18th US-Korea Forum on Nanotechnology
Arizona State University

Organic Nervetronics for Neuroprosthetics

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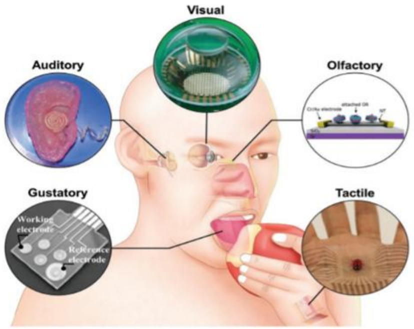
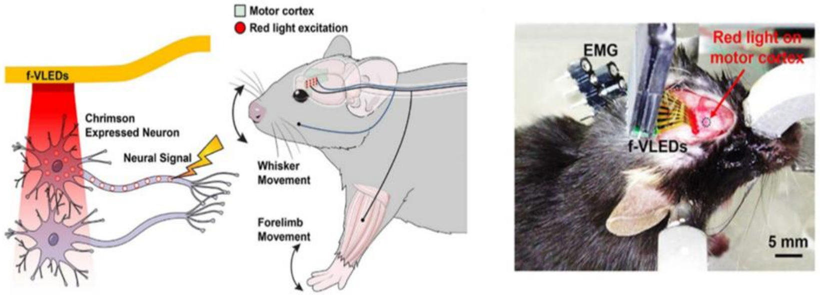
Contents

Bio-Inspired Systems for Engineering Devices

- Biological systems can inspire new generations of engineering devices.

