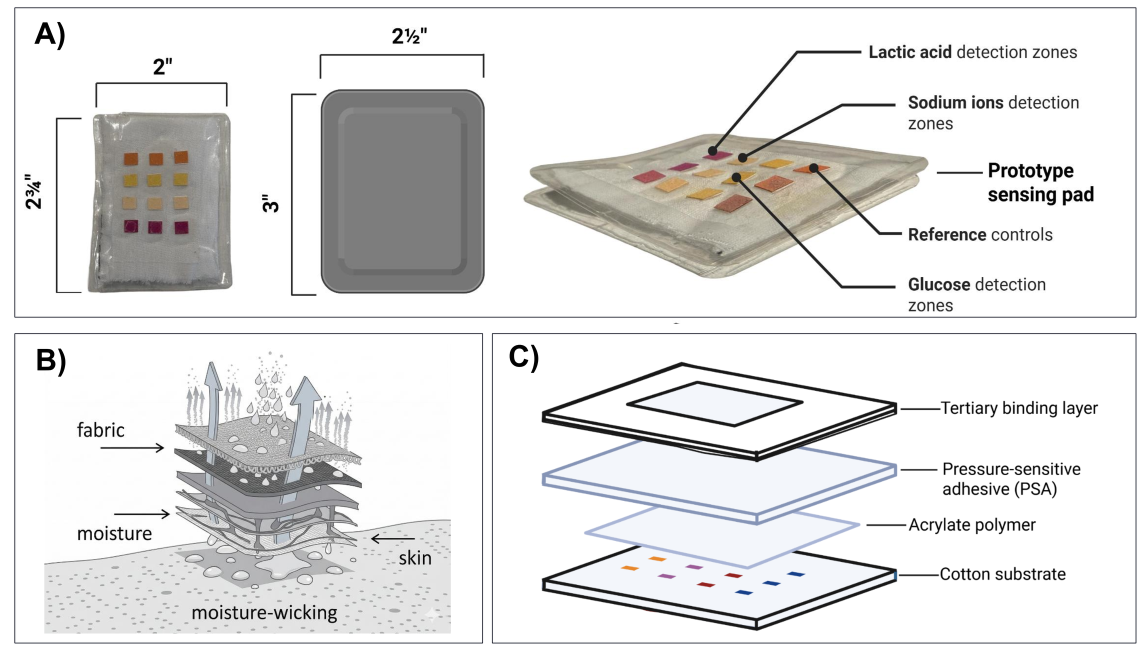


Figure 3. A) Wearable prototype from overhead and isometric perspective. B) Capillary action which drives sweat absorbance. C) Exploded-view drawing of SweatSense patch.

