ReFlex

Reimagining Stroke Recovery

Udit Garg, Aditya Gowd, Ryann Joseph, William Qi, Christopher Wun

Every 3 seconds

a stroke occurs worldwide

Kwakkel *et al.*, AHAIASA, 2003.

Every 3 seconds

a stroke occurs worldwide

101 million

stroke survivors

Kwakkel *et al.*, AHAIASA, 2003.

Every 3 seconds

a stroke occurs worldwide

101 million

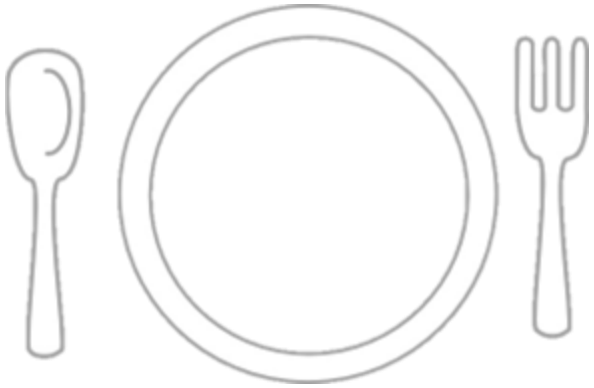
stroke survivors

89%

of stroke survivors are disabled for life

Kwakkel *et al.*, AHAIASA, 2003.

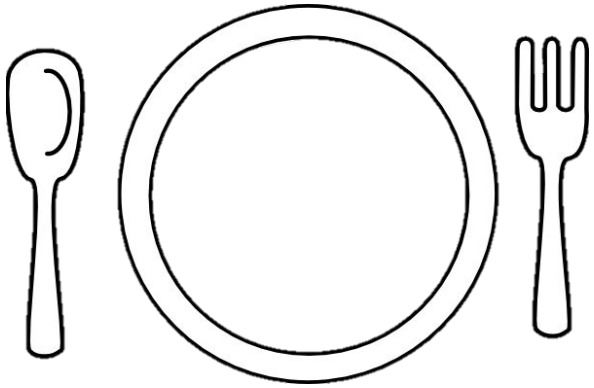
Dressing independently



Eating

Walking

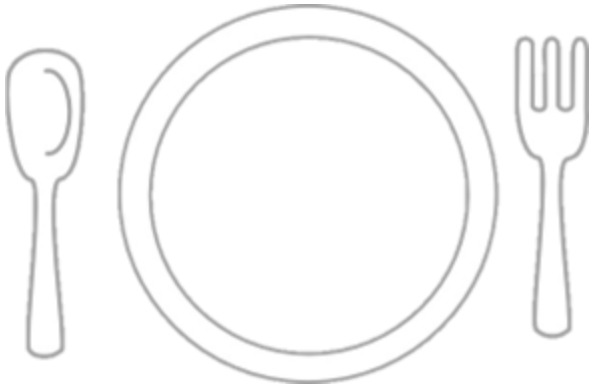
Dressing independently



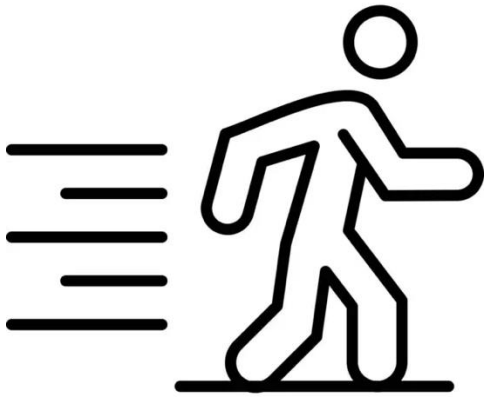
Eating

Walking

Dressing independently

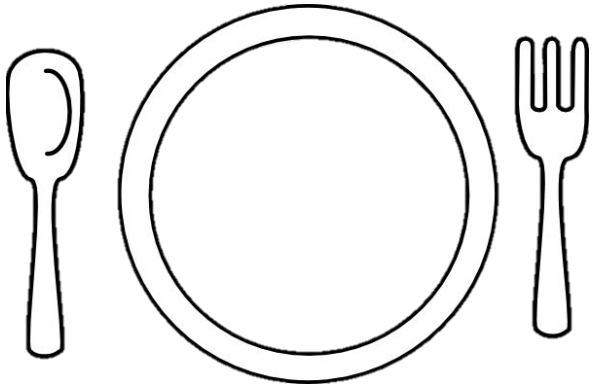


Eating



Walking

Dressing independently



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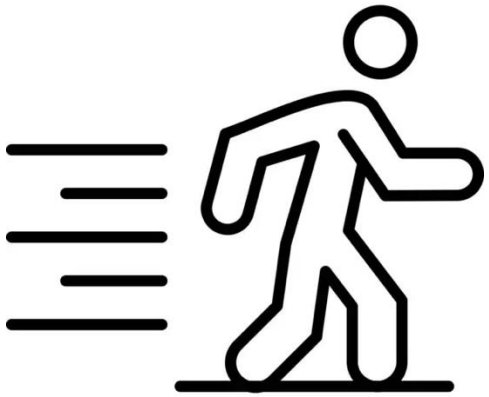
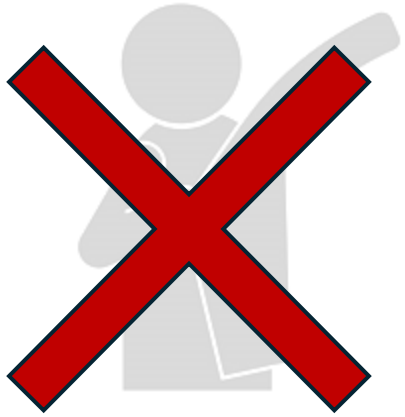
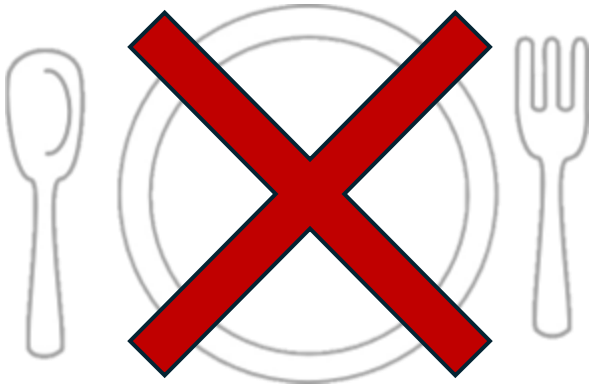