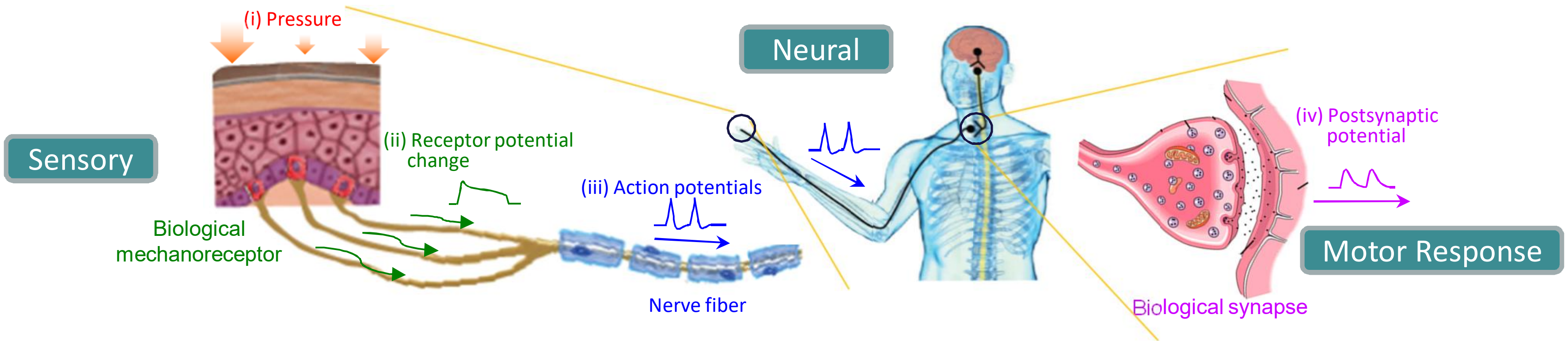


Y. H. Jung et al, *Adv. Mater.* 31, 1803637 (2018)



J. H, Park et al, *Nano Energy* 56, 531-546 (2019)

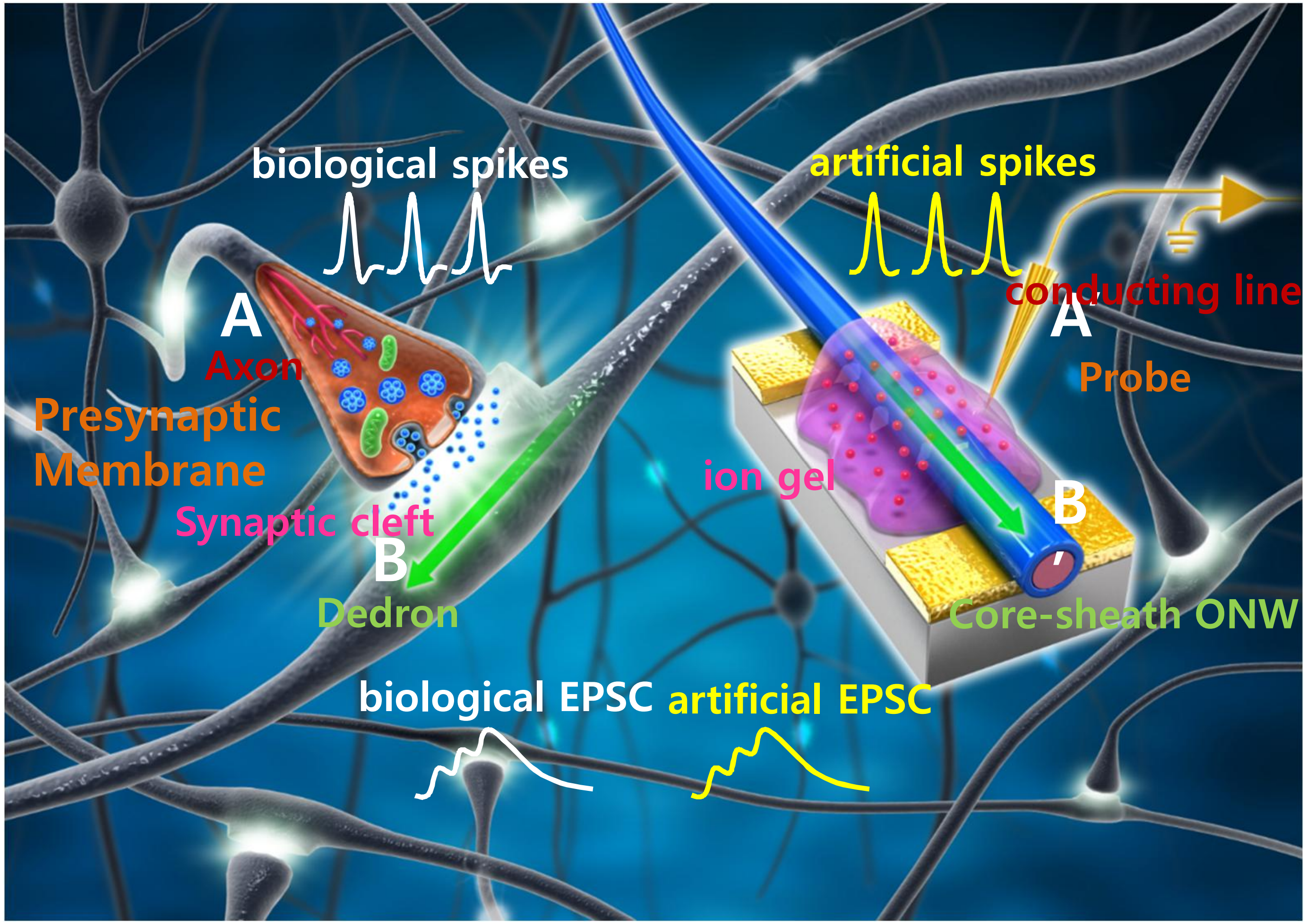
- In our brains and body, complex sensory, neural and motor processing tasks can be done very efficiently and robustly with energy-efficient neurons and cells.



High potentials for building systems that *automatically learn* and *adapt to a changing environment* by mimicking biological system

Organic Artificial Synapses

✔ **Organic synaptic transistor that emulates a biological synapse not only in morpholog y, but also in important working principles.**



- **The conducting line probe (A') mimics an axon (A) : delivering presynaptic spikes from a preneuron to the presynaptic membrane.**
- **An ONW (B') mimics a biological dendron (B) : EPSC generated in response to presynaptic spikes and delivered to a postneuron.**

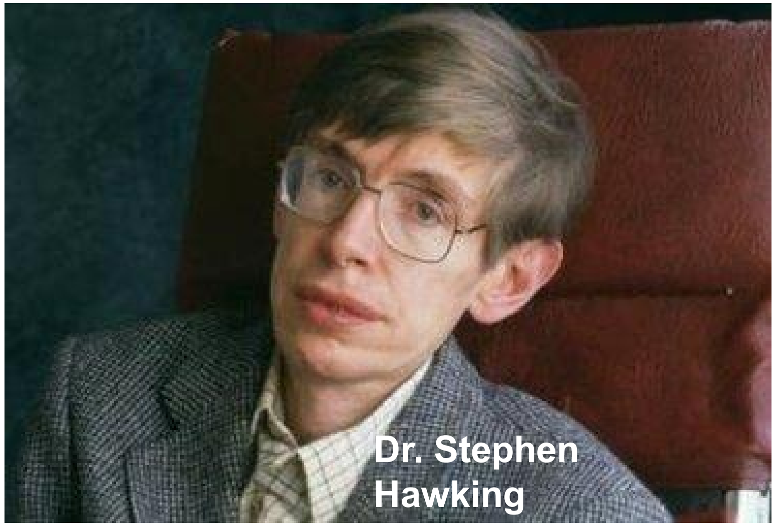
High-density integration, flexibility, and good scalability to large areas