MACHINE LEARNING MODEL

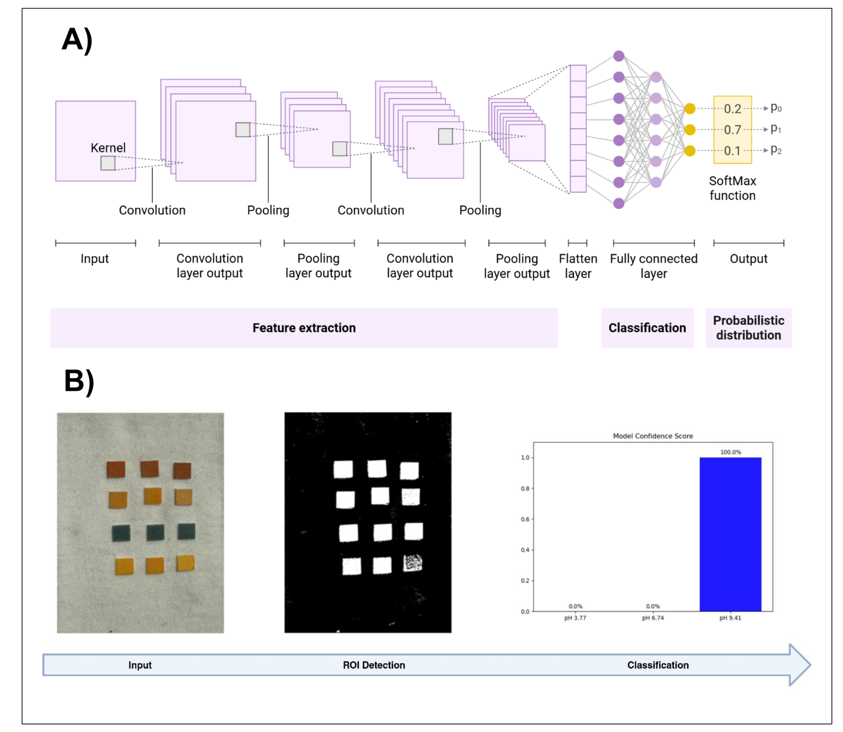
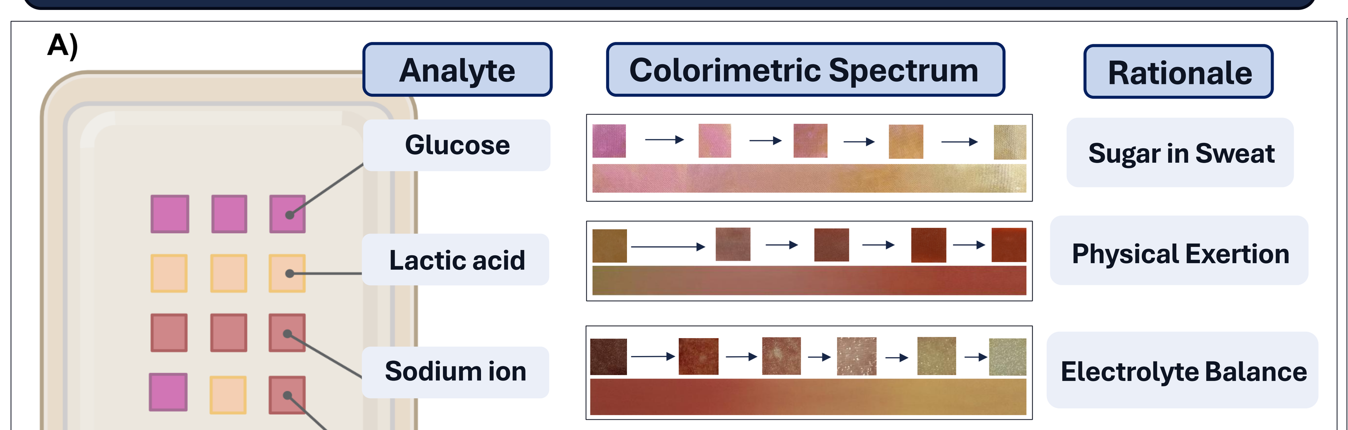


Figure 4. A) Nodes of a Convolutional Neural Network (CNN) B) ROI detection process for a sample input.

A Convolutional Neural Network (CNN) is implemented, being well established in feature extraction, in this case to detect the rows of colorimetric sensors in triplicates. The color information of each type of sensor is then corrected and normalized using one reference color from the input. Resulting analysis is completed by comparing color to calibration curve.

COLORIMETRIC SENSORS



Reference row is inert to change, serving the purpose of a color anchor to aid colorimetric analysis and calibration curve fitting to accommodate for variable lighting conditions.

C) (1) Low [ ]. (2) Medium [ ]. (3) High [ ].