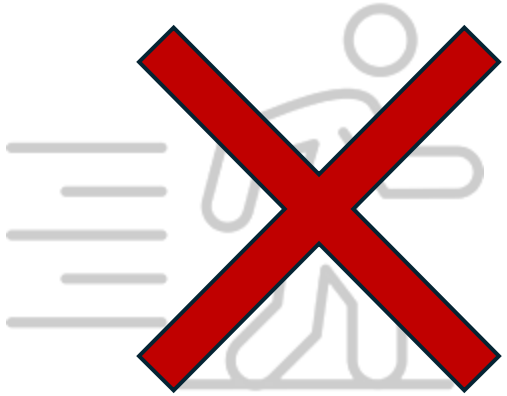
Walking



Dressing independently

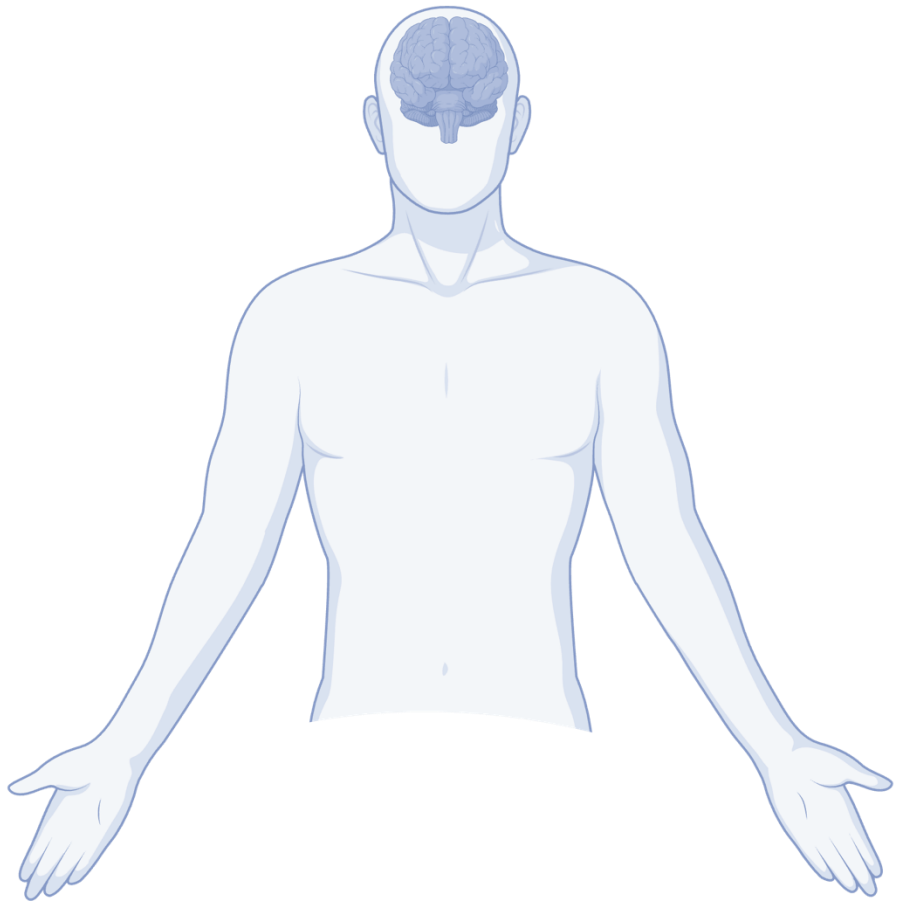


Eating

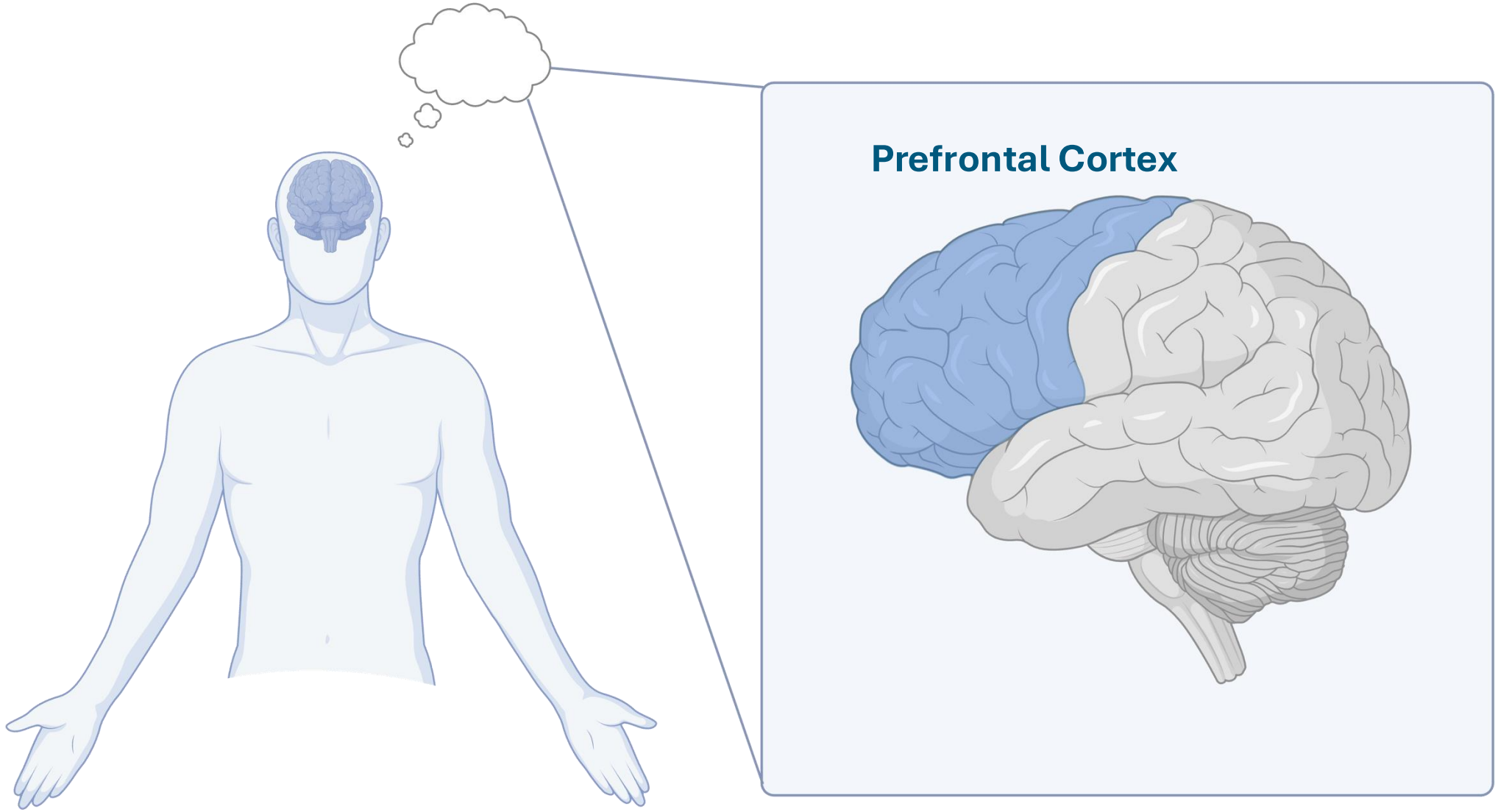


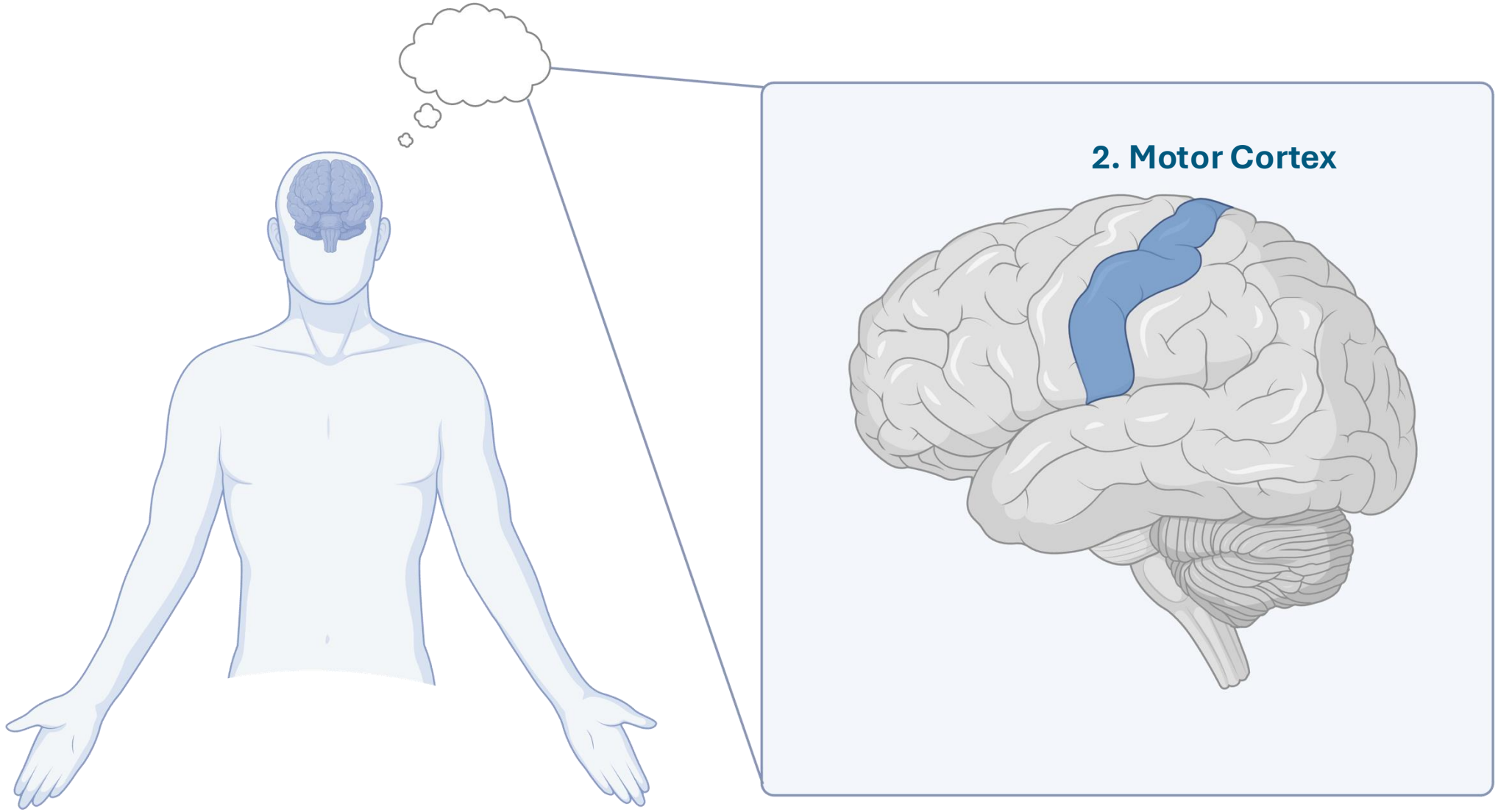
Walking

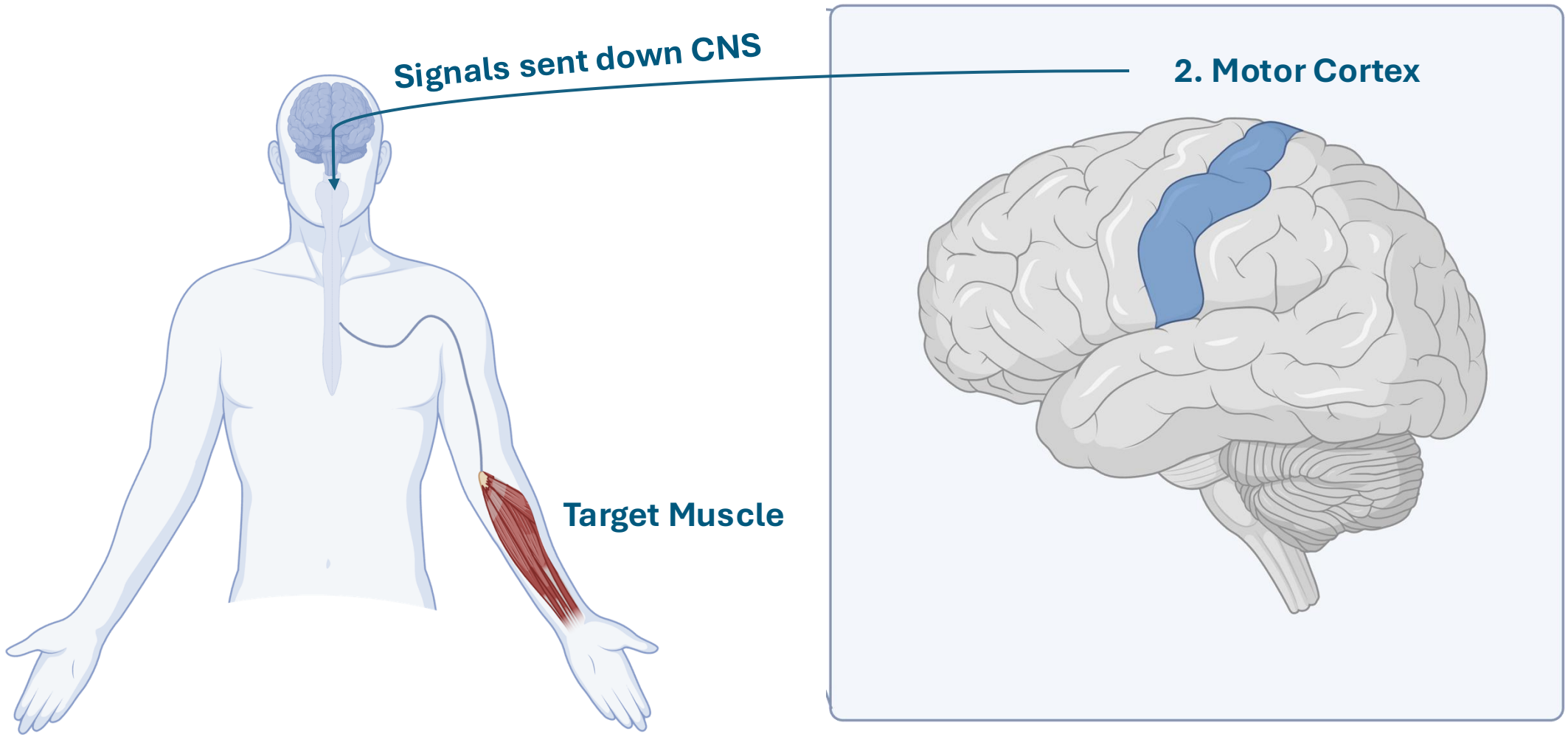
Motor Activation has 3 Steps

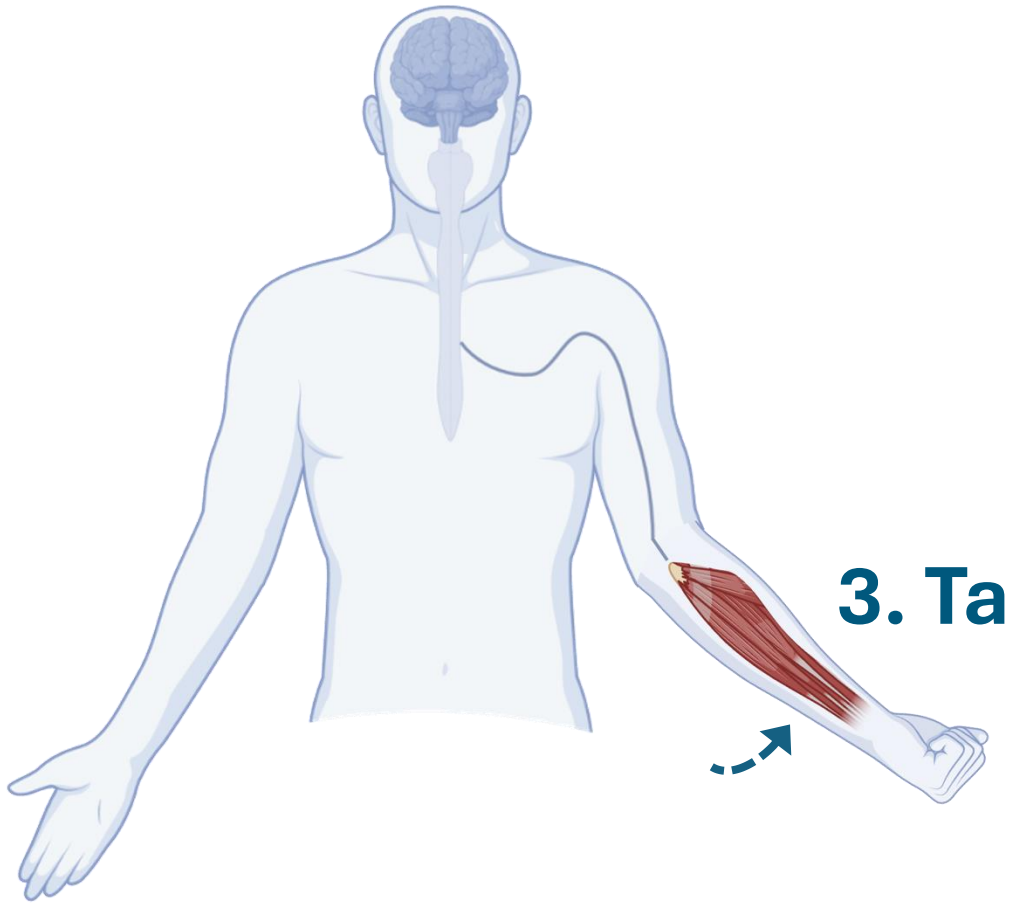


1. Thinking of movement

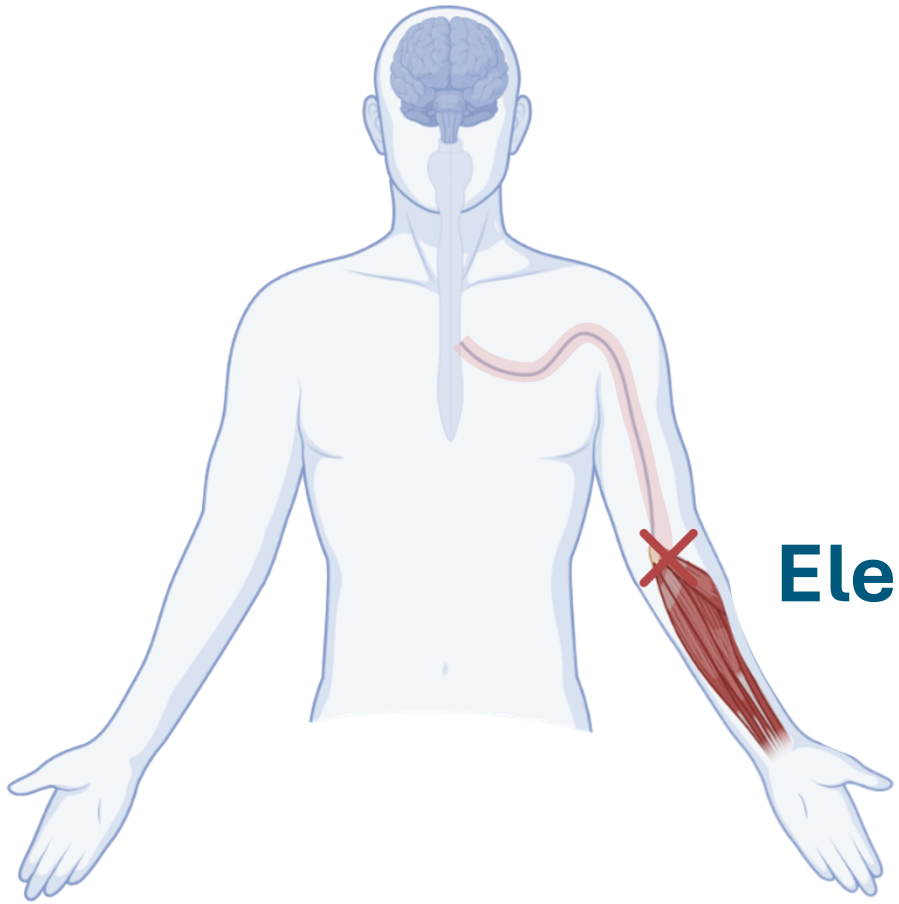

Prefrontal Cortex


2. Motor Cortex


Signals sent down CNS
2. Motor Cortex
Target Muscle



3. Target Muscle Activation



Electrical Signals nonexistent

Stroke Recovery Journey

Acute Care

~90% of Strokes

Inpatient Rehab

Outpatient Rehab

~70% of Strokes

Anywhere from 3-6 months to multiple years

Source: Stakeholder Interviews

The Gold Standard for Stroke Rehab is Electrical Stimulation

Purpose: Strengthen and restore neuromuscular connections using electrical pulses

“95% of the stroke recovery world is old-school.”

- Dr. Christopher Favilla, Penn Stroke Center

“Lack of equipment for FES therapy.”

- CSRS-Certified Stroke therapist

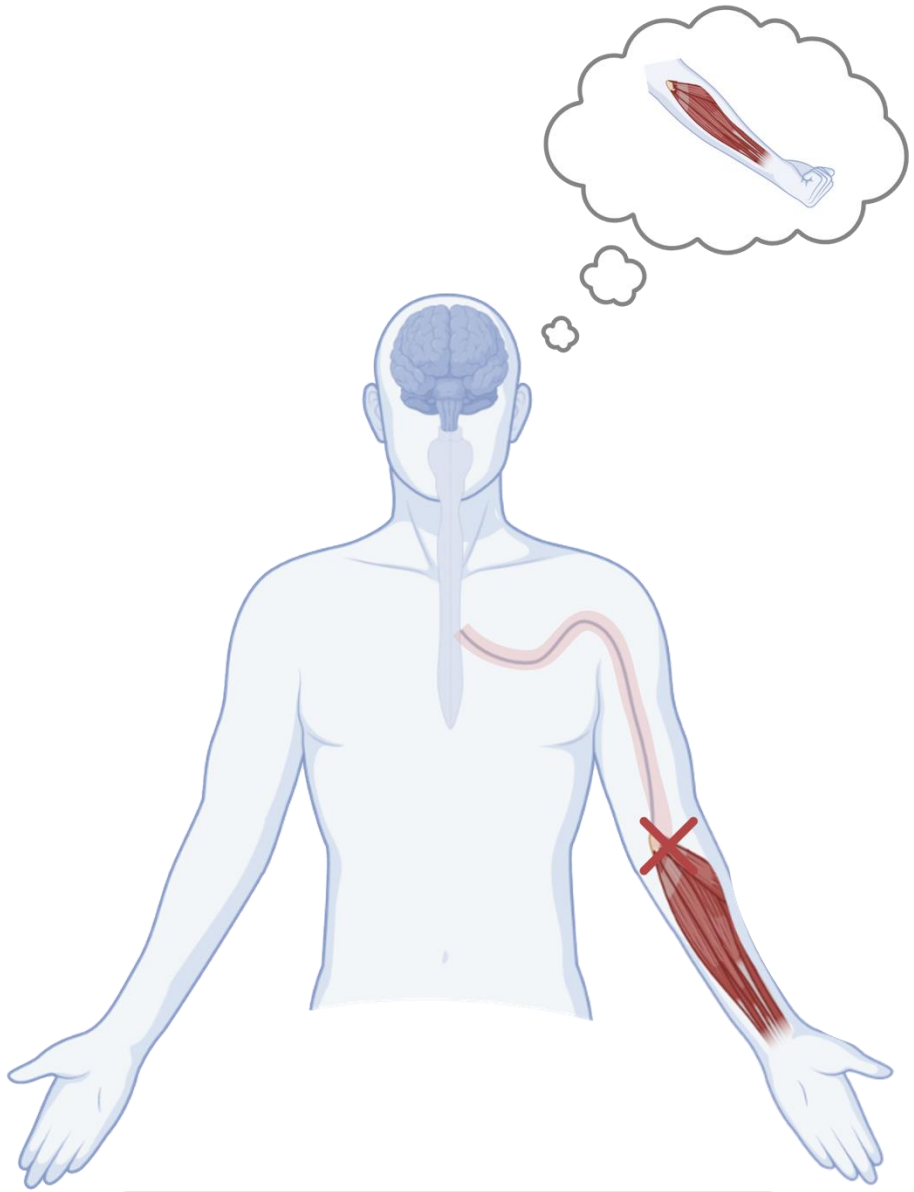
“FES is not user-friendly for patients and can be very expensive.”

- CSRS-Certified Stroke therapist

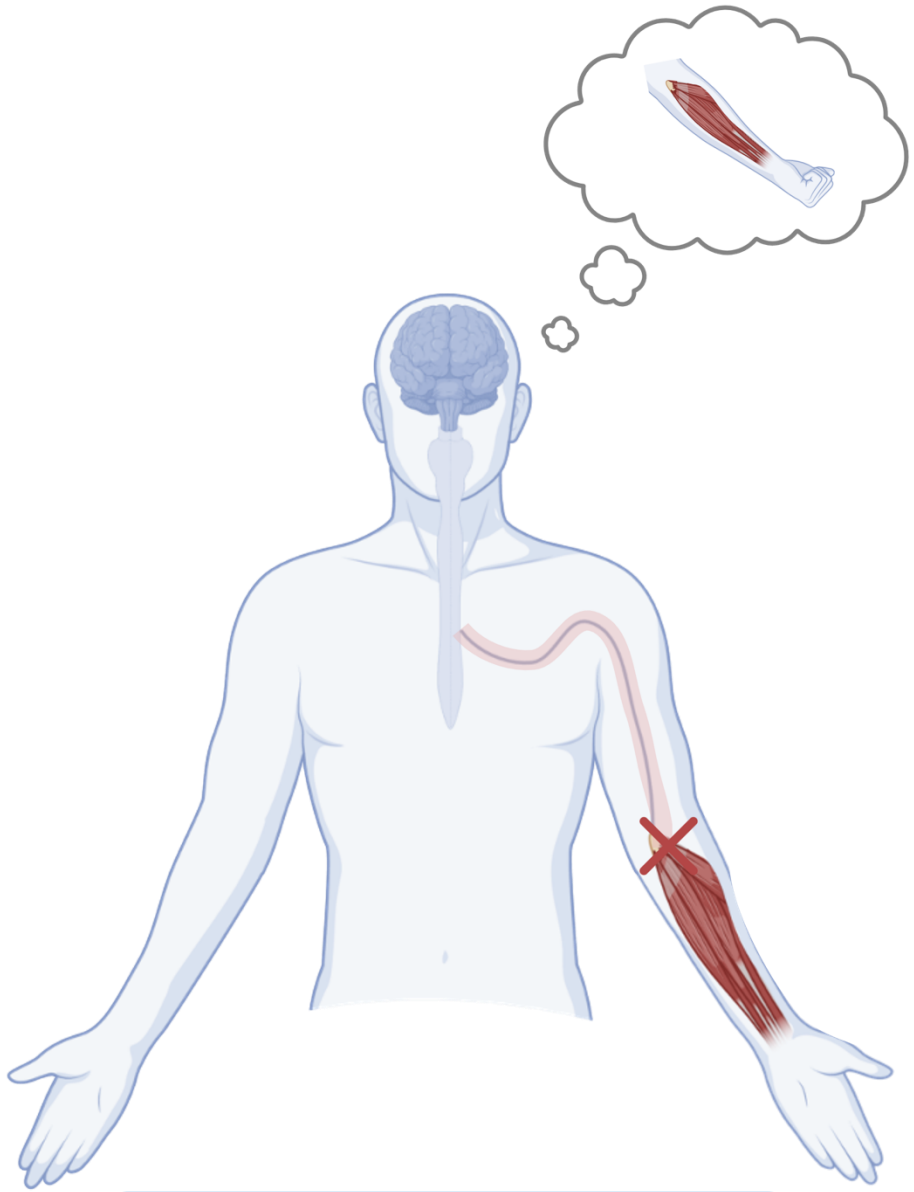
“FES outcomes are unpredictable and can’t be used at home without the presence of a therapist.”