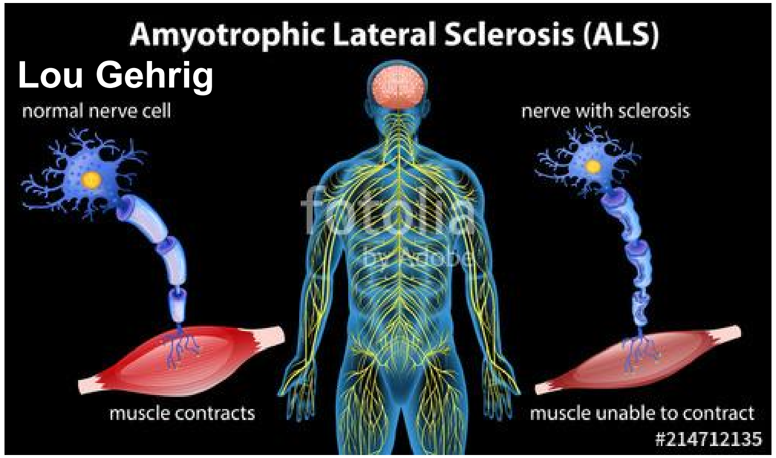
W. Xu, T.-W. Lee* et al, *Sci. Adv. 2, e1501326 (**2016**)*

Motor nervous system disorder:
SCI and Neuro degenerative disease

✓ *Spinal Cord Injury (SCI)*

✓ *Motor Neuron Disease (MND)*

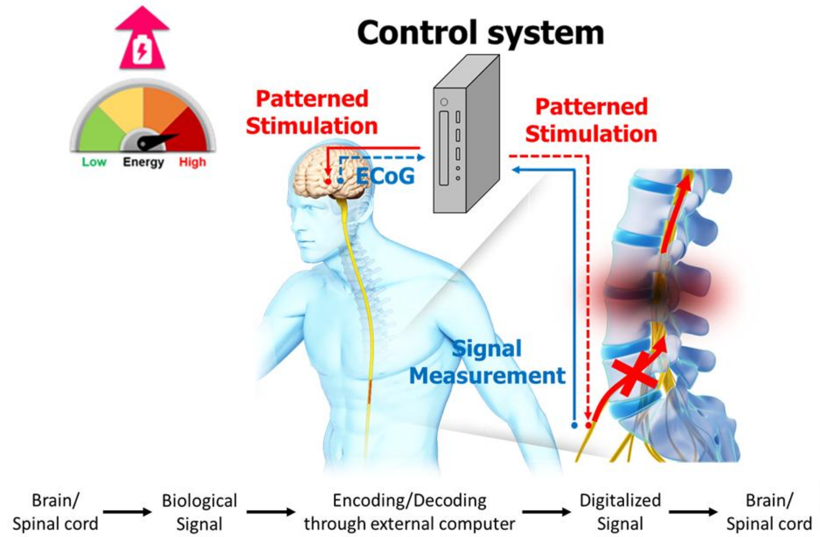




- ***Healthy brain and muscles, but damaged nerves → paralysis***

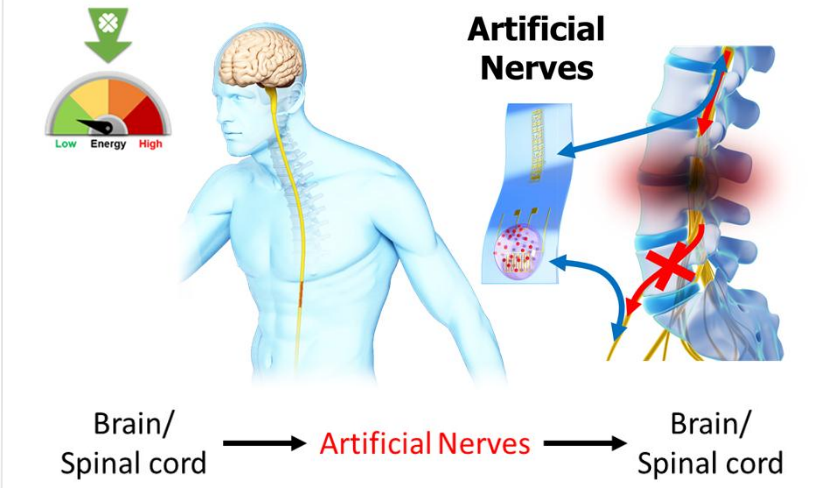
Our research direction: Nervetronics

Conventional method



- Neural signal processing requires computation through complex CMOS circuits
- **High energy consumption and heat**
- Unsuitable for the patient to carry on for long period of time
- **Mechanically transmitting electrical signals without neural properties like synaptic plasticity**

