Development of a Soft Wearable Hand Rehabilitation Robot Using Embedded Stretchable Sensors and a Predictive Trigger for Adaptive Assistance

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Background and Motivation

The Clinical Picture

- Hand impairment after stroke, spinal cord injury and trauma limits everyday function (**Feigin2021**; **Safdarian2023**; **Crowe2020**)
- Recovery depends on repeated finger movement to drive motor relearning
- Rigid exoskeletons: fixed structures, alignment and comfort challenges (**Chen2024**)
- Soft pneumatic gloves: flexible, air-driven, more comfortable – but control is usually just a fixed programme

The gap: a system that senses movement and decides assistance from that movement, not from a timer

Research Problem and Gap

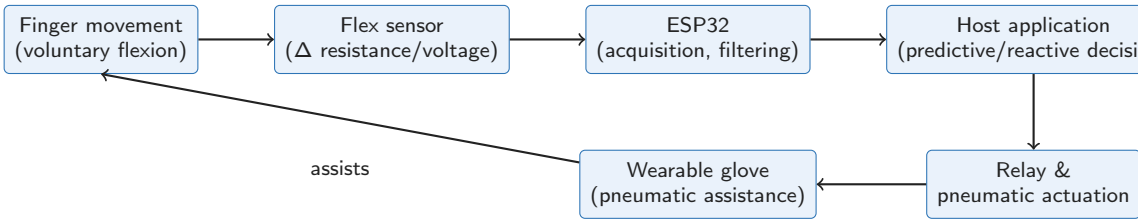
Existing challenge	Engineering need
Limited embedded movement sensing	Continuous movement measurement
Fixed assistance programmes	Adaptive assistance
Reactive triggering	Predictive decision-making
Nonlinear pneumatic behaviour	Suitable system modelling

Aim & Objectives

Aim: Develop a soft wearable hand rehabilitation robot combining embedded sensing with predictive control for adaptive assistance.

1. **Design**
   Soft wearable pneumatic rehabilitation system
2. **Sensing**
   Integrate embedded sensing for finger-movement detection
3. **Modelling**
   Mathematical models for sensing and control
4. **Control**
   Develop a predictive assistance strategy
5. **Evaluate**
   Experimental testing of the prototype

Proposed System Architecture



Proposed: 5 channels, one per finger. Prototype: 1 sensing channel, shared actuation.

Hardware and Software Components



The glove's bellows actuators

Components Used

- Commercial pneumatic hand-therapy glove (retrofitted)
- Resistive flex sensor, bonded to one finger
- ESP32-WROOM-32 microcontroller
- Host application (Node.js), USB serial communication

Prototype Development and Implementation

What Was Built

- Single-channel implementation
- One flex sensor
- Shared pneumatic actuator channel
- ESP32 sampling and filtering
- Host-based control decision

Firmware Safety Logic

- Release and squeeze outputs never both active
- Link-loss fail-safe: 3 s with no host command $\rightarrow$ pump and both solenoids off

Mathematical Modelling and Predictive Control

The Voluntary-Rise Model

$$\Delta V(t) = K\left(1 - e^{-t/\tau}\right)$$

- $\Delta V(t)$: measured voltage deviation from rest (mV)
- K: predicted steady-state deviation; τ: time constant of the response
- After 1τ: $\approx$63% of final value; after 3τ: $\approx$95%

Proposed: NMPC

Predicts future behaviour over a horizon; optimises control action; handles nonlinear dynamics and constraints

Implemented: Predictive Trigger

Estimates eventual deviation from a first-order model; checks the estimate against a threshold; does not perform full NMPC optimisation

Experimental Methodology

1
Sensor stability
Rest and voluntary-movement recordings

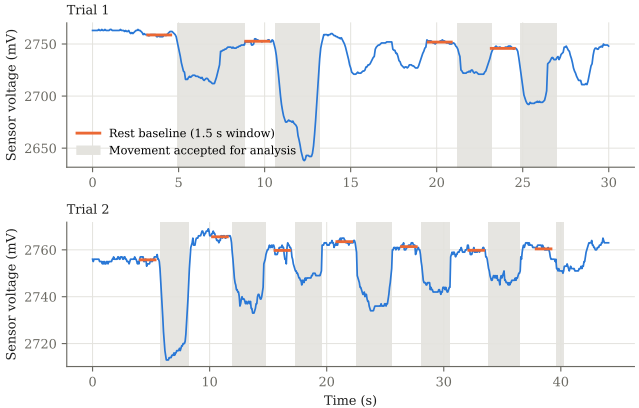
2
Sampling & timing
Timestamp analysis of logged readings

3
Rise-model identification
Fit & validate the first-order model

4
Predictive vs. reactive
Replay recorded movements through both trigger paths

5
Session-log screening
Plausibility check on 250 logged assists

Results and Discussion



Flat = resting hand; each bump = one voluntary squeeze; bump height = the deviation

16.67 Hz

Decision rate – above the 10 Hz design requirement

0.93 ms

RMS timing jitter around the 60 ms logging interval

2/121

Earlier predictive triggers in the main replay evaluation

52/250

Implausible assists flagged by the log screen

Limitations and Challenges

1. **Single channel:** not the proposed five-channel system
2. **Baseline drift:** required repeated recalibration
3. **Predictive trigger reliability:** limited in the main evaluation
4. **Full NMPC not implemented:** on/off actuation; actuator model not identified
5. **No clinical evaluation:** bench-level testing only

Recommendations and Future Work

1. **Scale up:** extend to five independent channels
2. **Calibration & plausibility:** improve sensor calibration and add plausibility checks
3. **Validate the predictive model:** on independent, representative recordings
4. **Characterise the actuator:** pressure, force and bending response
5. **Implement full NMPC:** once the actuator model is identified
6. **Add sEMG sensing:** let severely impaired patients trigger assistance without full bending
7. **Controlled user evaluation:** with appropriate ethical approval

Conclusion

- Developed and evaluated a single-channel soft pneumatic hand-rehabilitation prototype
- Integrated flex sensing, ESP32 acquisition, and host-based decision-making
- Achieved a 16.67 Hz decision rate
- Identified clear limitations in sensor stability and predictive triggering
- Established a foundation for extending toward a five-channel NMPC system

Thank You

Questions Welcome

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