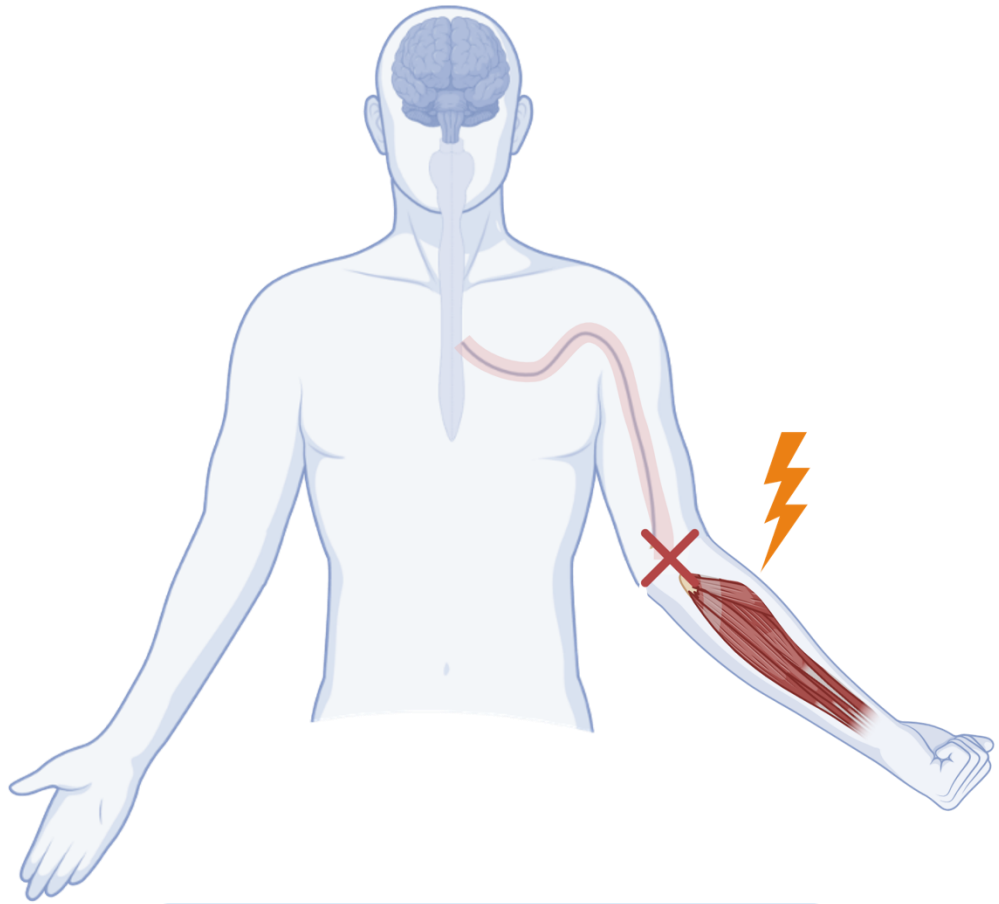
- CSRS-Certified Stroke therapist

N = 22 stakeholder interviews



Motor Imagery





Motor Imagery

FES Stimulation

Today, no clinical or commercial device achieves this

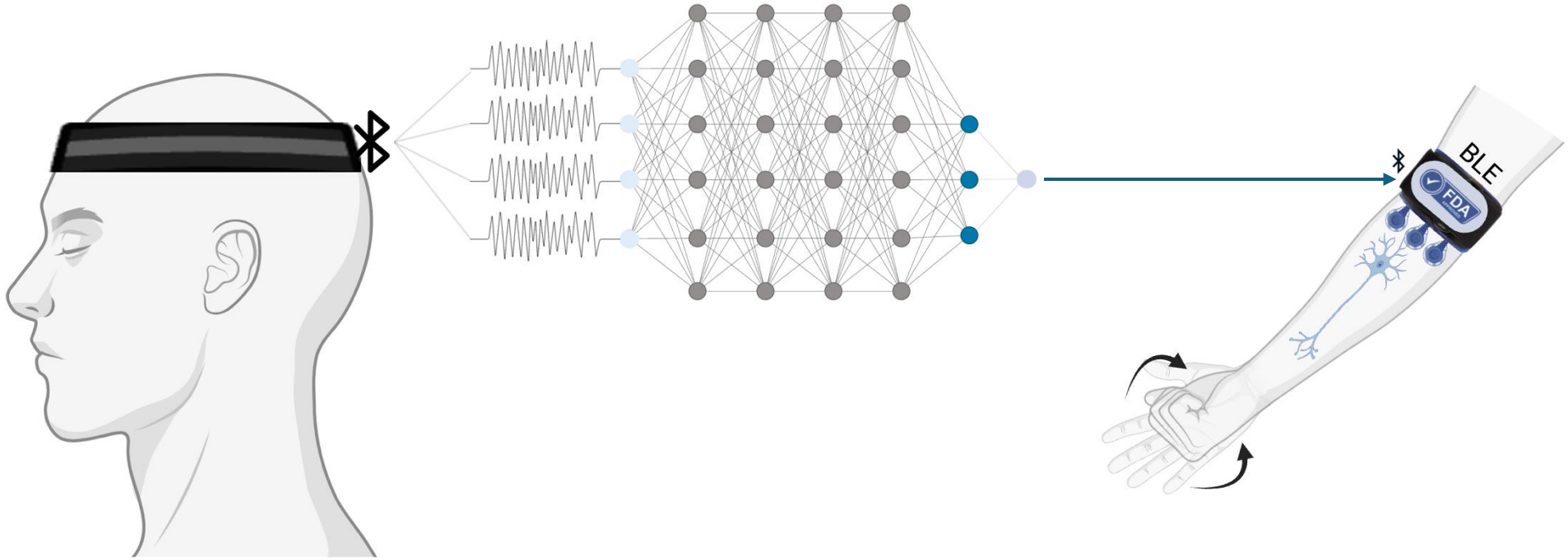
Motor Imagery → FES Stimulation

ReFlex

EEG Headset

AI Decoding

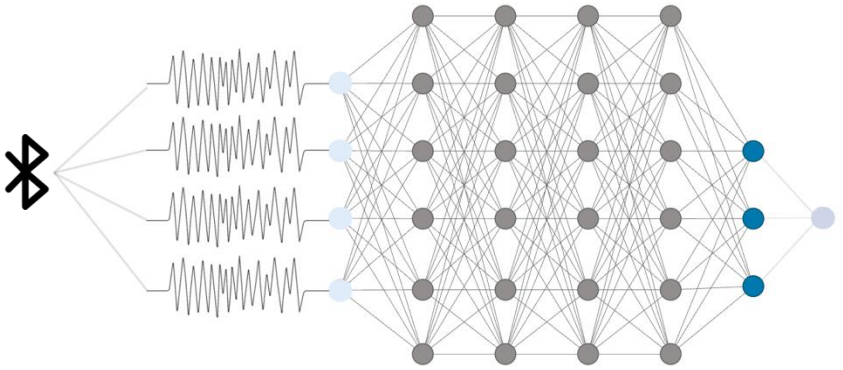
FES Actuator



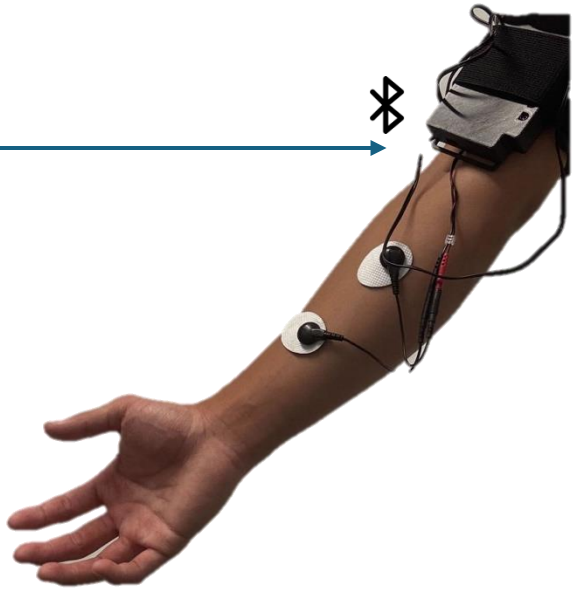
ReFlex

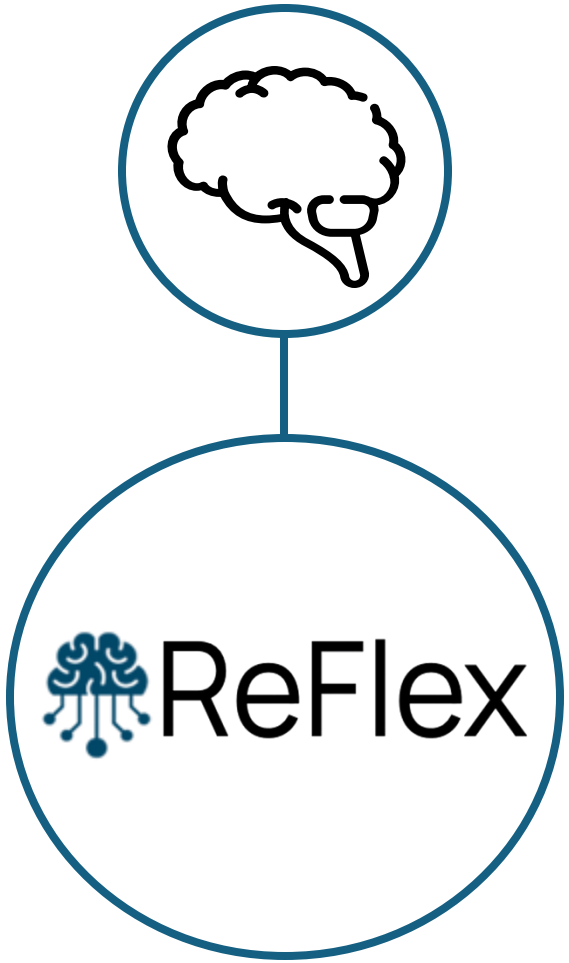
EEG Headset

AI Decoding



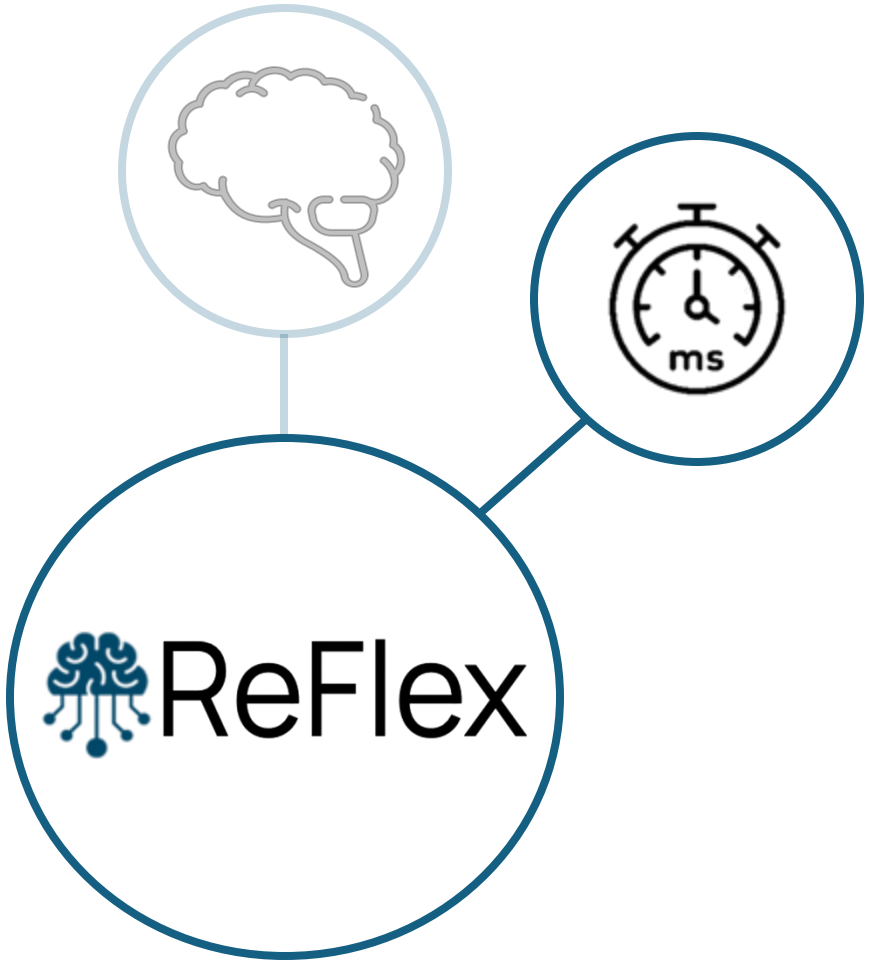
FES Actuator





Multi-channel EEG

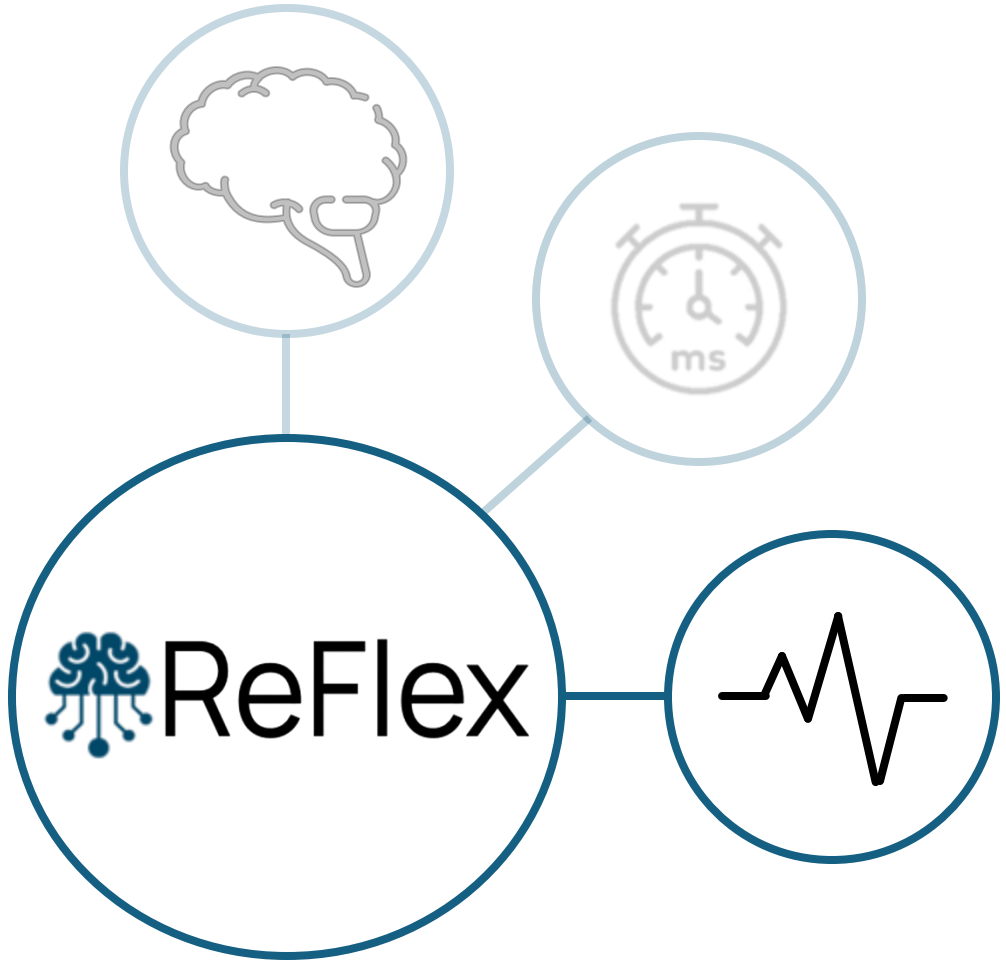
8 Channels with REF + GND



Reduced Latency

< 500 ms*

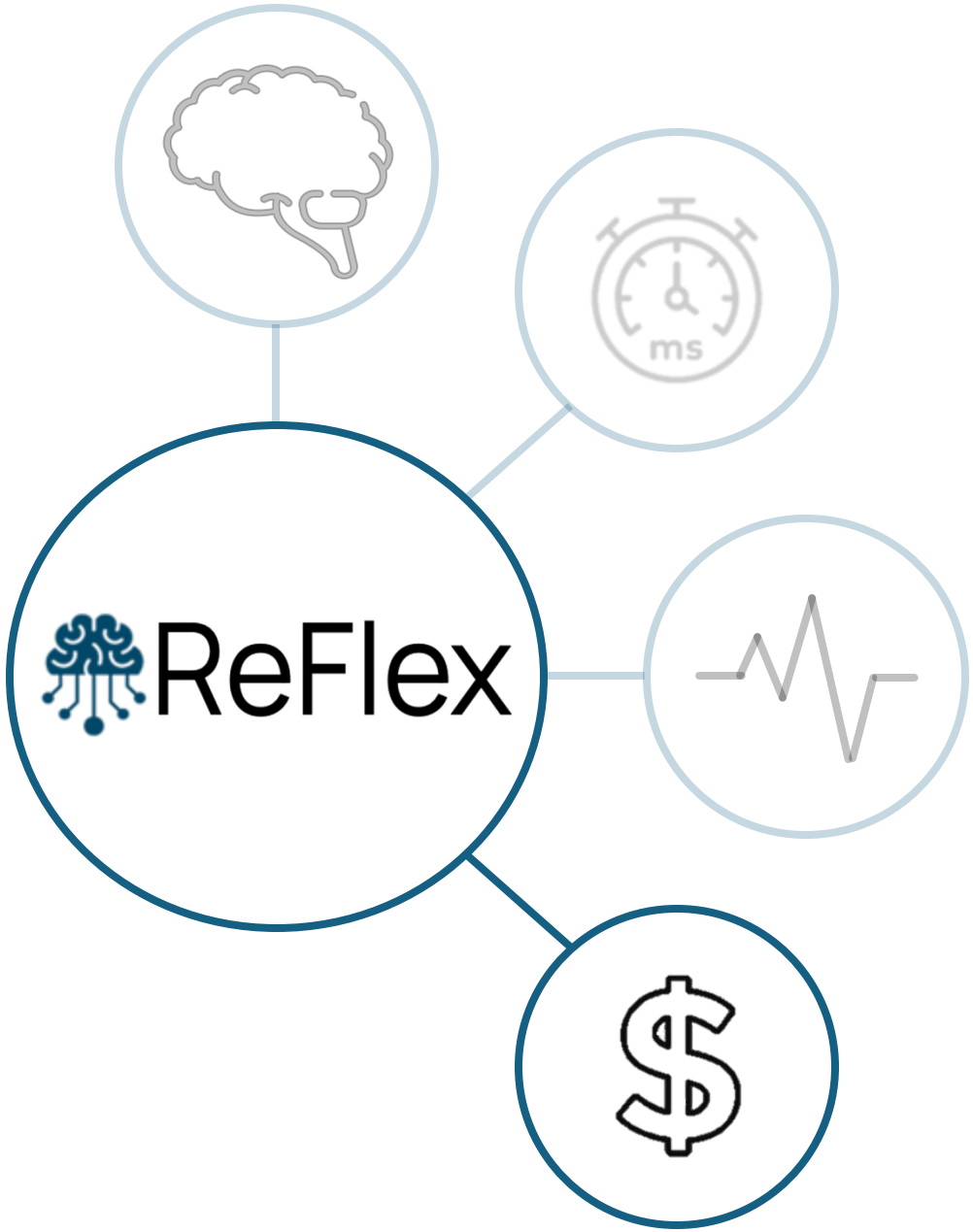
*Wilson, J. IEEE, 2010.



High Signal to Noise Ratio (SNR)

> 1.99 dB*

*Radüntz, T. Frontiers, 2023.



Accessible Cost

< $500*

*Emotiv.com.

Short Prep Time

< 10 minutes

Weight

< 2 lb*

*Zeto-inc.com.

Machine Learning

Real-time motor decoding

Accurate Decoding

> 80%* model accuracy

*De Oliveira, In Neuro, 2023.

ReFlex Workflow

ReFlex Workflow

Wear EEG Headset

EEG Data Recorded

ML Feature Extraction

Decode Motor Intent

Stimulate Muscle

ReFlex Workflow

ReFlex Workflow

Wear EEG Headset

EEG Data Recorded

ML Feature Extraction

Decode Motor Intent

Stimulate Muscle

ReFlex Workflow

ReFlex Workflow

Existing Options

Cost < $500

Noninvasive

Can be used independently

Electrically Stimulates

Connection to the mind

Existing Options

	 **Intracranial BCI***
Cost < $500	✗
Noninvasive	✗
Can be used independently	✗
Electrically Stimulates	☑
Connection to the mind	☑

* BCI = Brain Computer Interface

Existing Options

	 Intracranial BCI*	 TENS Unit
Cost < $500	✗	☑
Noninvasive	✗	☑
Can be used independently	✗	✗
Electrically Stimulates	☑	☑
Connection to the mind	☑	✗

* BCI = Brain Computer Interface

Existing Options

	 Intracranial BCI*	 TENS Unit	 Saebo Glove
Cost < $500	✗	☑	☑
Noninvasive	✗	☑	☑
Can be used independently	✗	✗	☑
Electrically Stimulates	☑	☑	✗
Connection to the mind	☑	✗	✗

* BCI = Brain Computer Interface

Existing Options

	 Intracranial BCI*	 TENS Unit	 Saebo Glove	ReFlex
Cost < $500	✗	☑	☑	☑
Noninvasive	✗	☑	☑	☑
Can be used independently	✗	✗	☑	☑
Electrically Stimulates	☑	☑	✗	☑
Connection to the mind	☑	✗	✗	☑

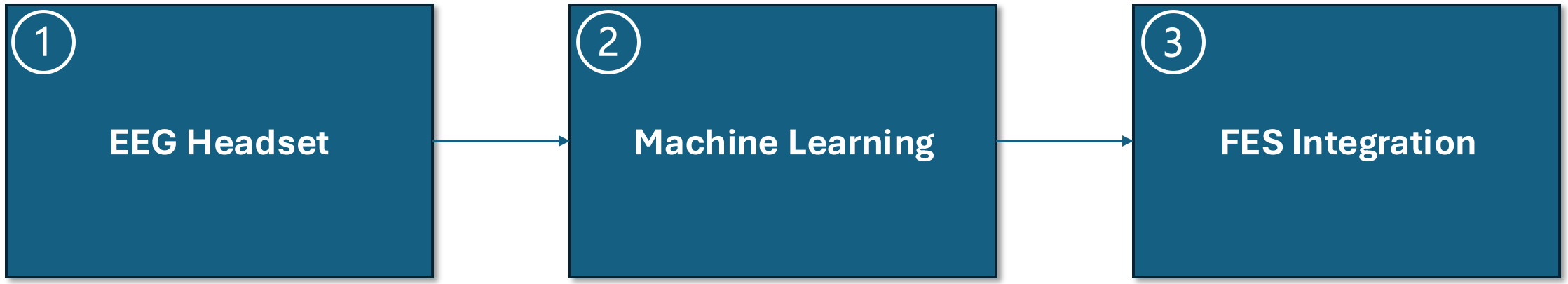
* BCI = Brain Computer Interface

Existing Options

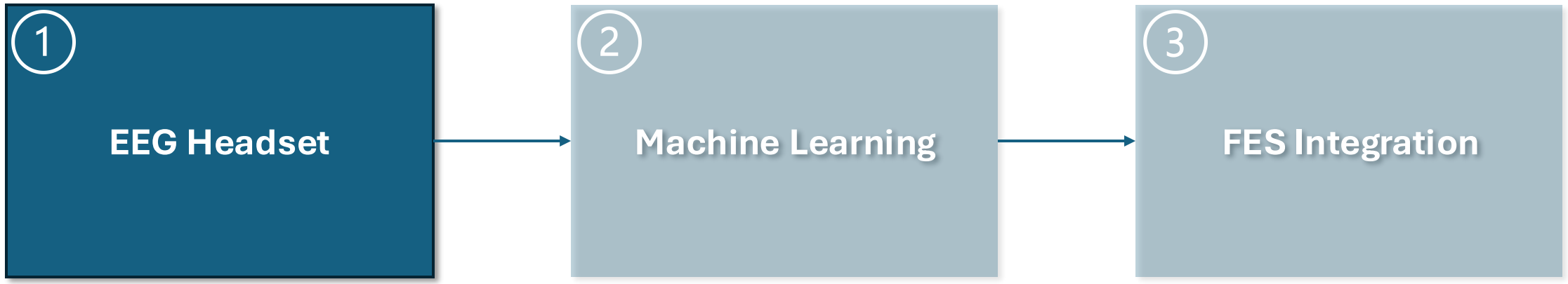
	 Intracranial BCI*	 TENS Unit	 Saebo Glove	ReFlex
Cost < $500	✗	☑	☑	☑
Noninvasive	✗	☑	☑	☑
Can be used independently	✗	✗	☑	☑
Electrically Stimulates	☑	☑	✗	☑
Connection to the mind	☑	✗	✗	☑