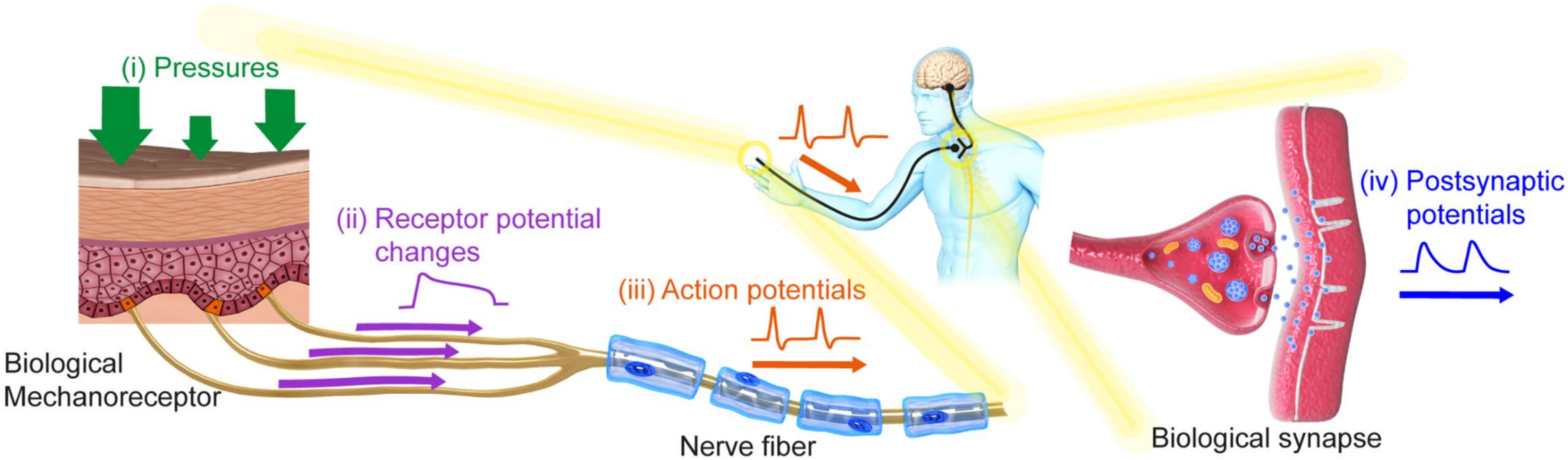
New Method (Research Idea)



- **Neural signal processing through artificial nerves is possible without a separate computational process**
- Low energy consumption at the biometric level of pJ or fJ
- Suitable for patients to carry on without discomfort
- **Through biomimetic of synaptic plasticity, expecting to induce neural plasticity**