$$MnO_4^- + 2H_2O_2 + 4H^+ \rightarrow Mn^{3+} + 2O_2 + 4H_2O \quad (1)$$

$$2KMnO_4 + 3H_2O_2 \rightarrow 2MnO_2(Mn^{4+}) + 3O_2 + 2KOH \quad (2)$$

$$MnO_4^- + 5H_2O_2 + 6H^+ \rightarrow 2Mn^{2+} + 5O_2 + 8H_2O \quad (3)$$

D) $$[Fe(phen)_3]^{3+} + L^- \rightarrow [Fe(phen)_3]^{2+}$$

E) $$2KNO_3 + Ag_2CrO_4 + 2NaCl \rightarrow 2AgCl + 2NaNO_3 + K_2CrO_4$$

METHODOLOGY

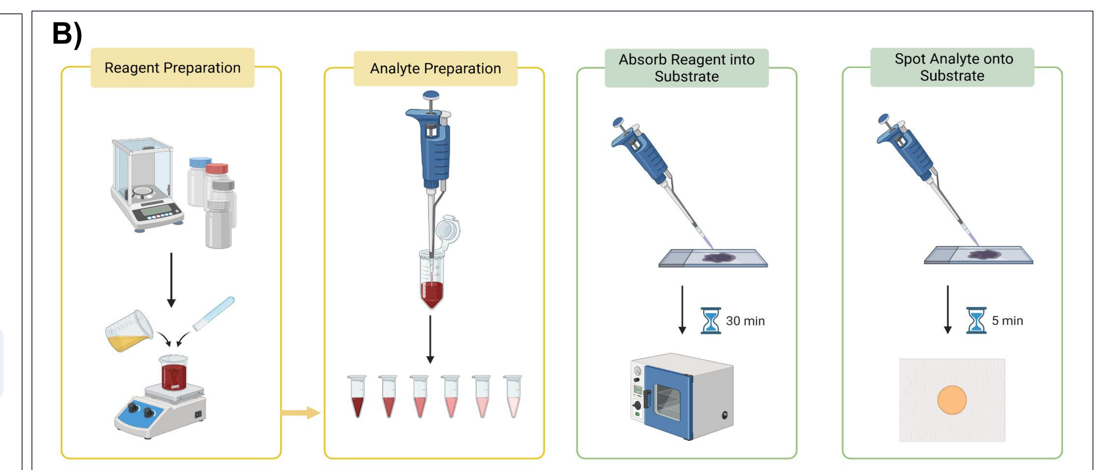
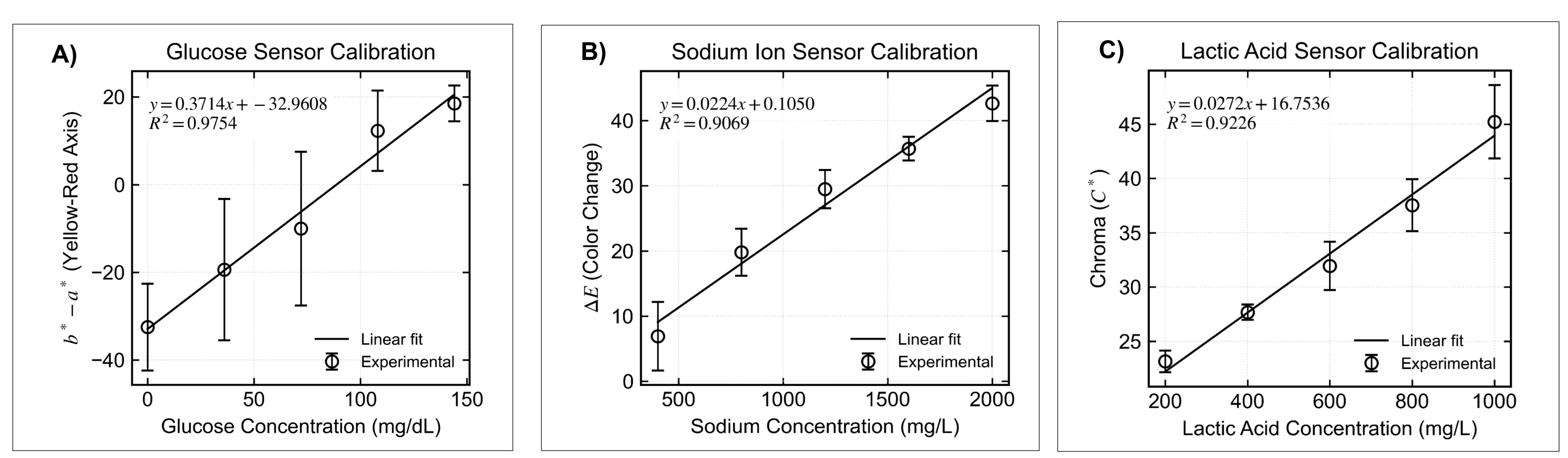


Figure 5. A) Types, spectrum, and rationale for each colorimetric sensor. B) General methodology for *in-vitro* testing of colorimetric regions. C) Glucose detection reactions. D) Sodium ion detection reaction. E) Lactic acid detection reaction.