* BCI = Brain Computer Interface

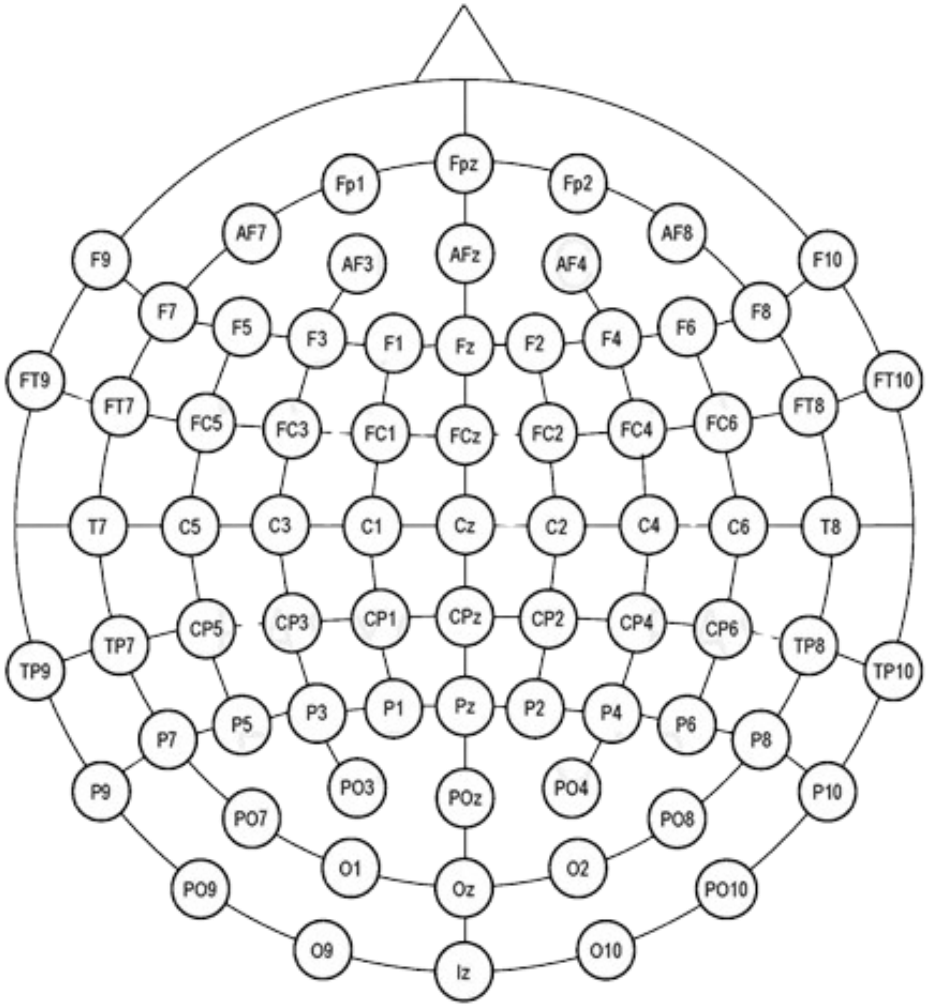
Technical Overview



Technical Overview: EEG Headset

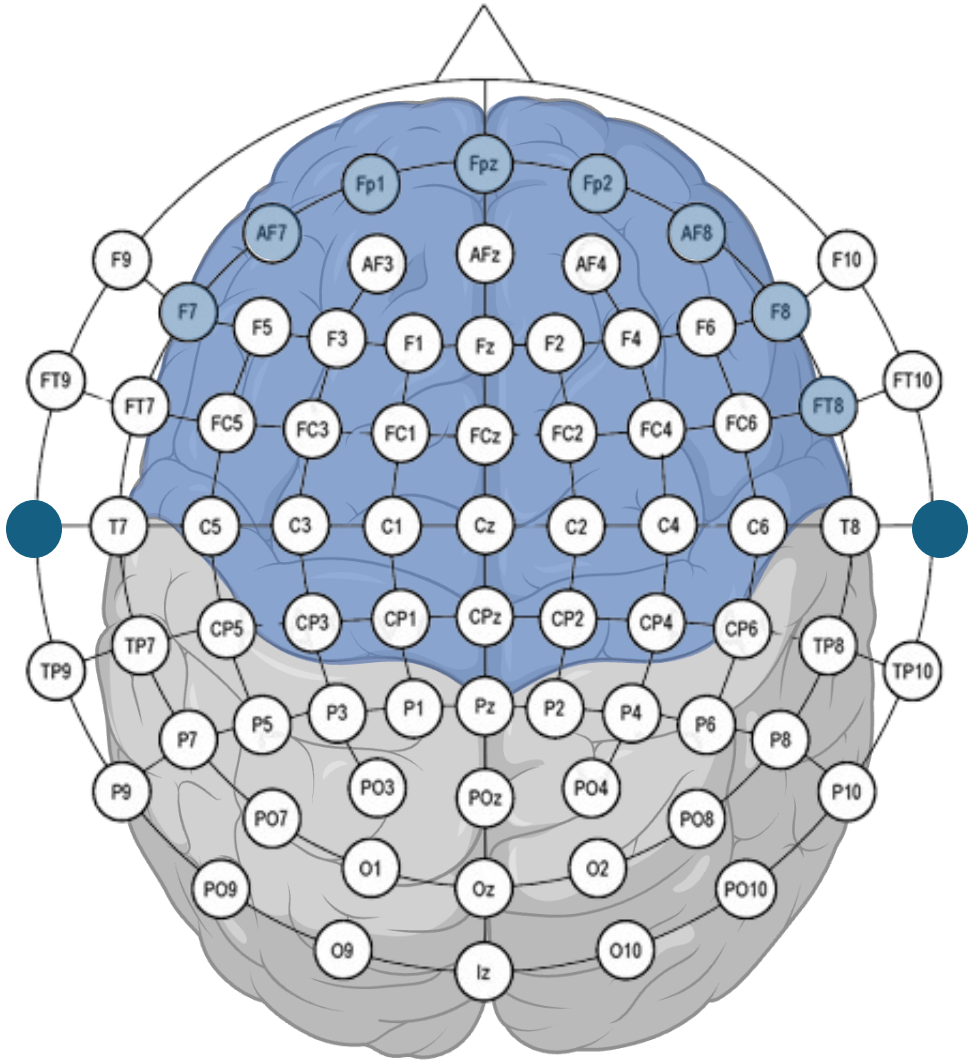


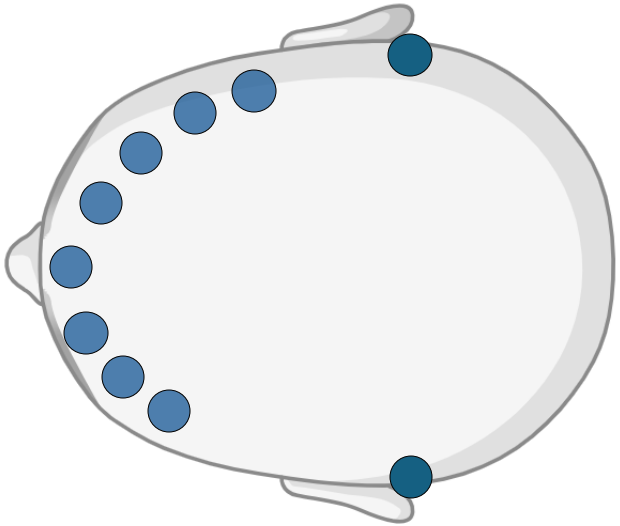
64 EEG Electrodes



10-10 EEG placement system

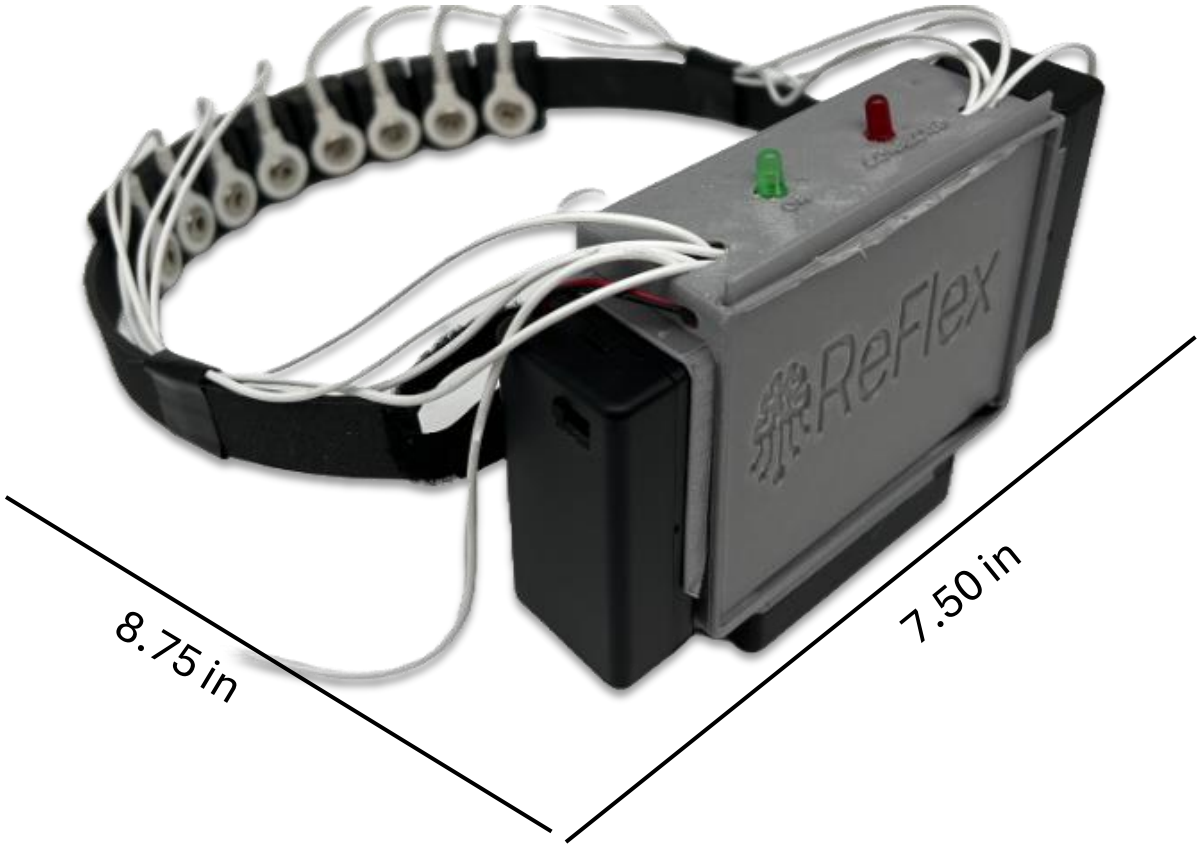
8 Electrode Headset



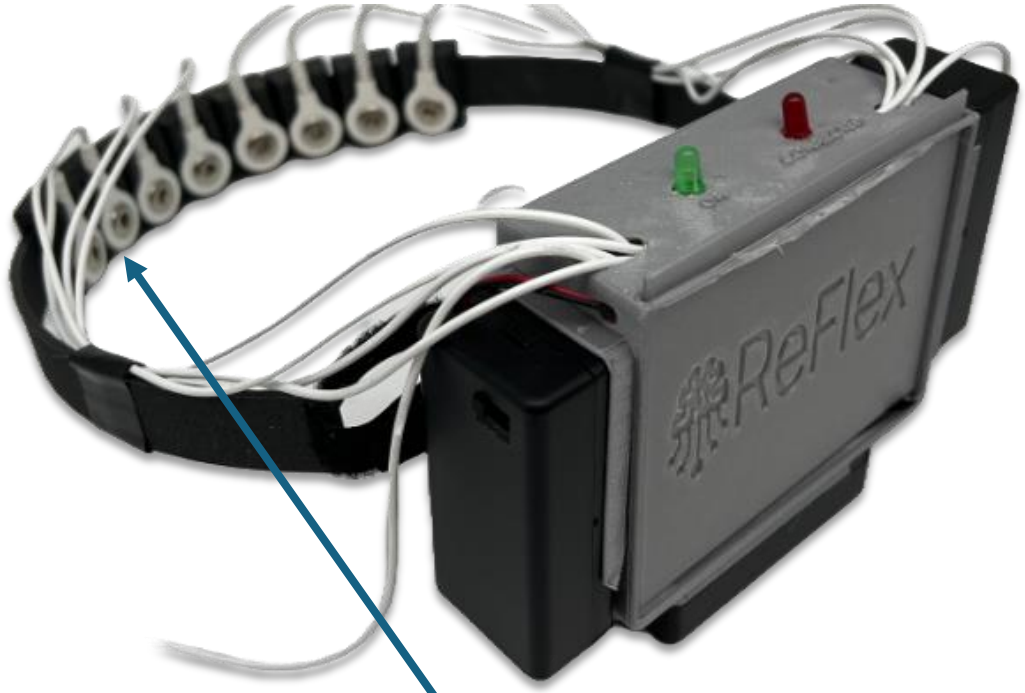



ReFlex

8 Electrode Headset

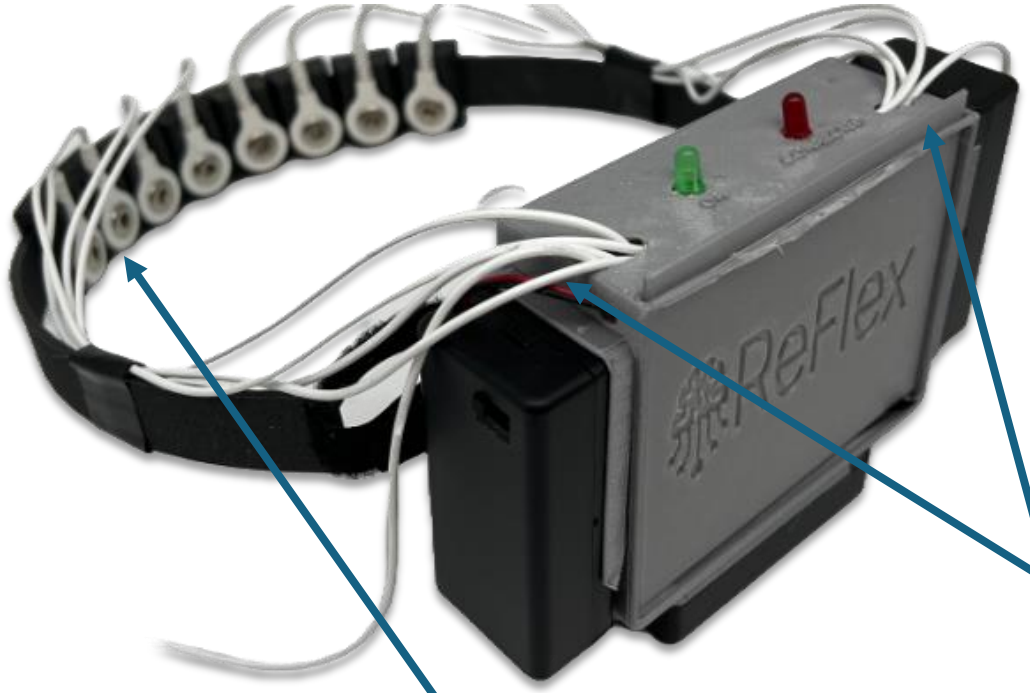


8 Electrode Headset



8 adjustable frontal electrode channels

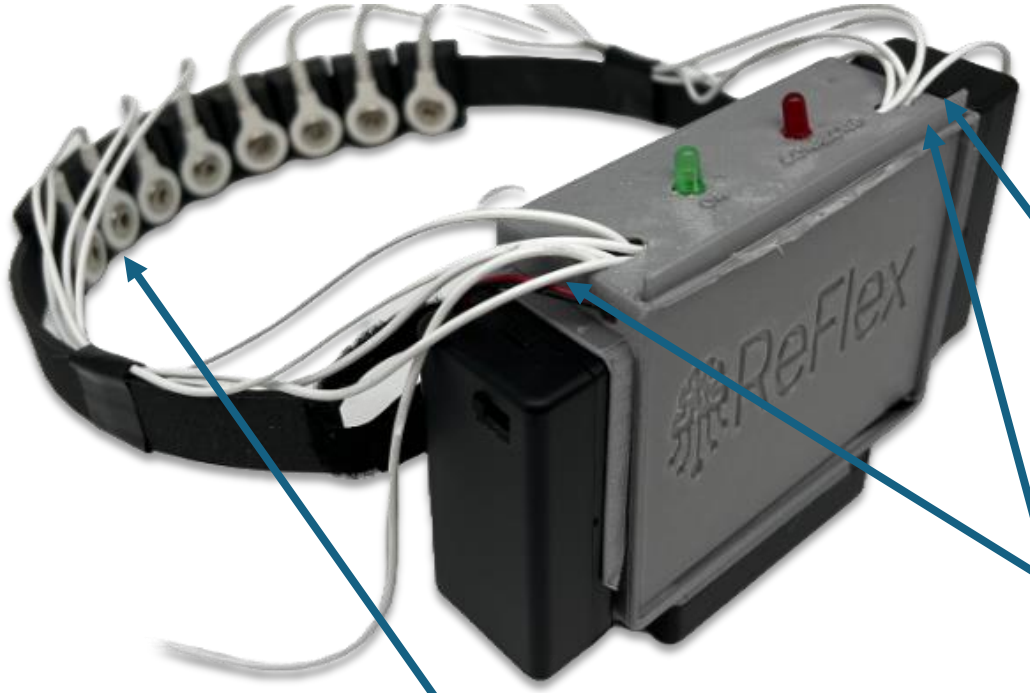
8 Electrode Headset



Reference + ground channels behind ear

8 adjustable frontal electrode channels

8 Electrode Headset

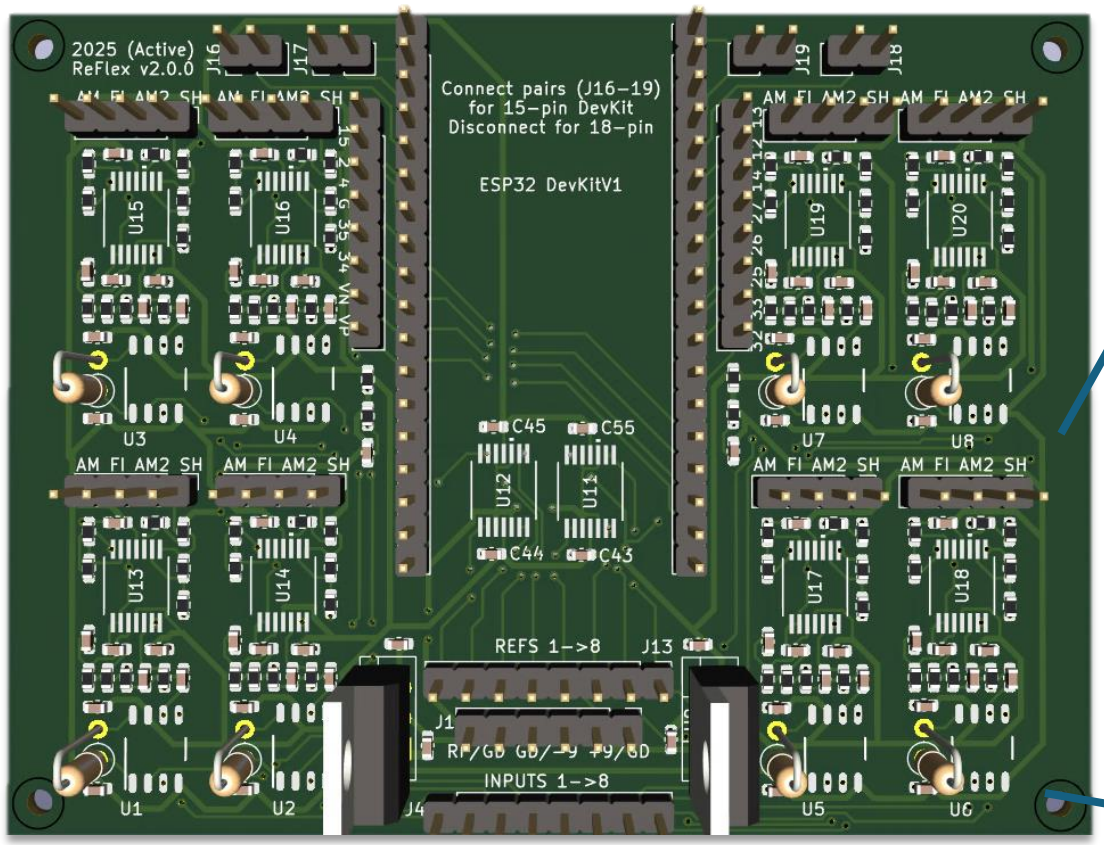


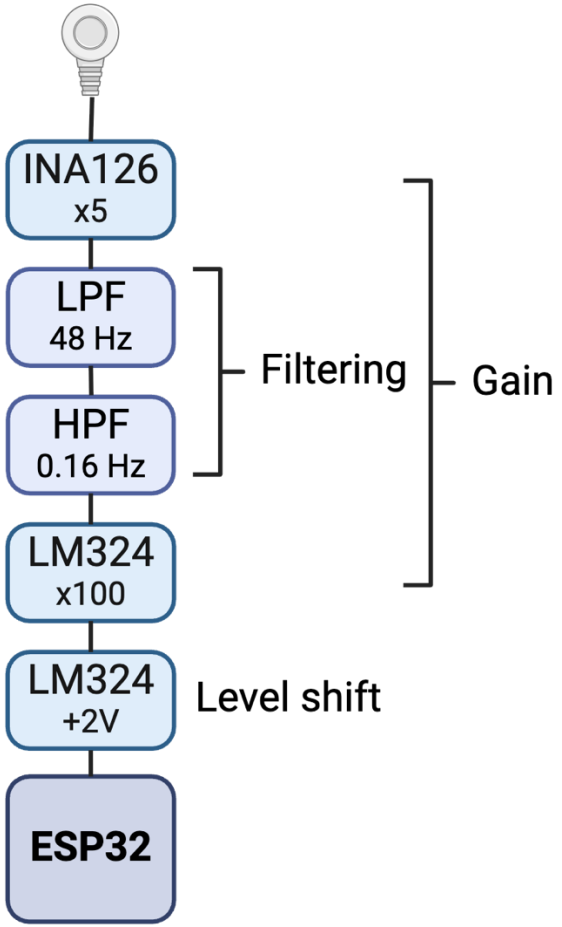
Lightweight headband with PCB housing behind head

Reference + ground channels behind ear

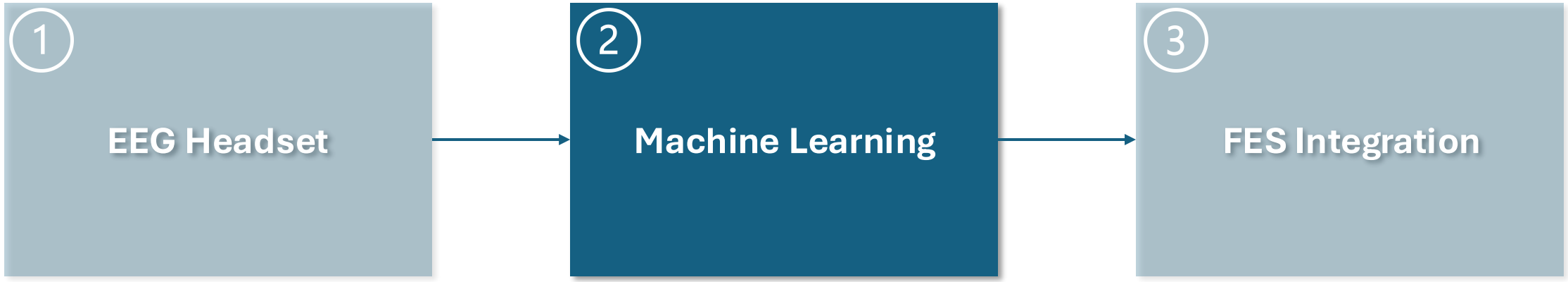
8 adjustable frontal electrode channels

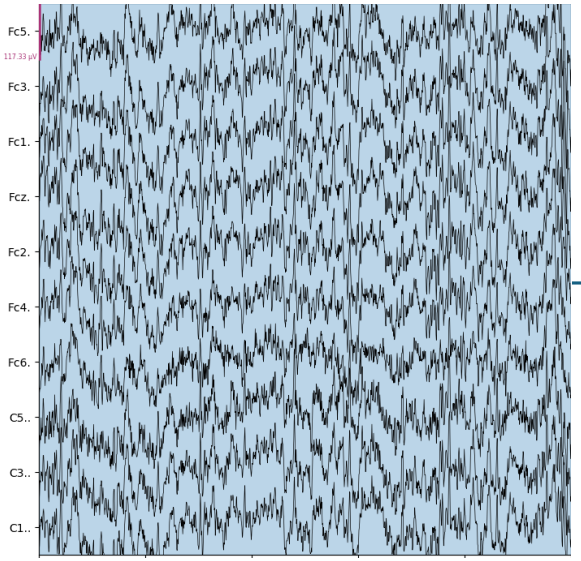
Custom PCB


2025 (Active)
ReFlex v2.0.0
Connect pairs (J16–19)
for 15–pin DevKit
Disconnect for 18–pin
ESP32 DevKitV1
AM FI AM2 SH
REFS 1–>8
INPUTS 1–>8
62.15 mm
89.95 mm


INA126
x5
LPF
48 Hz
HPF
0.16 Hz
Filtering
Gain
LM324
x100
LM324
+2V
Level shift
ESP32

Technical Overview: Machine Learning

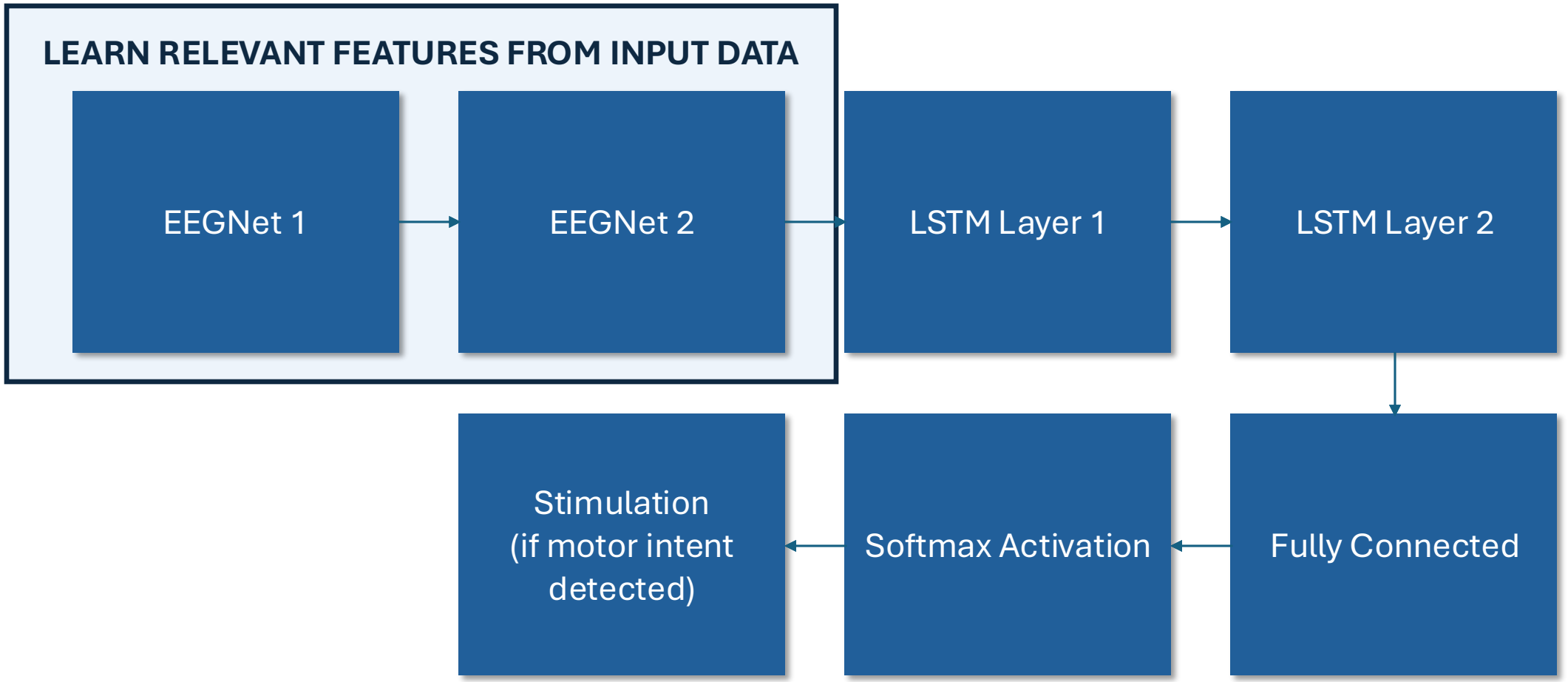




8 Channel EEG

EEGNet 1 → EEGNet 2 → LSTM Layer 1 → LSTM Layer 2 → Fully Connected → Softmax Activation → Stimulation (if motor intent detected)

De Oliveira, H., *et al.*, R. Front. In Neuro. 2023.