Contents

Biological mechanosensory nerve

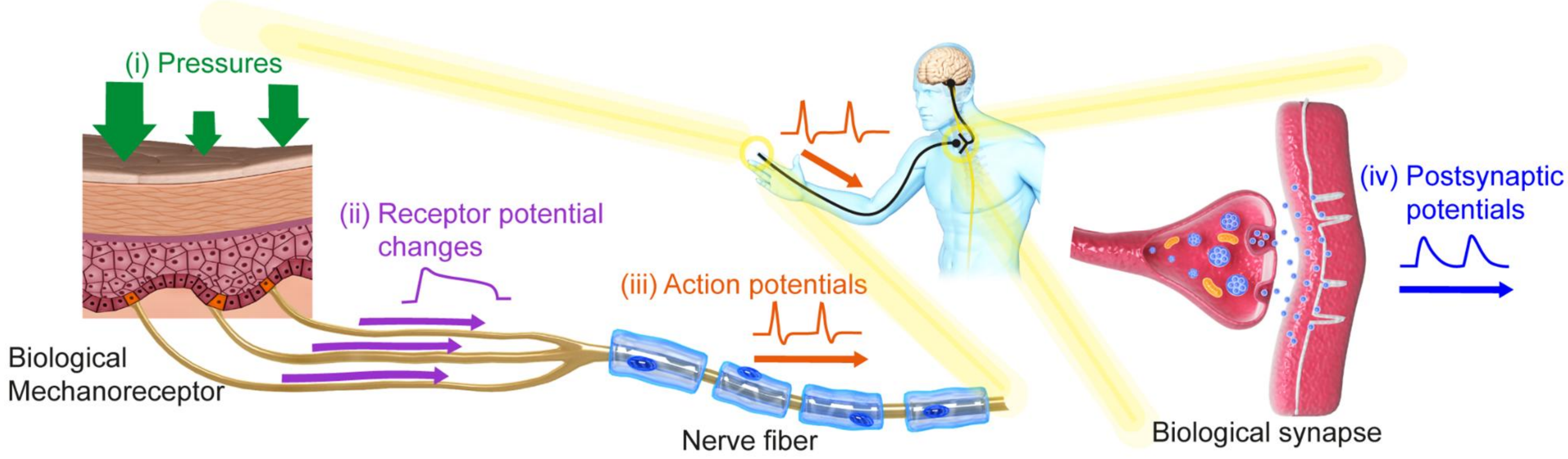


- **Their frequencies deliver information**

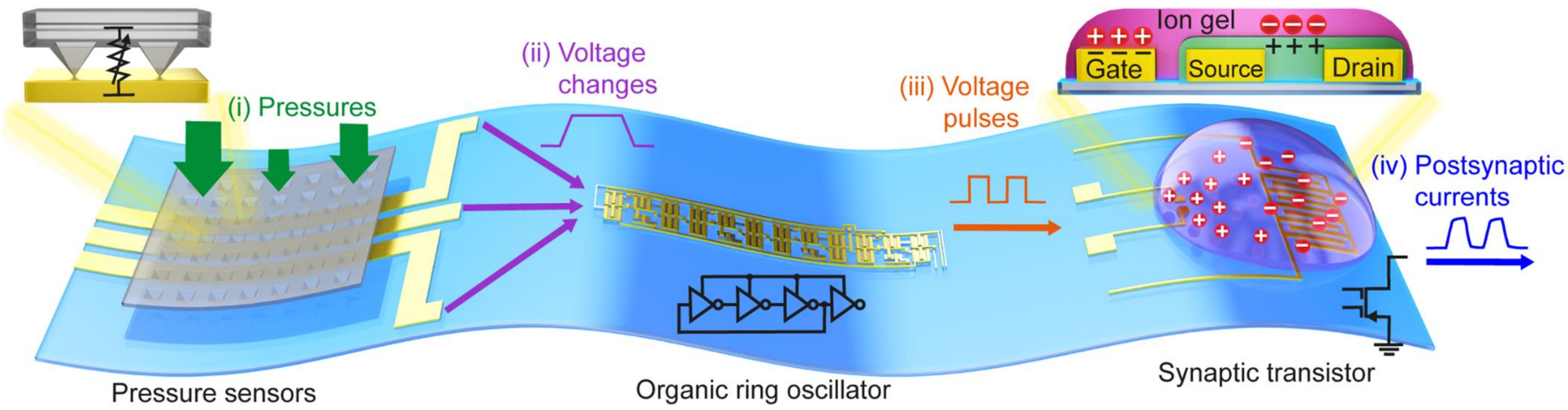
→ Biological mechanosensory system processes pressure information

Artificial mechanosensory nerve: Artificial Afferent Nerve(AAN)