The testing procedure for each of the colorimetric sensing zones involved absorbing specific reagents onto a cotton substrate, drying, and spotting of analyte solutions (with different concentrations): **0, 36, 72, 108, 144 mg/dL** (Glucose); **400, 800, 1200, 1600, 2000 mg/L** (Sodium ion); **200, 400, 600, 800, 1000 mg/L** (Lactic acid). Photos were captured five minutes after initial analyte exposure. Each concentration trial was conducted with at least triplicates.

RESULTS & DATA ANALYSIS



	Glucose Detection	Sodium Ion Detection	Lactic Acid Detection
Linear Equation	$y = 0.3714x - 32.9608$	$y = 0.0224x + 0.1050$	$y = 0.0272x + 16.7536$
Correlation (R^2)	0.9754	0.9069	0.9226
Sensitivity	$0.3714\,\Delta(b^* - a^*) \cdot \mathrm{dL/mg}$	$0.0272\,\Delta C^* \cdot \mathrm{L/mg}$	$0.0224\,\Delta E \cdot \mathrm{L/mg}$
Limit of Detection (LOD)	88.01 mg/dL	592.44 mg/L	273.15 mg/L

Glucose Detection Accuracy

Concentration (mg/dL)	Mean (b^* - a^*)	Std. Deviation (σ)
0	-32.49	±5.64
36	-19.39	±17.65
72	-10.05	±17.42
108	12.28	±12.39
144	18.52	±5.37

Sodium Ion Detection Accuracy

Concentration (mg/L)	Mean ΔE	Std. Deviation (σ)
400	6.92	±5.26
800	19.80	±3.59
1200	29.49	±2.95
1600	35.70	±1.82
2000	42.64	±2.73

Lactic Acid Detection Accuracy

Concentration (mg/L)	Mean C^*	Std. Deviation (σ)
200	23.15	±1.00
400	27.68	±0.71
600	31.94	±2.21
800	37.54	±2.39
1000	45.23	±3.38

The Limit of Detection (LOD) or the lowest analyte concentration that can be reliably distinguished from a blank sample was defined:

$$LOD = \frac{3.3\sigma}{m}$$

Sensitivity (S) of the sensors is determined by the change in output in relation to the change in input. Of the sensors' calibration curves, sensitivity (S) is defined:

$$S = \frac{\partial y}{\partial x}$$

Figure 6. A) Glucose calibration curve with a linear regression over a sample set of 88 images. B) Sodium ion calibration curve with a regression completed over a dataset of 44 images. C) Lactic acid calibration curve with a linear regression completed over a 36 image dataset.

CONCLUSIONS

The SweatSense technology was engineered to create a more flexible, inexpensive, non-invasive, and specialized platform to manage diabetes and prediabetes during exercise. Some of the special features, advantages, and limitations are described.

Special Features

- Proof-of-Concept implementation of colorimetric (optical-based) biosensing of 3 analytes.
- Effective integration of a neural network (CNN) for feature extraction and quantitative prediction of analyte concentrations from Smart Phone captures.
- Improved accuracy under variable lighting by using a more robust color space.
- Development of a robust and reproducible calibration curve for sensitive analyte detection

Advantages

- The wearable is more flexible and reduced irritation with its short-term usage.
- Thorough analysis and feedback can be provided for multiple critical analytes.
- Wearable is more accessible, being inexpensive and relatively simple to manufacture, resulting from no power requirement or electronics.
- Sweat analysis enables non-invasive collection.

Limitations

- Accessibility of moderate-high sweat flow rate for rapid measurements.
- Smartphone operation requirement.
- Moisture, extreme temperature conditions can delay and cause inaccurate analyte readings.
- Quantification is less precise compared to modern electrochemical biosensors.

FUTURE DIRECTION

There are several notable extensions to this project which are either in-planning or being considered in the near-future.

- More thorough machine learning model training with a significantly upscaled dataset to improve calibration curve and prediction accuracy.
- Initiation of human trials to ensure reliability, pace of device operation, and specific sweat flow rate requirements.
- Development of ROIs detection algorithm through continued testing with complete substrate model.
- Further experimentation into reagent immobilization for less stable colorimetric sensing reagent zones.
- Experimentation into the use of sensitizers to produce greater accuracy with quantification and detection.

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