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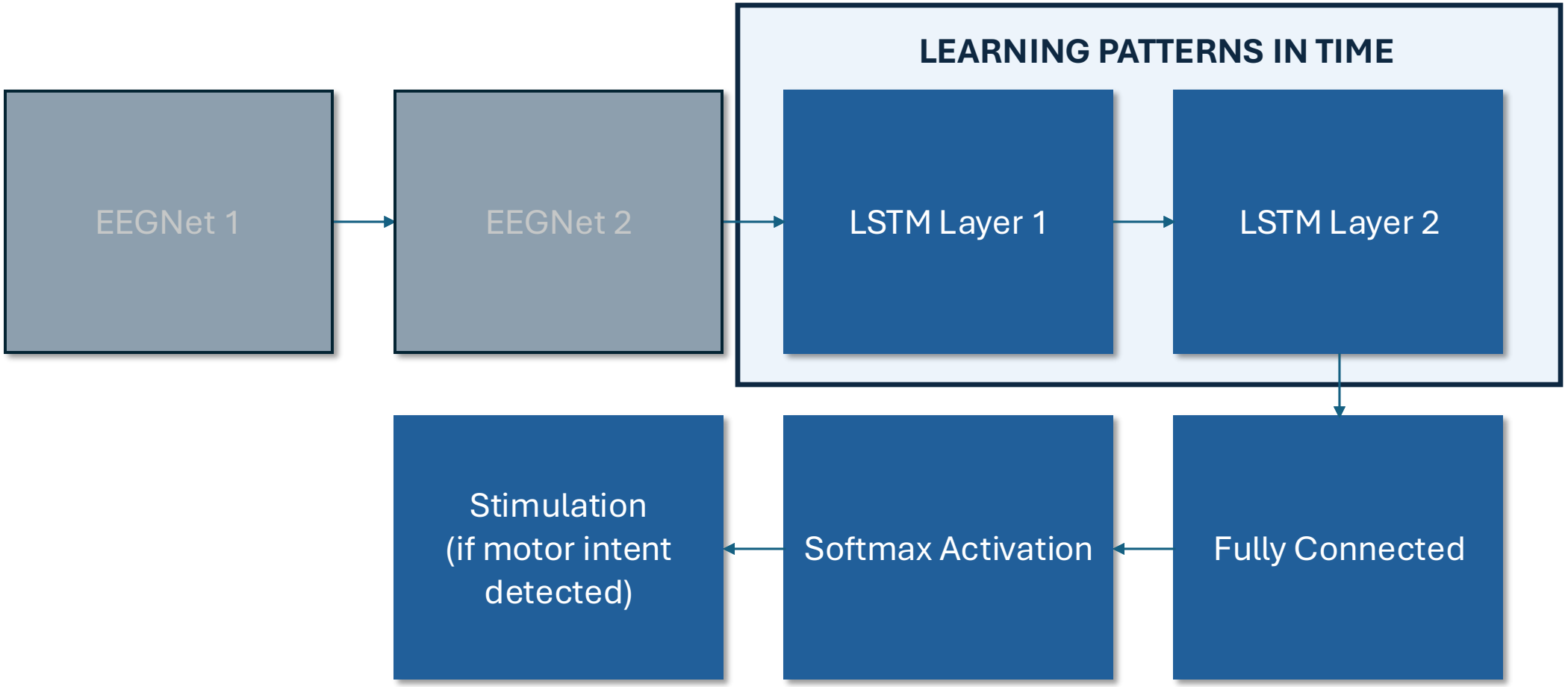
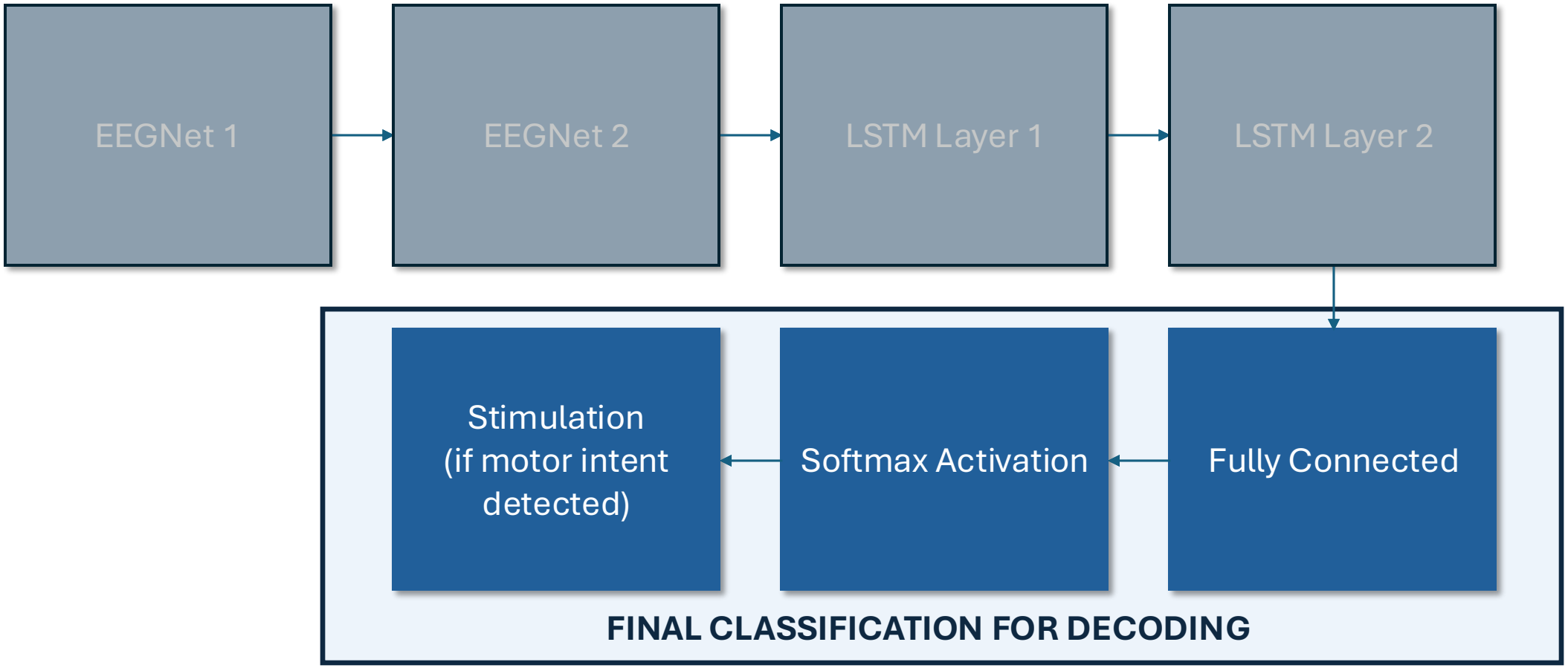
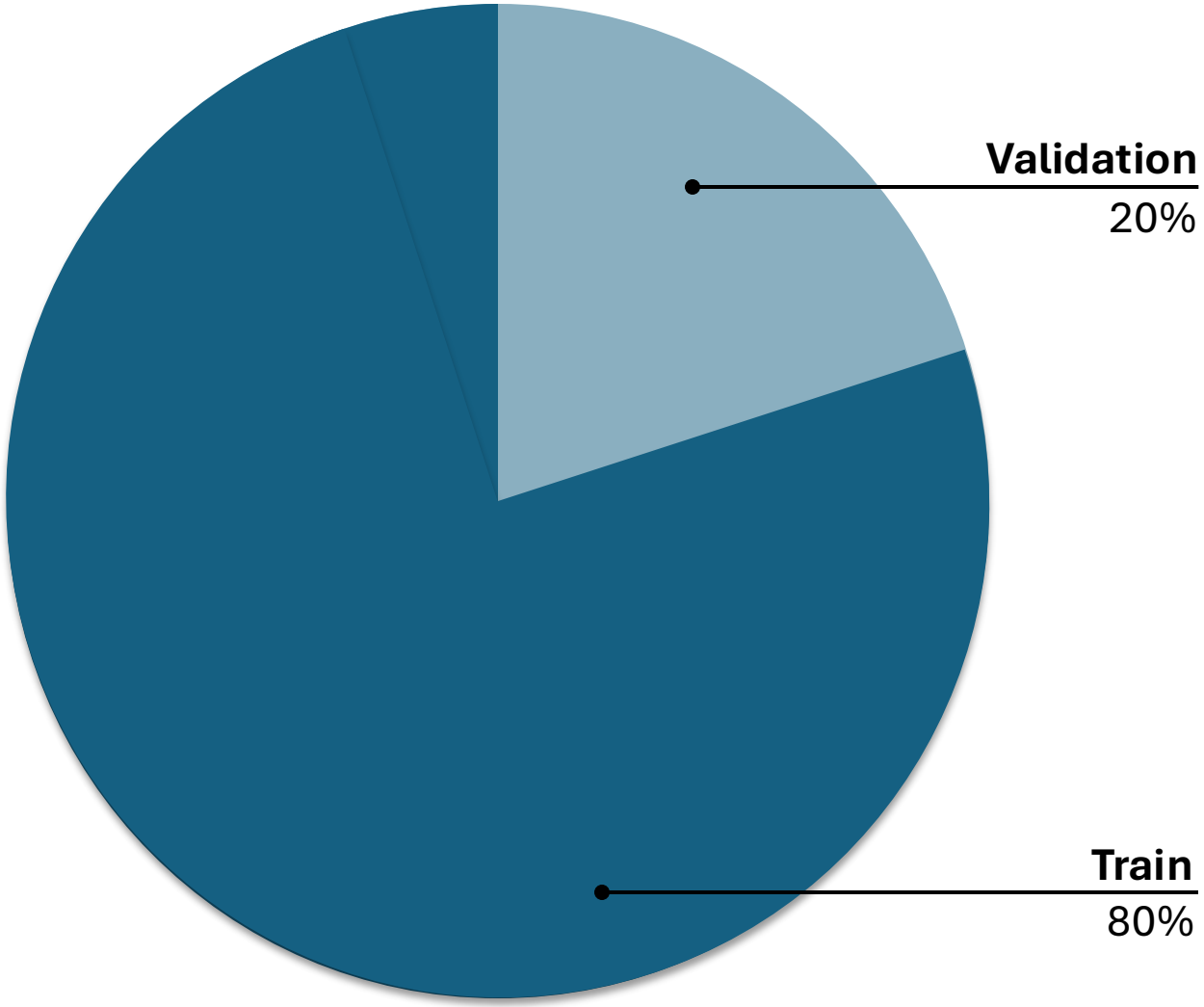


De Oliveira, H., *et al.*, R. Front. In Neuro. 2023.

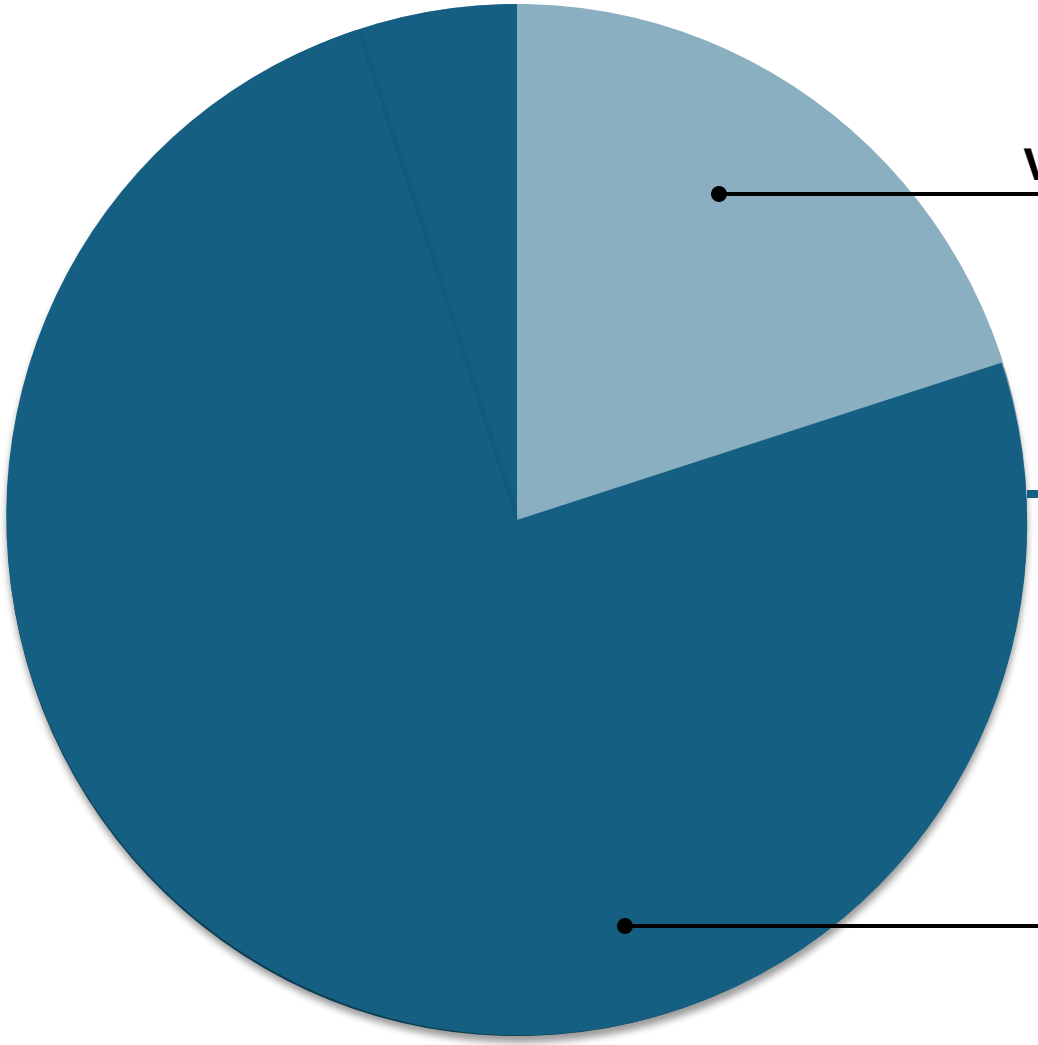


De Oliveira, H., *et al.*, R. Front. In Neuro. 2023.

PhysioNet EEG Motor Imagery Dataset

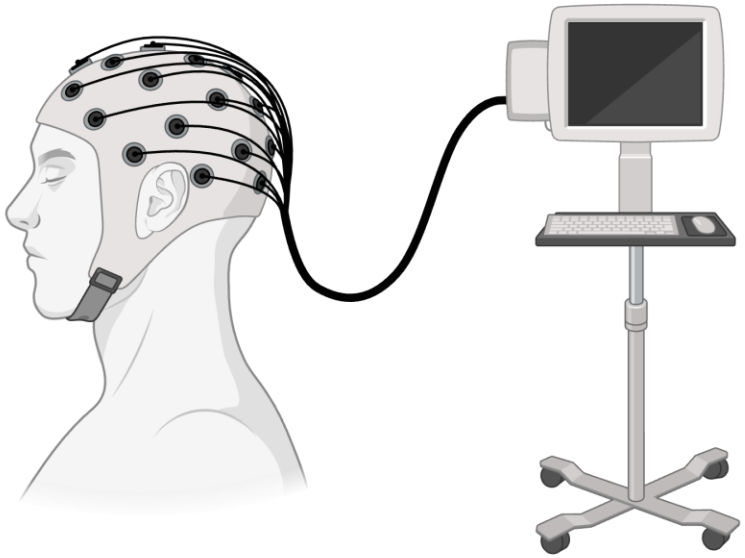


PhysioNet EEG Motor Imagery Dataset

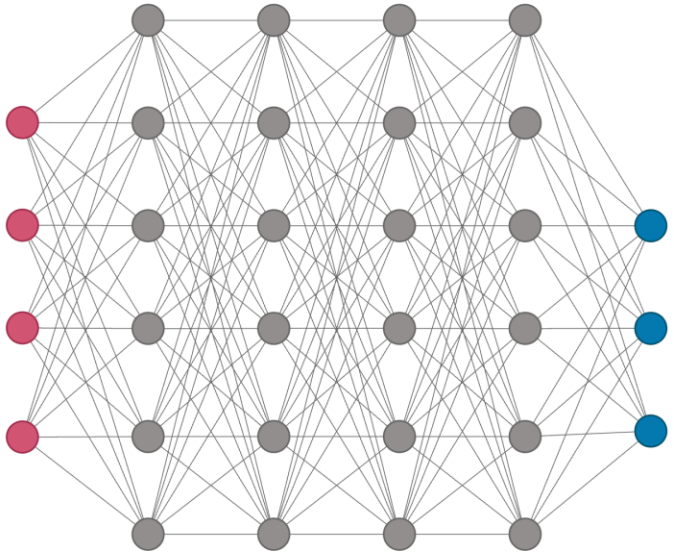


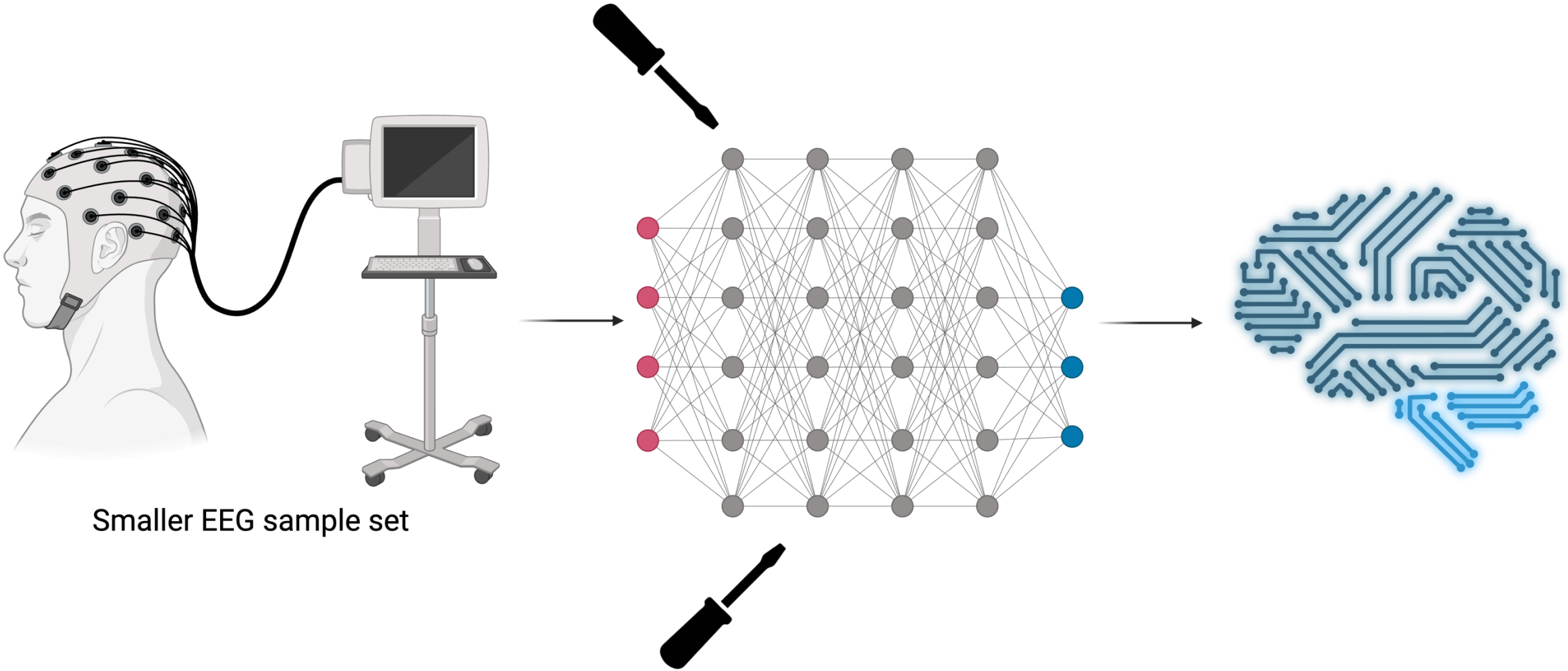
Motor Imagery Tasks

- Imagining hand grasp
- Performing hand grasp
- Imagining toe flexion
- Performing toe flexion



> 5,000 EEG samples





Smaller EEG sample set

Technical Overview: Integration

Our System

Bluetooth Commands →

3rd Party Electrical Stimulation Device

Can be extended to work with ANY existing FES device

FES Device

FES Device

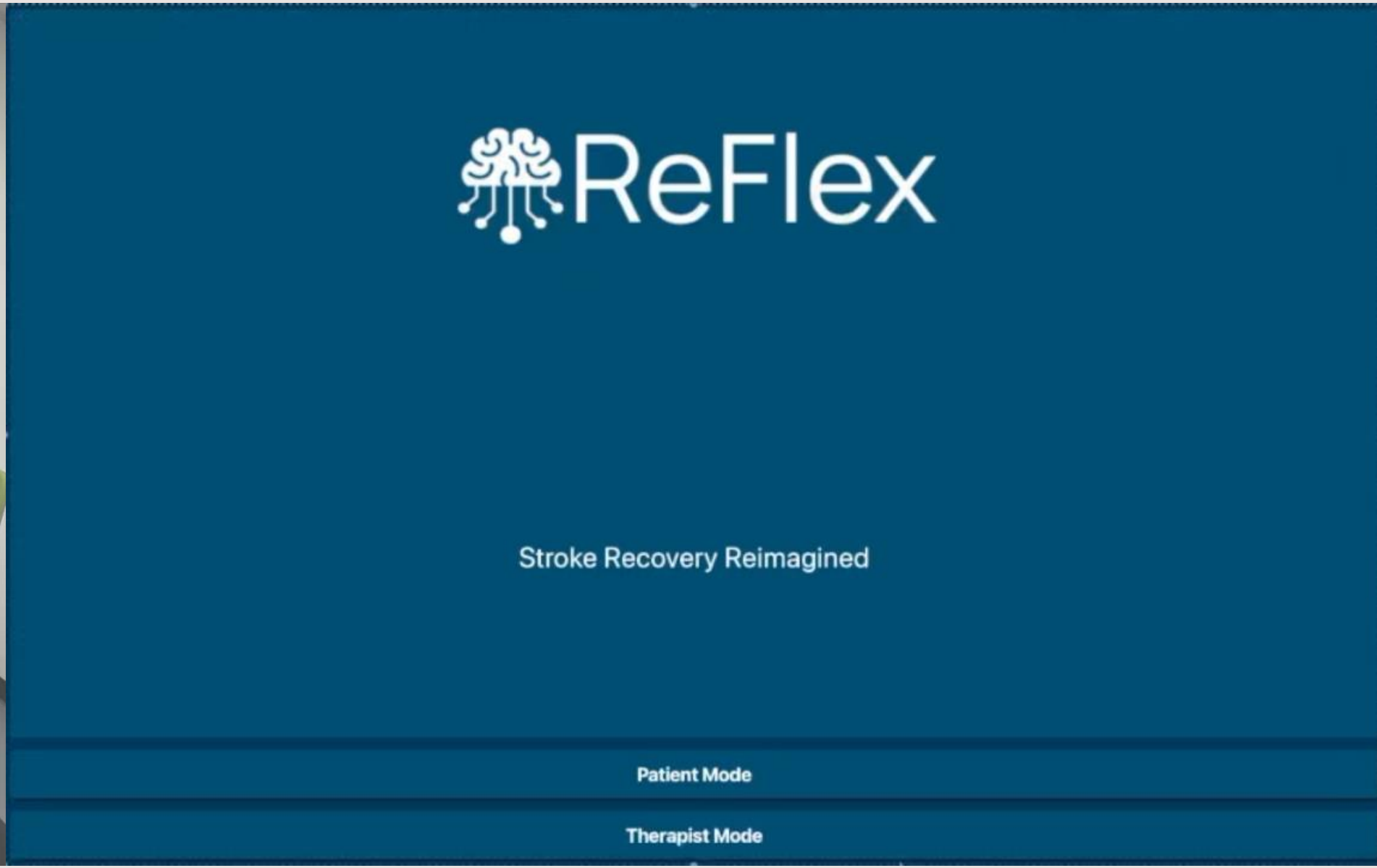
CIONIC

2,200+ patients use CIONIC's FES device today

FES Device

Adjustable strap for any limb

4 electrodes for stimulation

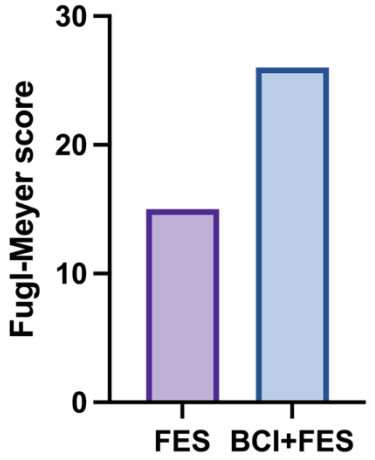

ReFlex
Stroke Recovery Reimagined
Patient Mode
Therapist Mode

At-Home Rehabilitation

- 4 sets of 20 reps
- 3 times per week

At-Home Rehabilitation

- 4 sets of 20 reps
- 3 times per week
- Shown to improve clinical measures of rehab outcomes by 100% in **just 1 month**