Biological sensory nerves

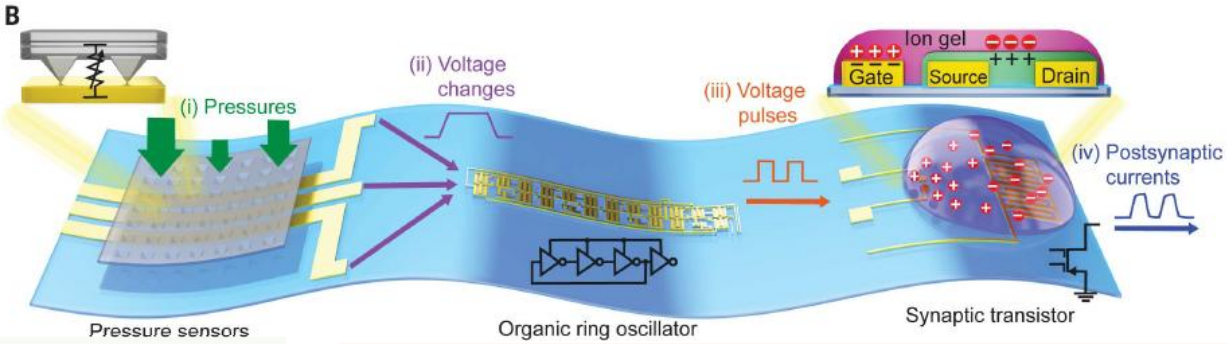


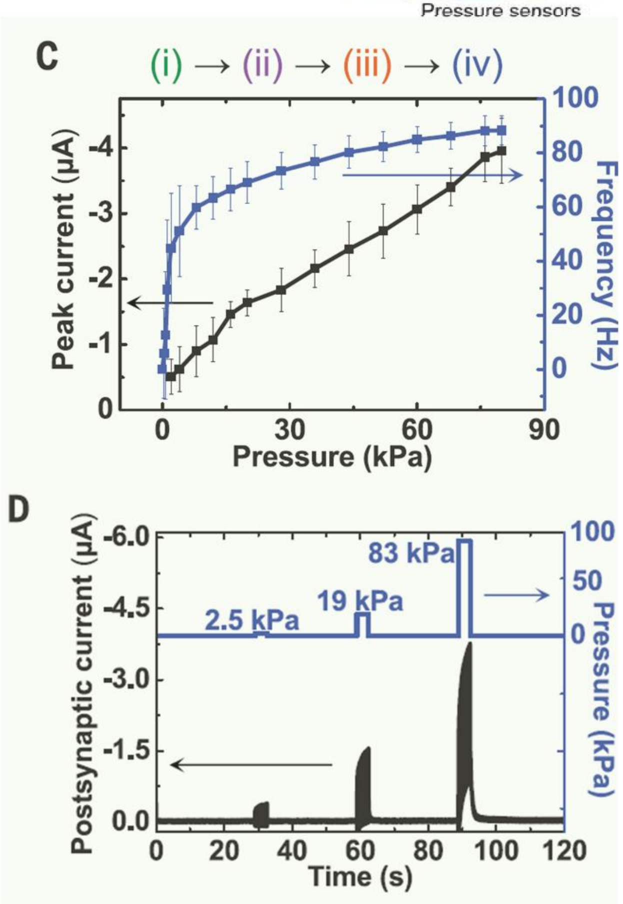
Artificial sensory nerves

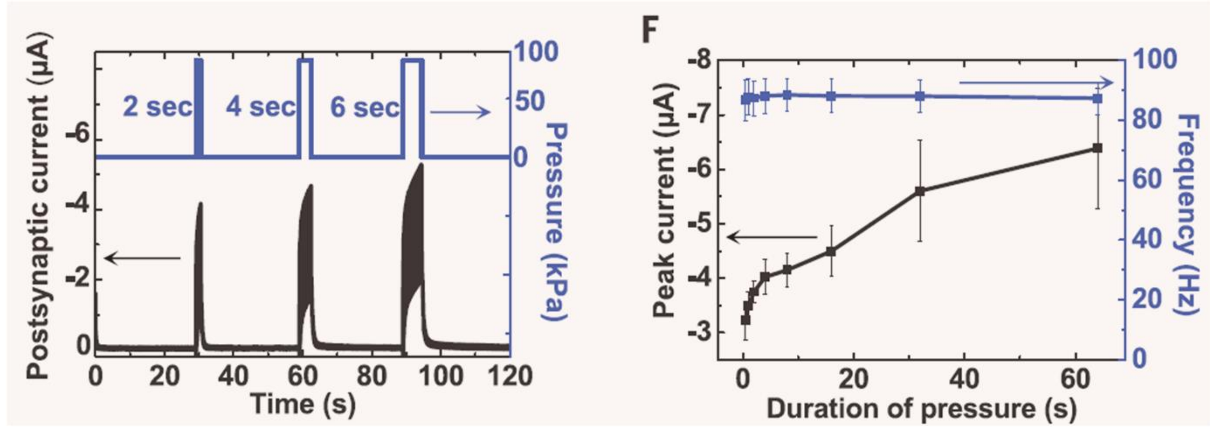


Y. Kim+, A. Chortos+, W. Xu+*, Z. Bao*, T.-W. Lee*, et al, *Science*, 360, 998 (**2018**)

Artificial Afferent Nerves (AAN)
: Pressure sensor + ring oscillator + synaptic transistors







· Increase of magnitude (C, D) & duration (E, F) of pressure

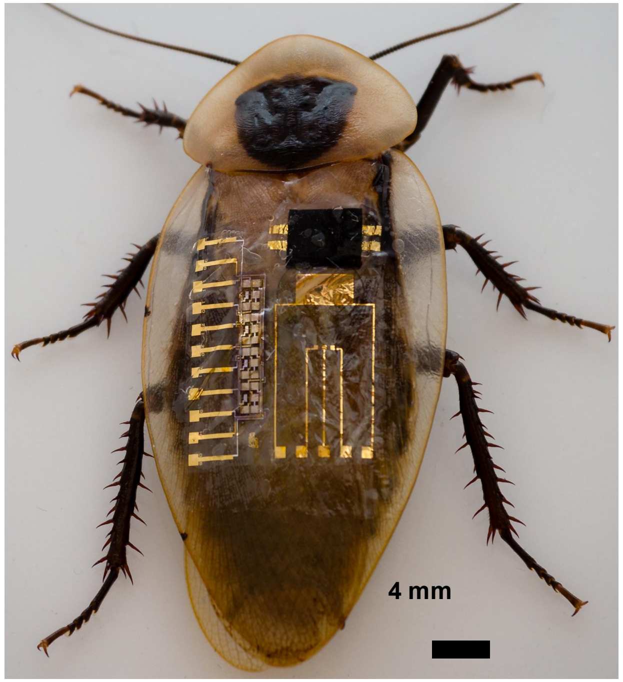
→ increase of peak postsynaptic currents

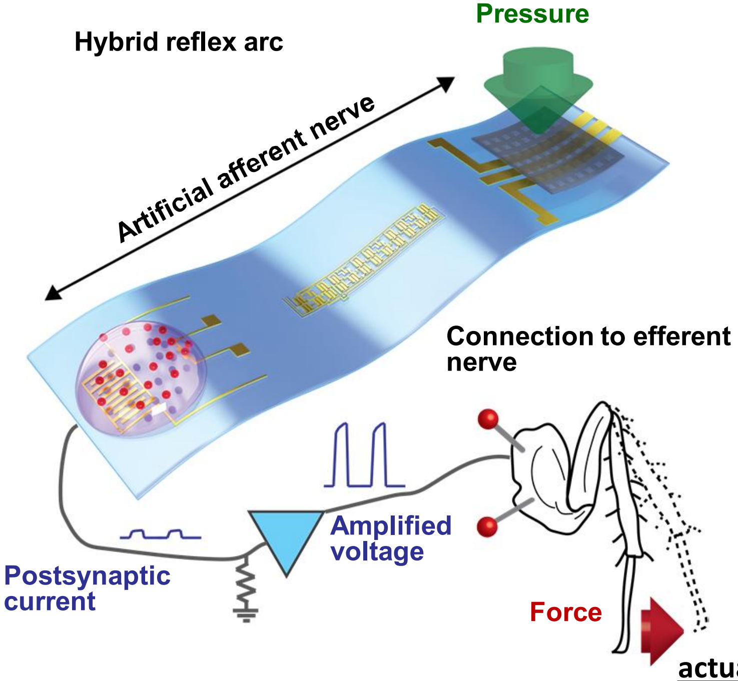
· Frequency of postsynaptic currents independent of duration of pressure stimulus

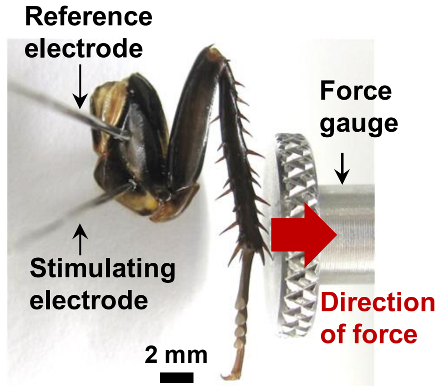
· SA-I receptors (pressure input frequencies are <~5 Hz, pressure durations are >~200 ms)