Testing and Evaluation

Performance

- Model Accuracy
  > 80%
- SNR
  > 1.99 dB
- Latency
  < 500 ms

Accessibility

- Cost
  < $500
- Prep Time
  < 10 min
- Weight
  < 2 lb

Performance

80.2%

ReFlex test accuracy

~76%

Current research gold standard

Performance

80.2%

ReFlex test accuracy

~76%

Current research gold standard

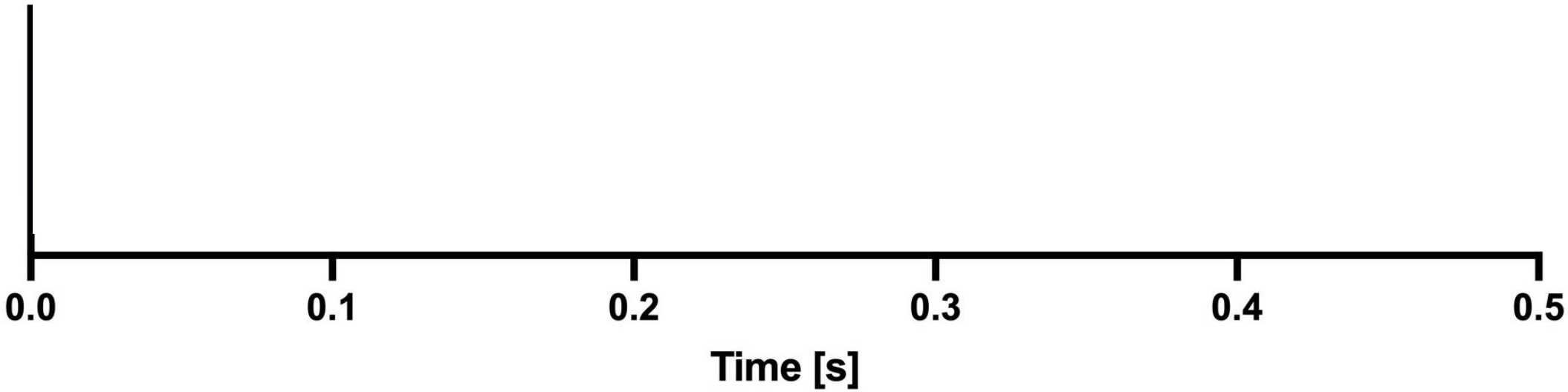
4.76 dB

ReFlex signal-to-noise ratio

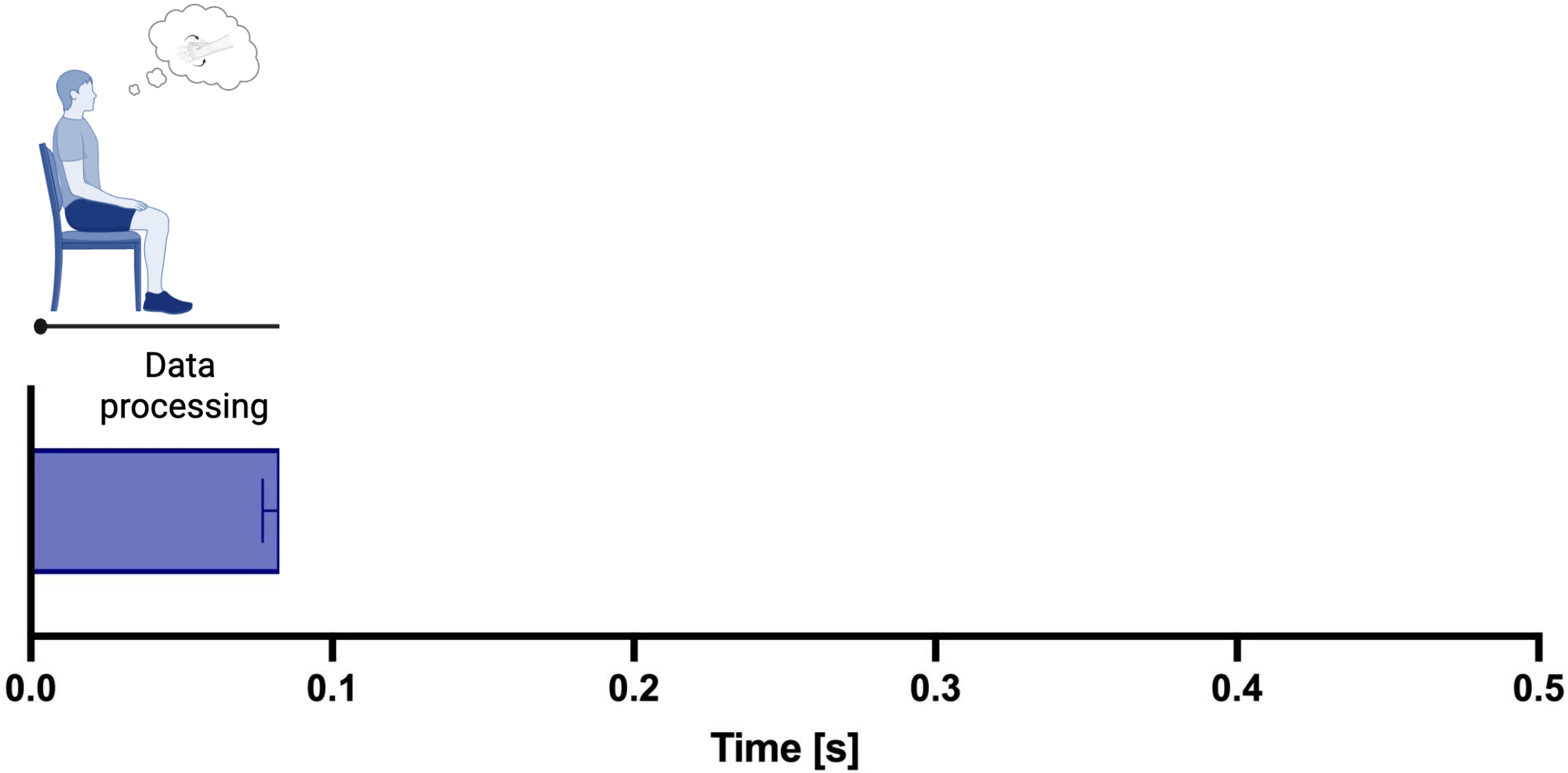
~3.9 dB

Median industry signal-to-noise ratio (g.LADYBIRD)

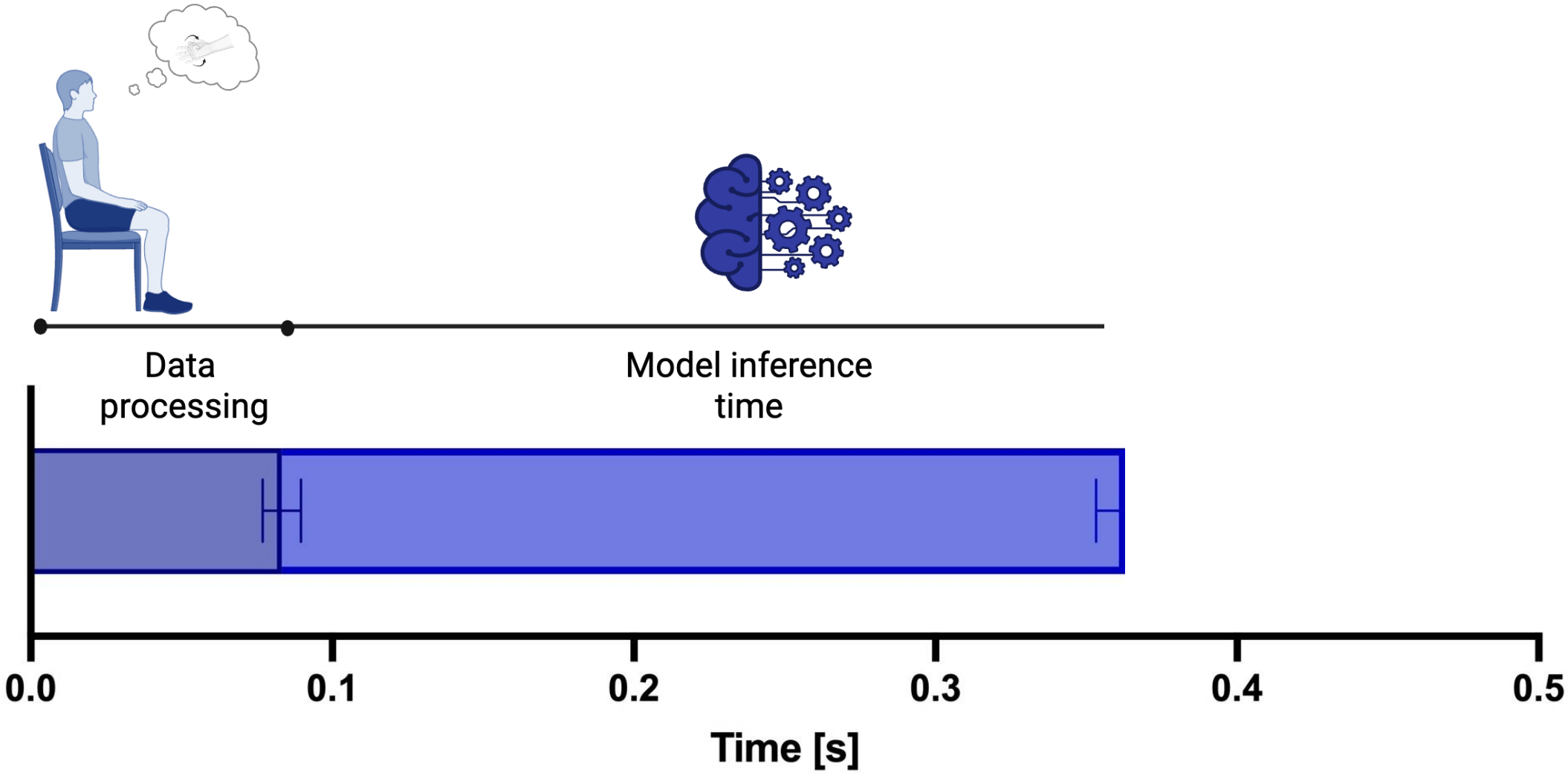
Performance: Latency



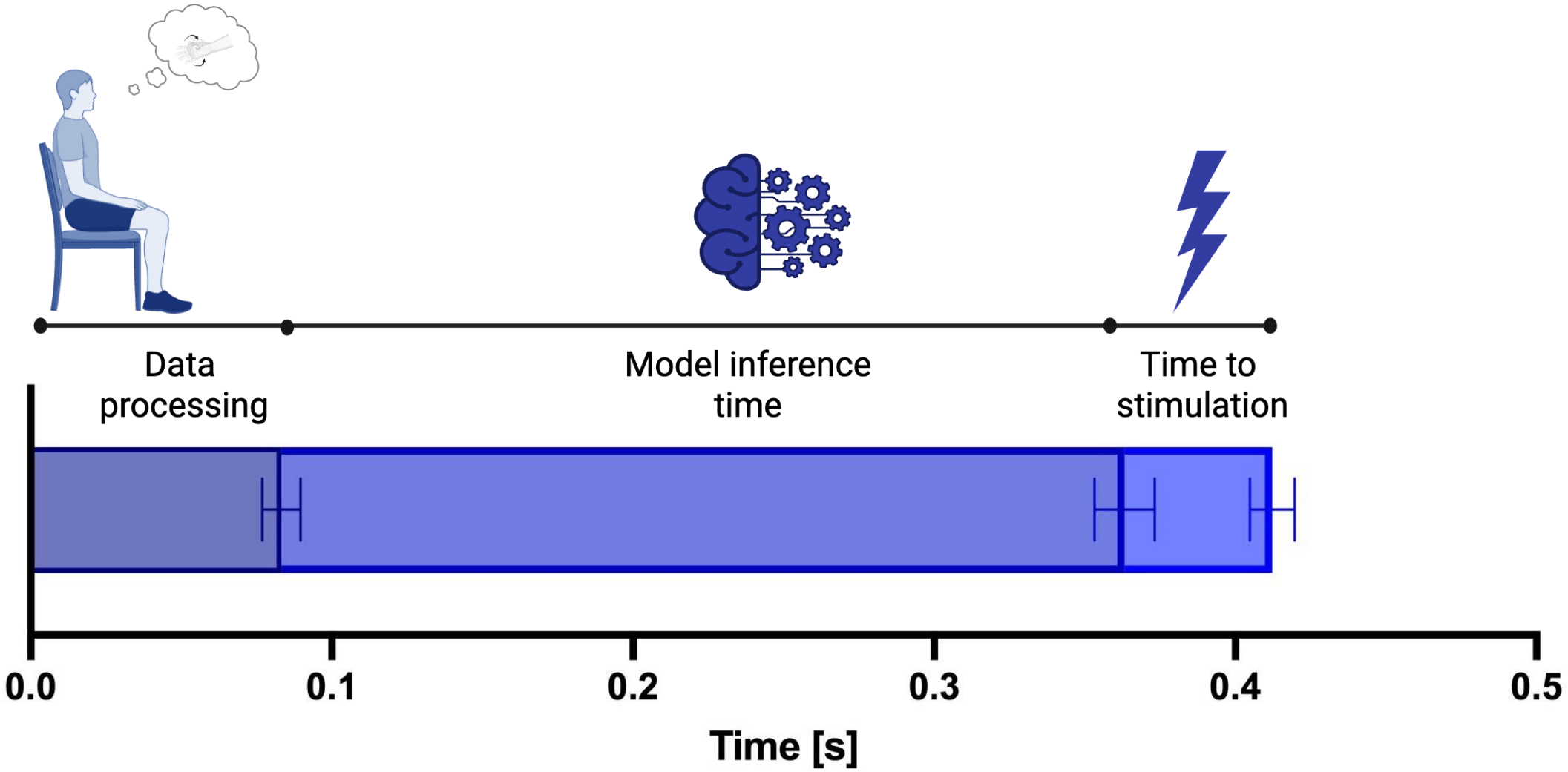
Performance: Latency

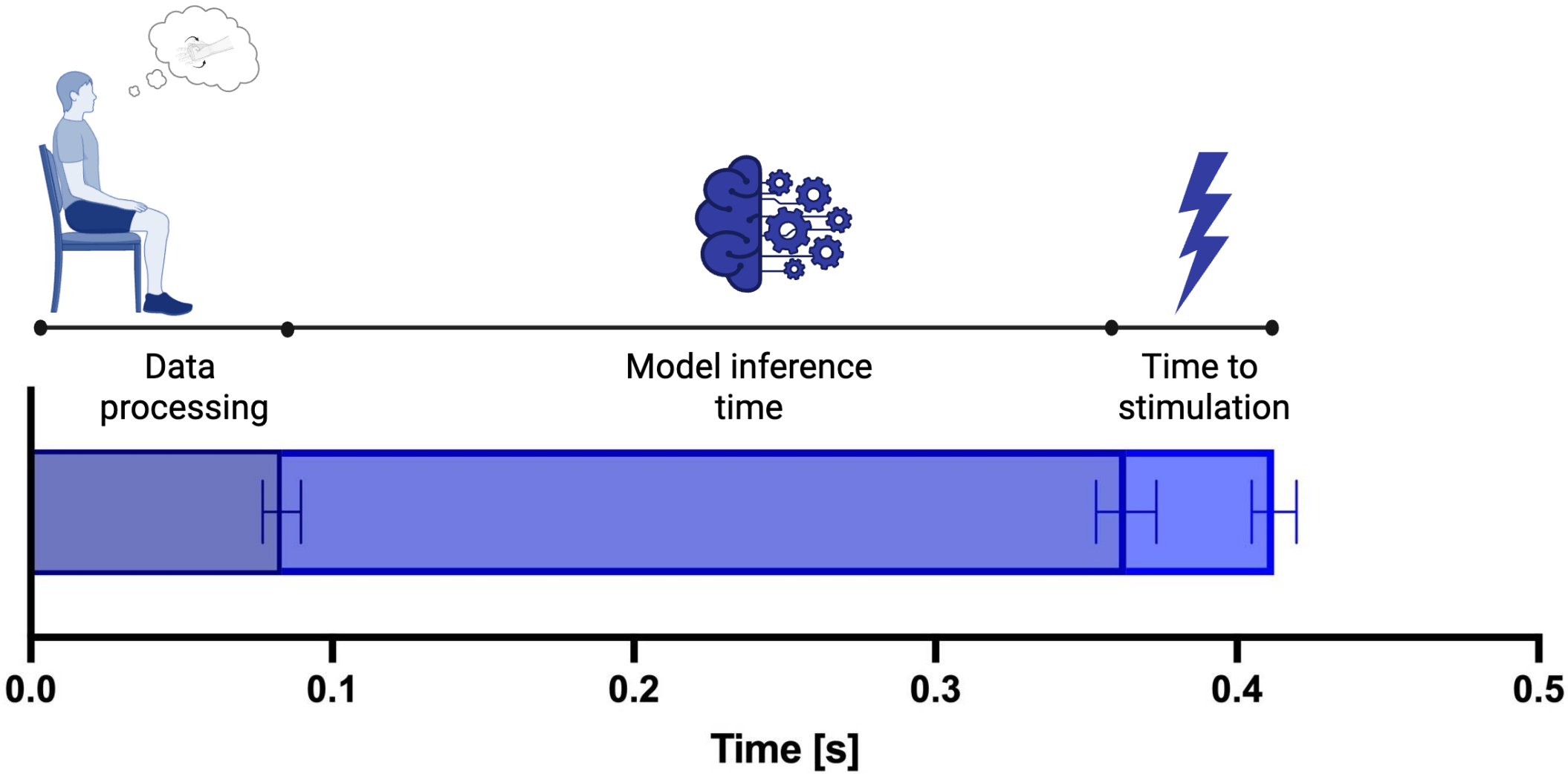


Performance: Latency

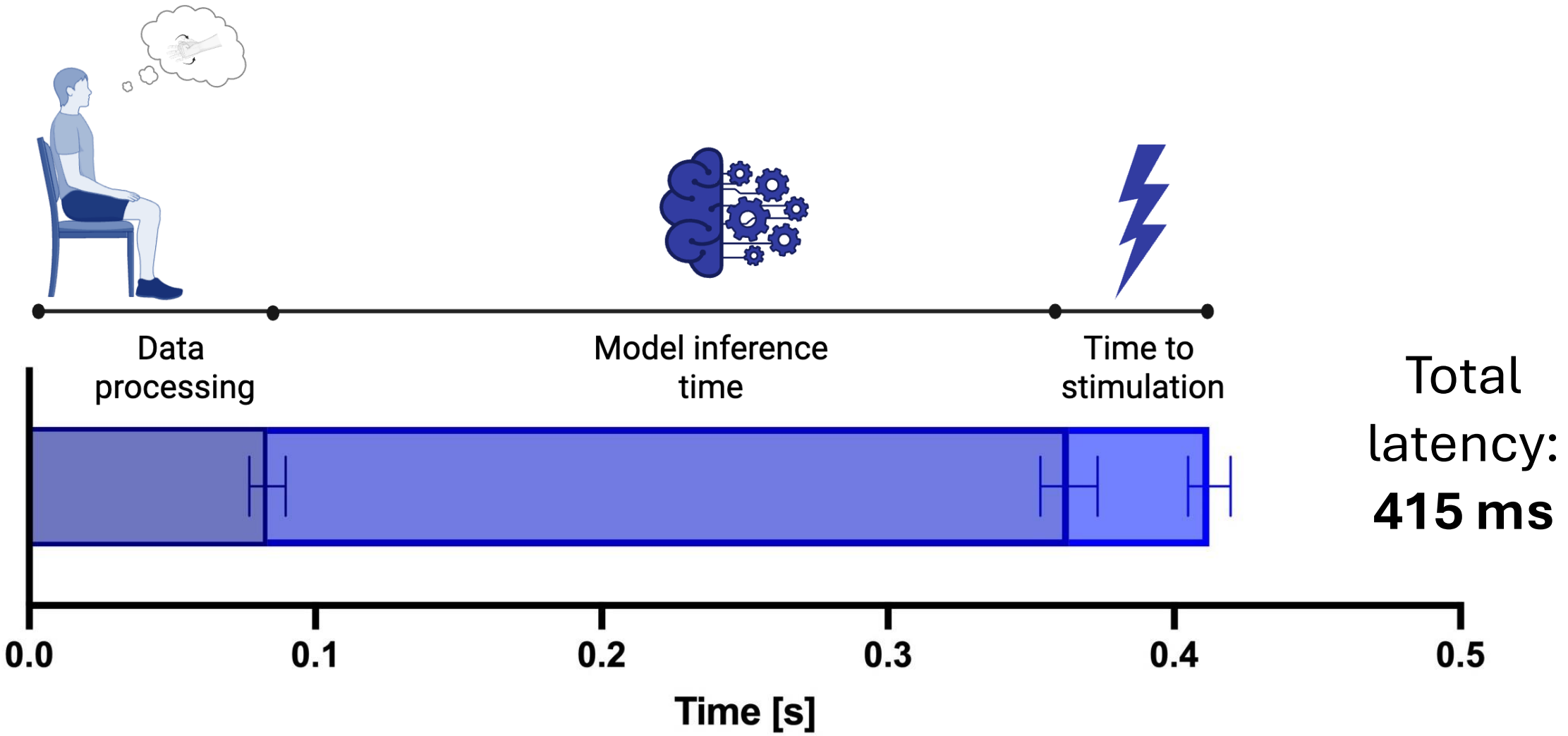


Performance: Latency



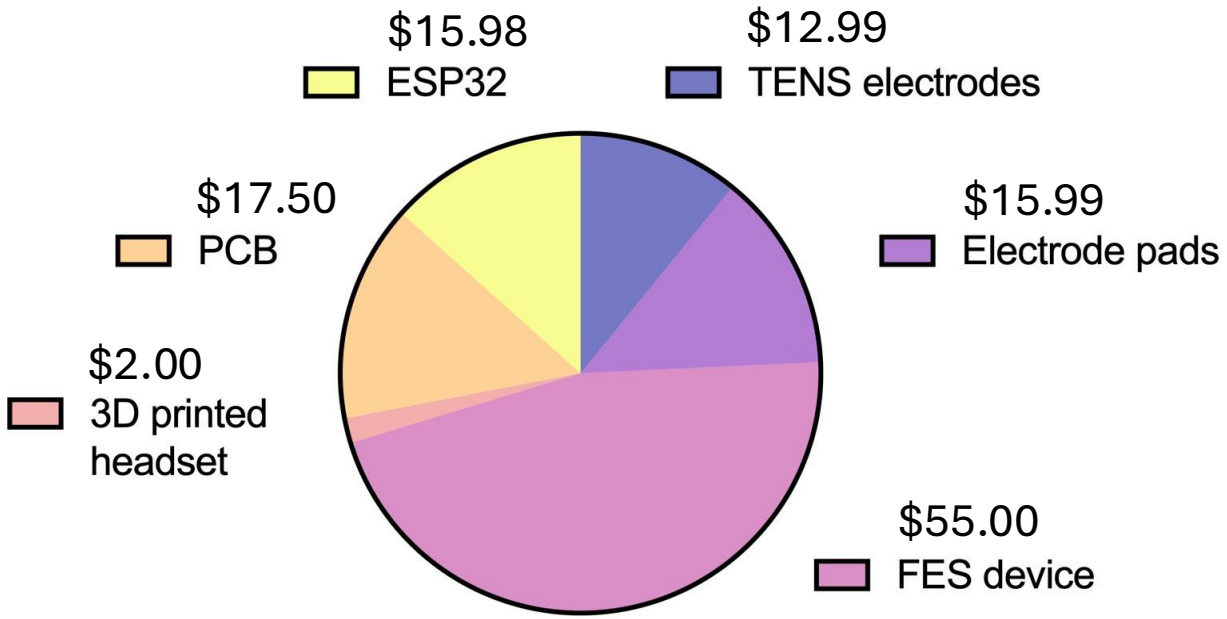

Data processing
Model inference time
Time to stimulation
0.0
0.1
0.2
0.3
0.4
0.5
Time [s]

Performance: Latency



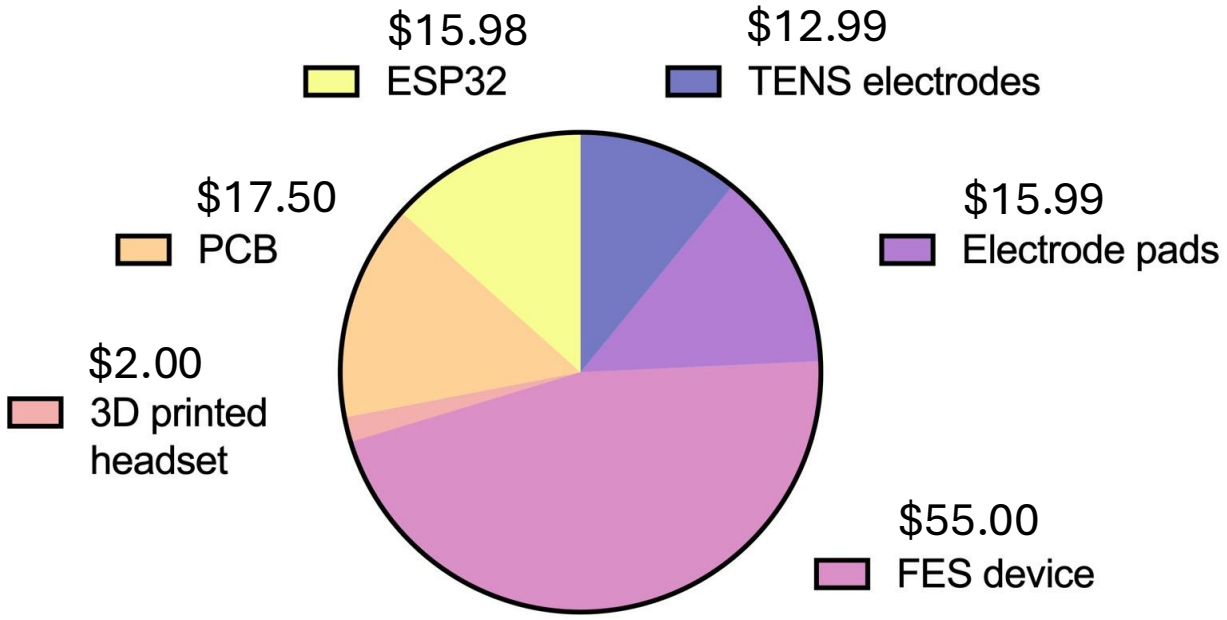
Total latency: **415 ms**

Accessibility

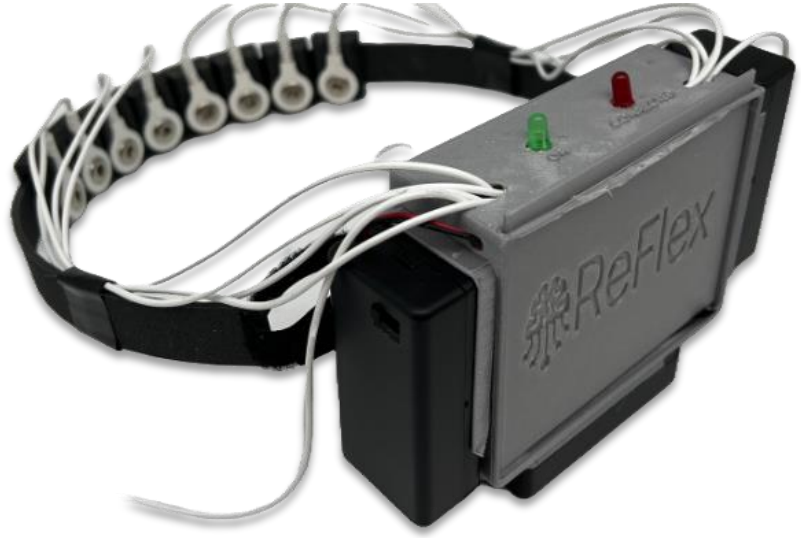


Total Cost: $119.46

Accessibility

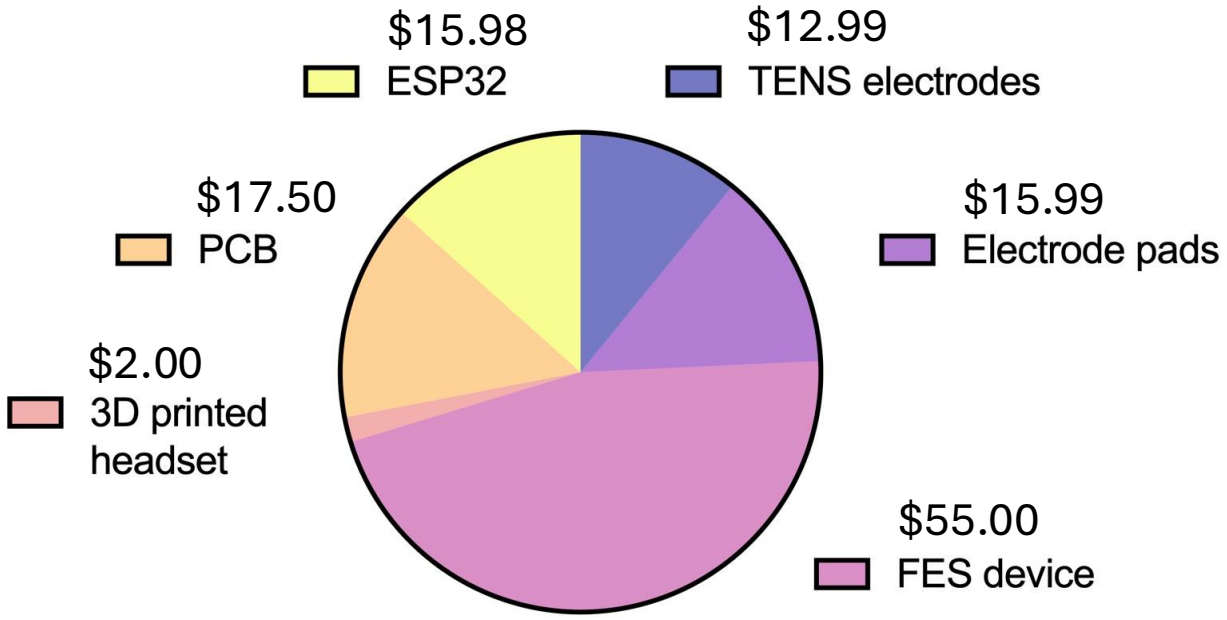


Total Cost: $119.46

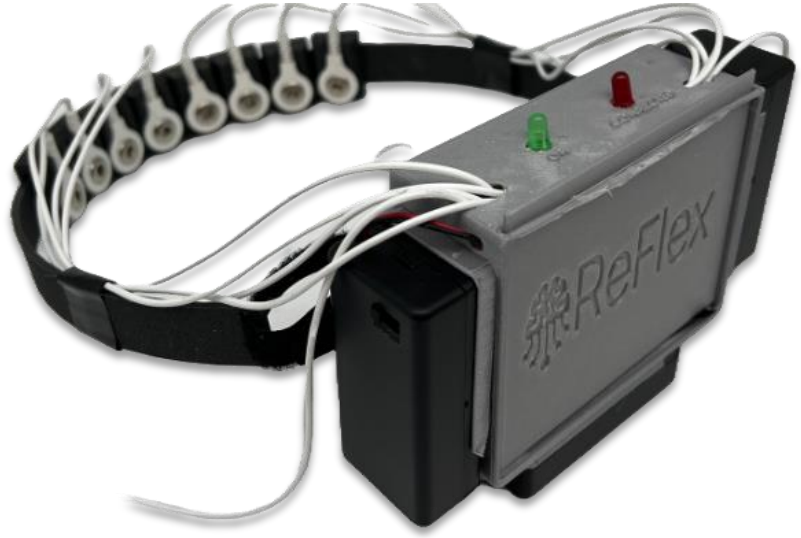


Total Weight: 1.5lb

Accessibility



Total Cost: $119.46



Total Weight: 1.5lb

Prep Time: 5-8 min

Testing and Evaluation

Performance

Model Accuracy

~~> 80%~~

80.2%

SNR

~~> 1.99 dB~~

4.76 dB

Latency

~~< 500 ms~~

415 ms

Accessibility

Cost

~~< $500~~

$120

Prep Time

~~< 10 min~~

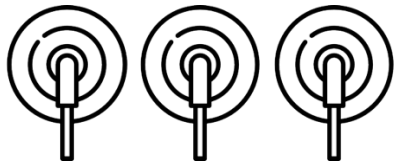
5-8 min

Weight

~~< 2 lb~~

1.5 lb

POC | MVP | FINAL



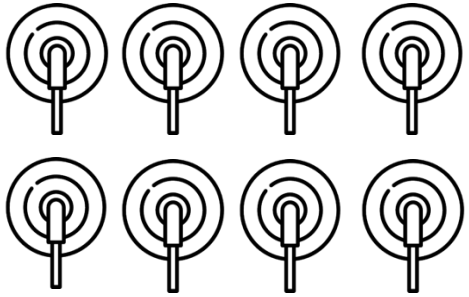
3 channels of EEG acquisition

ML model trained on 10 patients

No user application

No live integration

POC | **MVP** | FINAL



8 channels of EEG acquisition with bulky circuit

ML model trained on full online dataset

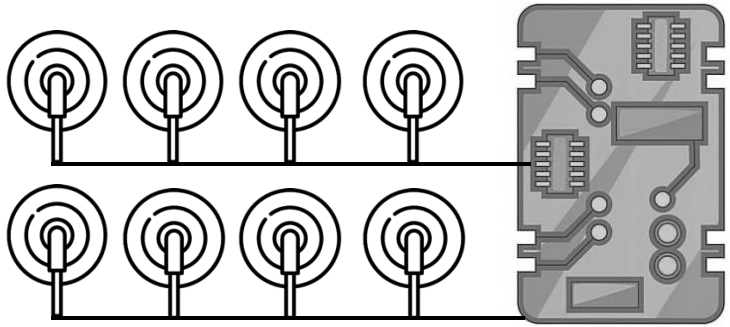
No live motor decoding in user application

No live integration

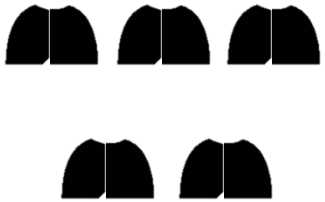
POC

MVP

FINAL



PCB-enabled fully integrated headset



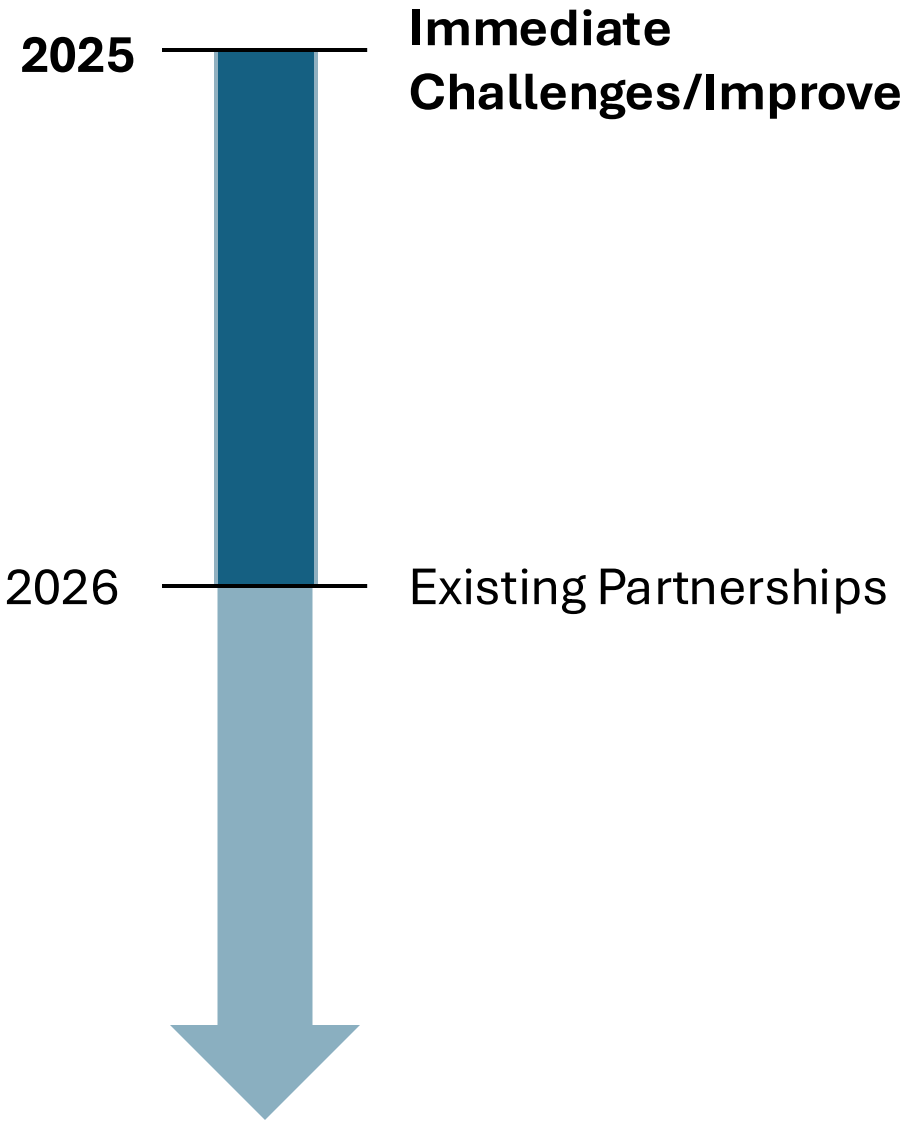
ML model finetuned on custom human data

Independent user application with live motor decoding

Live Integration

In-Person Demo

Next Steps



- Provisional Patent
- IRB-approved user validation studies with Penn Center for Neuroengineering and Therapeutics (Vitale lab)

CN&T Center *for* Neuroengineering *and* Therapeutics

Next Steps

2025 — Immediate Challenges/Improvements

2026 — Existing Partnerships

- Leverage relationship with CIONIC and other FES providers

CIONIC

ReFlex

Our Grand Vision

Empowering Personalized Recovery

ReFlex empowers patients to *take control* of their rehabilitation journey, enabling faster, more cost-effective, and independent recovery.

Our Advisors

Dr. Flavia Vitale, PhD

Dr. Tania Khanna, PhD

Dr. Pratik Chaudhari, PhD

Thank You!

Dr. David Meaney

Dr. Erin Berlew

Dr. Michael Siedlik

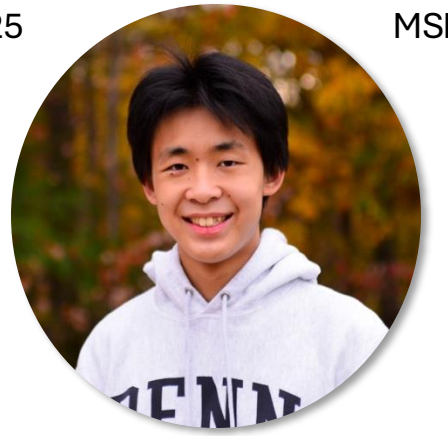
Annika Eisner

ReFlex Team

Udit Garg
BSE BE ‘25
MSE BE ‘25

Aditya Gowd
BSE BE ‘25
MSE ROBO ‘25

Ryann Joseph
BSE BE ‘25



William Qi
BSE EE ‘25
MSE DATS ‘25

Christopher Wun
BSE BE & CIS ‘25
MSE ROBO ‘25

Motor Imagery → **FES Stimulation**

Mustile *et al.*, Frontiers, 2024.

FUGL-MEYER Assessment

Gold-standard

FMA-UE PROTOCOL — Rehabilitation Medicine, University of Gothenburg

FUGL-MEYER ASSESSMENT
UPPER EXTREMITY (FMA-UE)
Assessment of sensorimotor function

ID:
Date:
Examiner:

Fugl-Meyer AR, Jaasko L, Leyman I, Olsson S, Steglind S: The post-stroke hemiplegic patient. A method for evaluation of physical performance. Scand J Rehabil Med 1975, 7:13-31.

A. UPPER EXTREMITY, sitting position

I. Reflex activity		none	can be elicited
Flexors: biceps and finger flexors (at least one)		0	2
Extensors: triceps		0	2
	Subtotal I (max 4)		

II. Volitional movement within synergies, without gravitational help			none	partial	full
Flexor synergy: Hand from contralateral knee to ipsilateral ear. From extensor synergy (shoulder adduction/ internal rotation, elbow extension, forearm pronation) to flexor synergy (shoulder abduction/ external rotation, elbow flexion, forearm supination). **Extensor synergy:** Hand from ipsilateral ear to the contralateral knee	Shoulder	retraction	0	1	2
		elevation	0	1	2
		abduction (90°)	0	1	2
		external rotation	0	1	2
	Elbow	flexion	0	1	2
	Forearm	supination	0	1	2
	Shoulder	adduction/internal rotation	0	1	2
	Elbow	extension	0	1	2
	Forearm	pronation	0	1	2
		Subtotal II (max 18)			

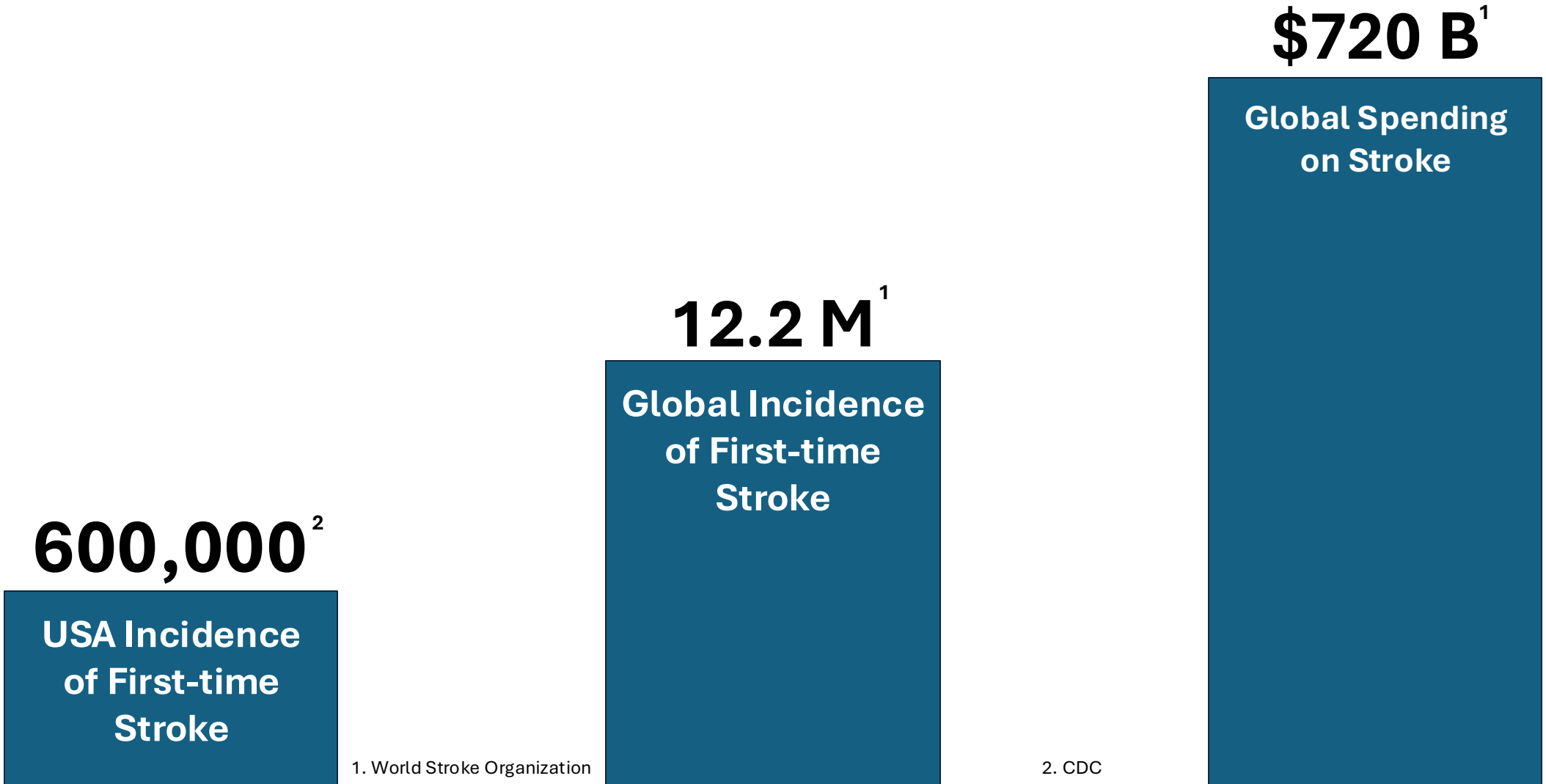
III. Volitional movement mixing synergies, without compensation		none	partial	full
Hand to lumbar spine hand on lap	cannot perform or hand in front of ant-sup iliac spine	0		
	hand behind ant-sup iliac spine (without compensation)		1	
	hand to lumbar spine (without compensation)			2
Shoulder flexion 0°- 90° elbow at 0° pronation-supination 0°	immediate abduction or elbow flexion	0		
	abduction or elbow flexion during movement		1	
	flexion 90°, no shoulder abduction or elbow flexion			2
Pronation-supination elbow at 90° shoulder at 0°	no pronation/supination, starting position impossible	0		
	limited pronation/supination, maintains starting position		1	
	full pronation/supination, maintains starting position			2
	Subtotal III (max 6)			

IV. Volitional movement with little or no synergy		none	partial	full
Shoulder abduction 0 - 90° elbow at 0° forearm pronated	immediate supination or elbow flexion	0		
	supination or elbow flexion during movement		1	
	abduction 90°, maintains extension and pronation			2
Shoulder flexion 90° - 180° elbow at 0° pronation-supination 0°	immediate abduction or elbow flexion	0		
	abduction or elbow flexion during movement		1	
	flexion 180°, no shoulder abduction or elbow flexion			2
Pronation/supination elbow at 0° shoulder at 30°- 90° flexion	no pronation/supination, starting position impossible	0		
	limited pronation/supination, maintains start position		1	
	full pronation/supination, maintains starting position			2
	Subtotal IV (max 6)			

V. Normal reflex activity assessed only if full score of 6 points is achieved in part IV; compare with the unaffected side		0 (IV), hyper	lively	normal
biceps, triceps, finger flexors	2 of 3 reflexes markedly hyperactive or 0 points in part IV	0		
	1 reflex markedly hyperactive or at least 2 reflexes lively		1	
	maximum of 1 reflex lively, none hyperactive			2
	Subtotal V (max 2)			
	Total A (max 36)			

Approved by Fugl-Meyer AR 2010 — 1 — Updated 2015-03-11

1 in 4 adults will have a stroke in their lifetime[1]



1. World Stroke Organization

2. CDC

Stroke Stats

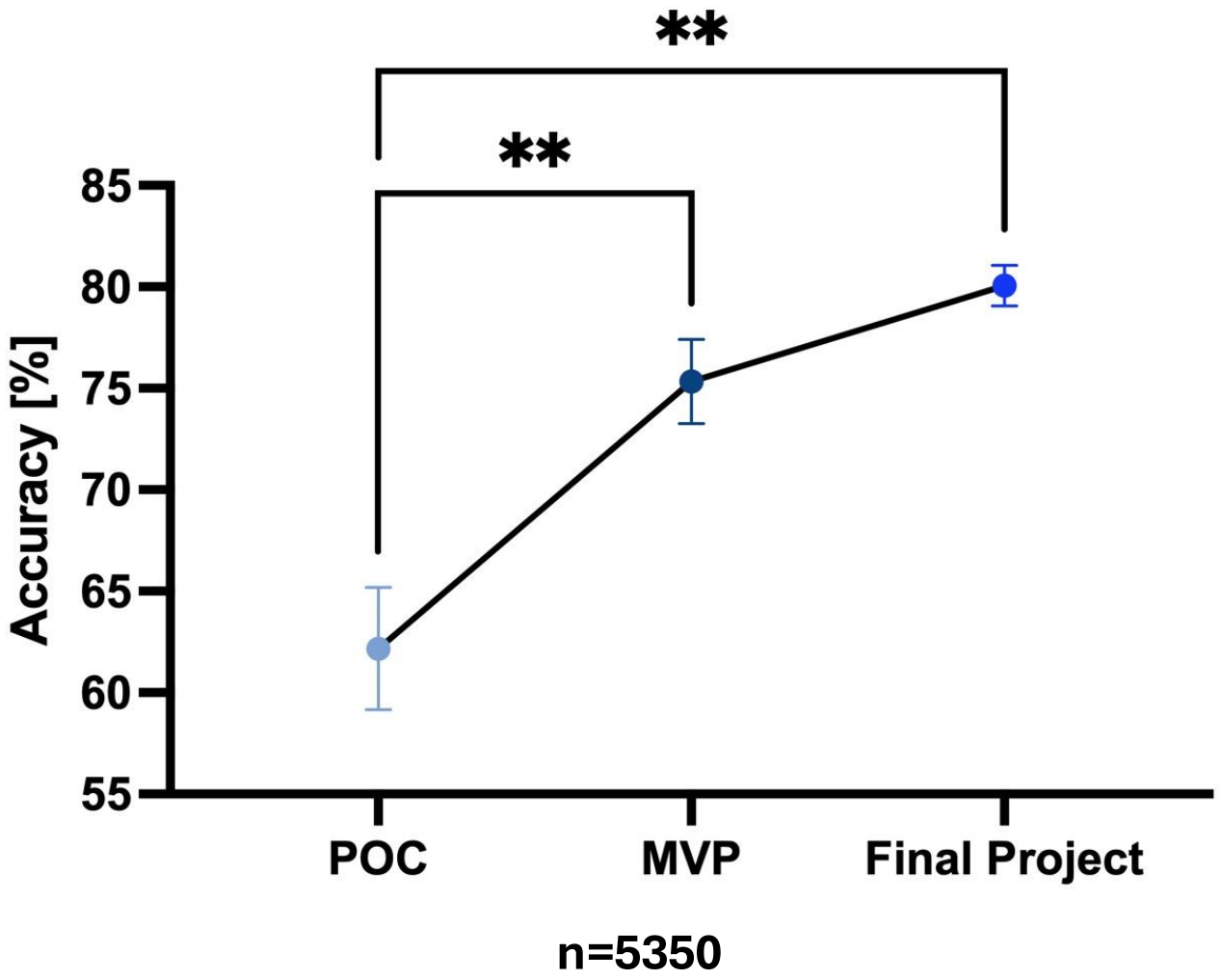
- Inpatient Rehab costs $70,601 per patient
- Outpatient Rehab costs $27,473 per patient
- Outpatient Rehab costs $27,473 per patient

Stroke Market

$50B Outpatient and At-Home Rehabilitation Market

11% CAGR through 2035

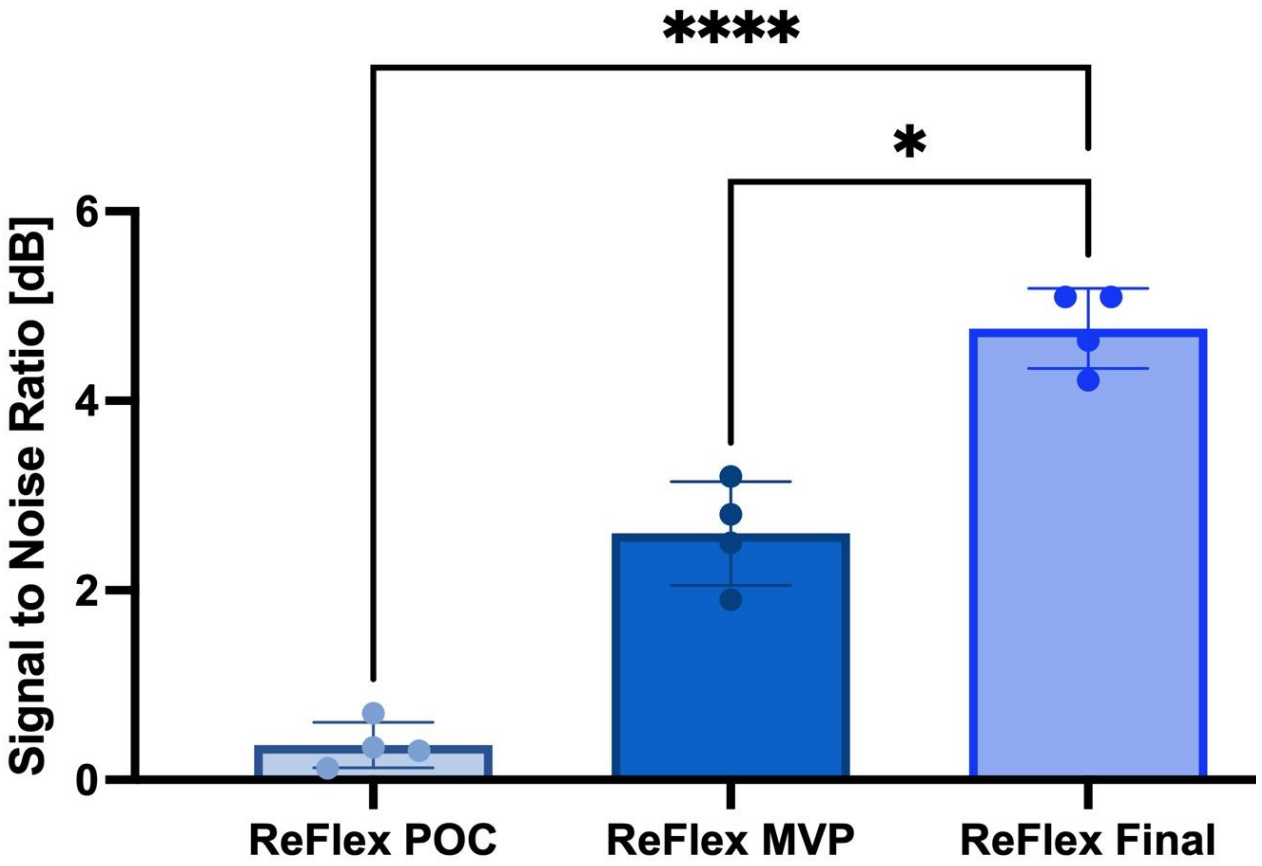
Performance: Model Accuracy



** Significance measured via two-way ANOVA, alpha=0.05 (n=3)

** indicates $p < 0.01$

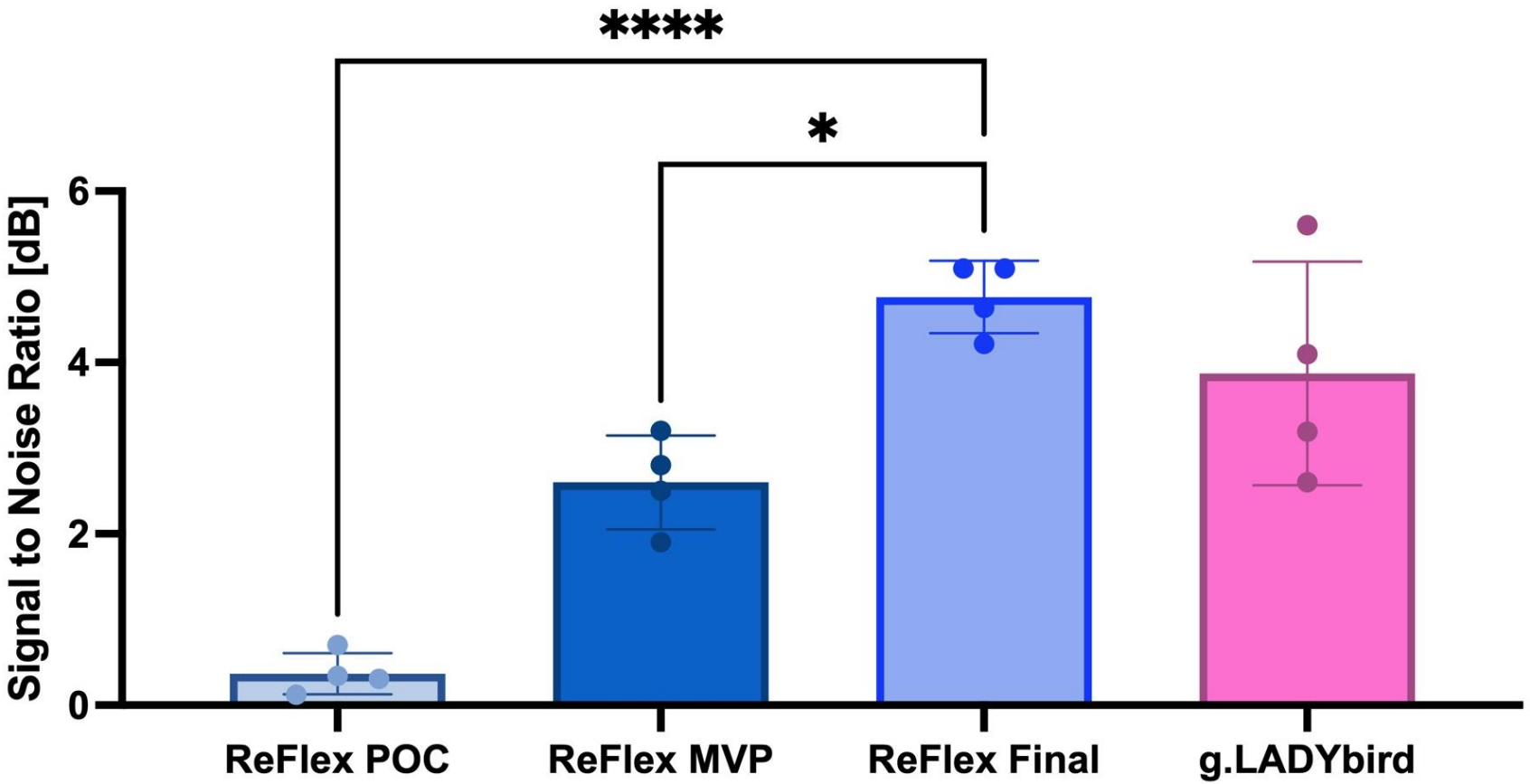
Performance: Signal Quality



Significance measured via two-way ANOVA, alpha=0.05 (n=4)
**** indicates p < 0.0001, * indicates p = 0.0122

Radüntz *et al.*, T. Frontiers, 2023.

Performance: Signal Quality



Significance measured via two-way ANOVA, alpha=0.05 (n=4)
**** indicates p < 0.0001, * indicates p = 0.0122

Radüntz *et al.*, T. Frontiers, 2023.

Concurrent Processing

EEG Data Thread

500 Hz Intake + Buffering
Connect/Disconnect Handling

Concurrent Processing

EEG Data Thread

500 Hz Intake + Buffering
Connect/Disconnect Handling

Processing Thread

Digital Signal Processing
ML Inference

Concurrent Processing

EEG Data Thread

500 Hz Intake + Buffering
Connect/Disconnect Handling

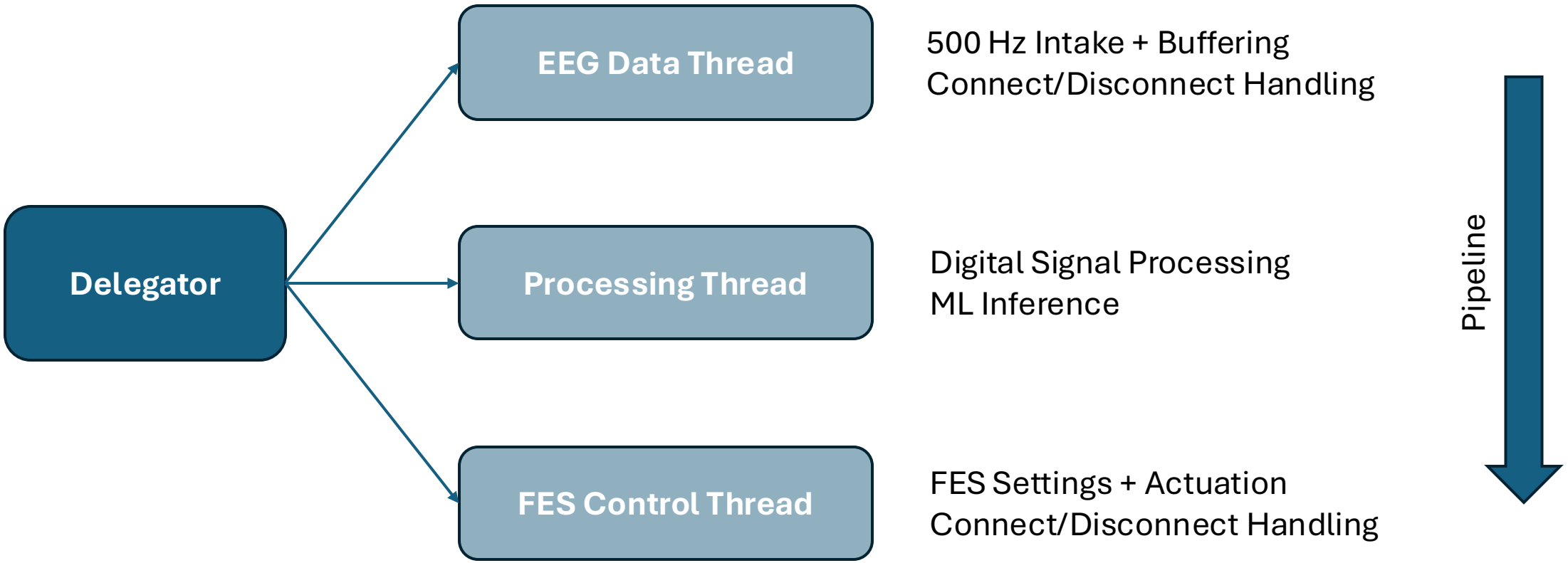
Processing Thread

Digital Signal Processing
ML Inference

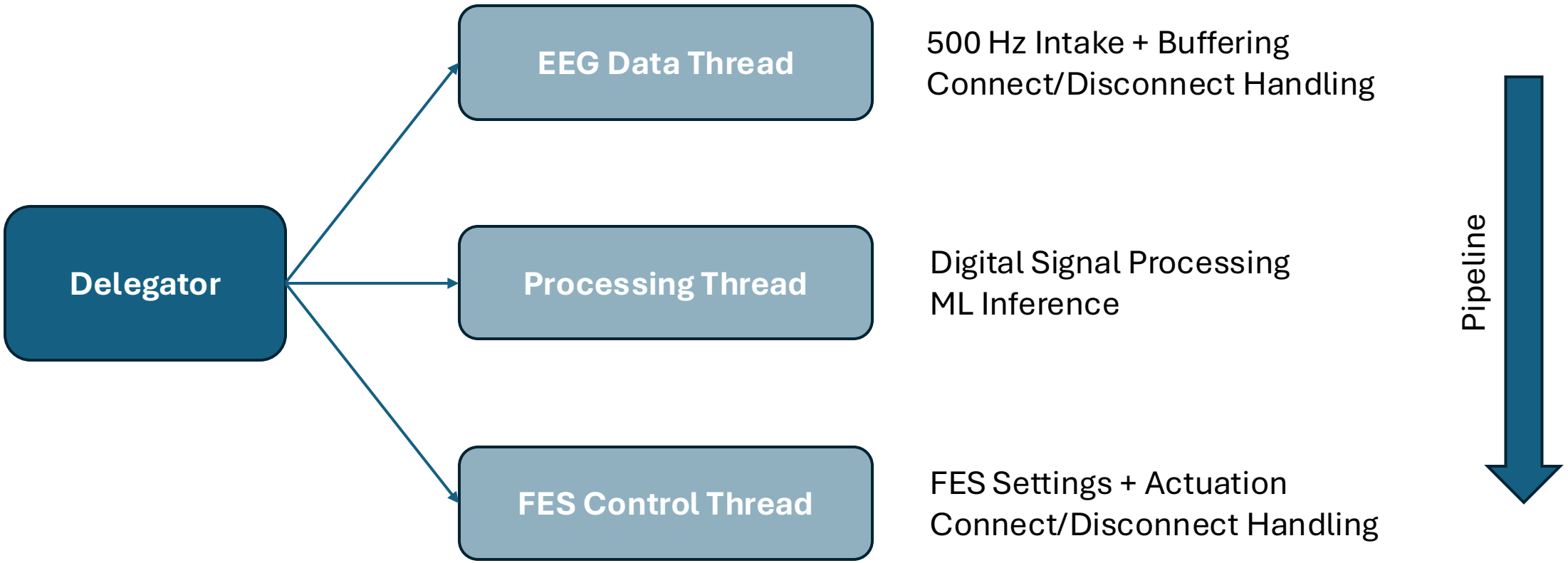
FES Control Thread

FES Settings + Actuation
Connect/Disconnect Handling

Concurrent Processing



Concurrent Processing



415 ms latency

Motor Imagery → Muscle Activation

- **Goal and intention originate in prefrontal areas.** When you decide "I'm going to imagine moving my right hand," that choice and the maintenance of that goal live in dorsolateral and frontopolar PFC.

- **Planning and sequencing immediately engage premotor/SMA.** Almost as soon as the intention is formed, your supplementary motor area (SMA) and dorsal premotor cortex take over to construct the detailed motor plan—in parallel with the PFC holding the task "in mind."

- **Sensorimotor simulation follows.** Those premotor signals propagate into M1 and parietal circuits to simulate proprioceptive and kinematic aspects of the movement, even though no muscles fire.