Y. Kim+, A. Chortos+, W. Xu+*, Z. Bao*, T.-W. Lee*, et al, *Science*, 360, 998 (**2018**)

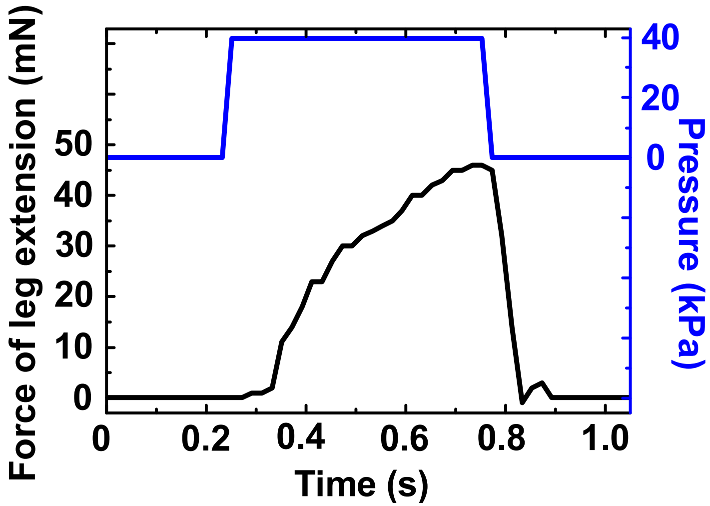
AAN: Movement Recognition & Braille Reading

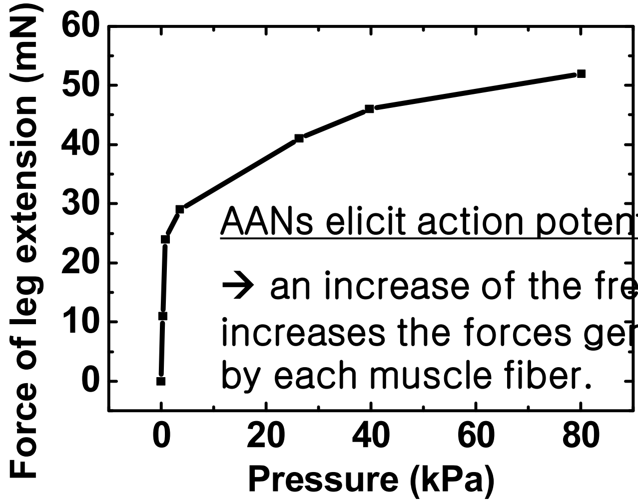






actuation of the tibial extensor muscle





AANs elicit action potentials in nerves

→ an increase of the frequency increases the forces generated by each muscle fiber.

Y. Kim[+], A. Chortos[+], W. Xu[+*], Z. Bao*, T.-W. Lee*, et al, *Science*, 360, 998 (**2018**)

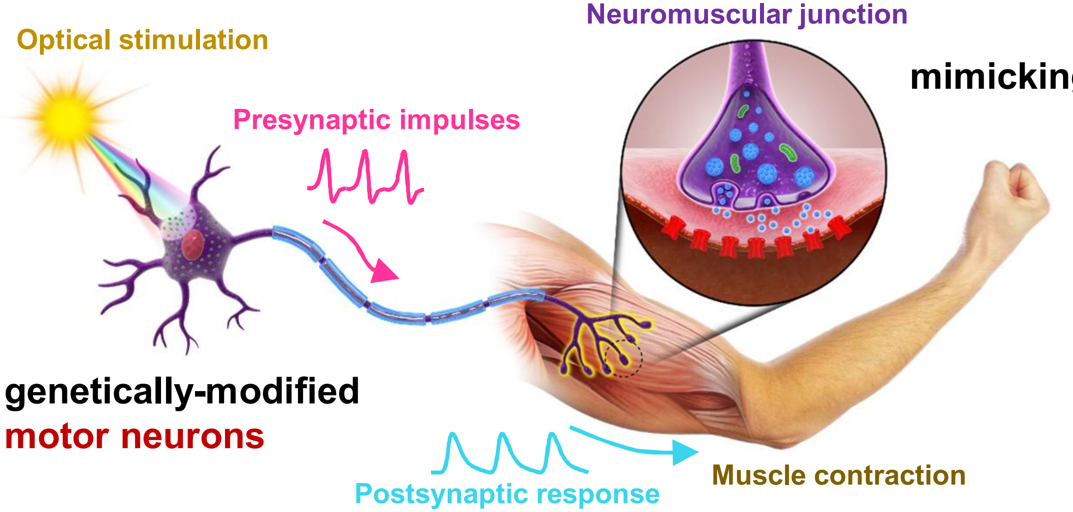
Hybrid reflex arc (artificial afferent nerve)

Pressure intensity
= 2.2 kPa

Y. Kim[+], A. Chortos[+], W. Xu[+*], Z. Bao[*], T.-W. Lee[*], et al, *Science*, 360, 998 (**2018**)

Contents

Artificial Optoelectronic Neuromuscular System

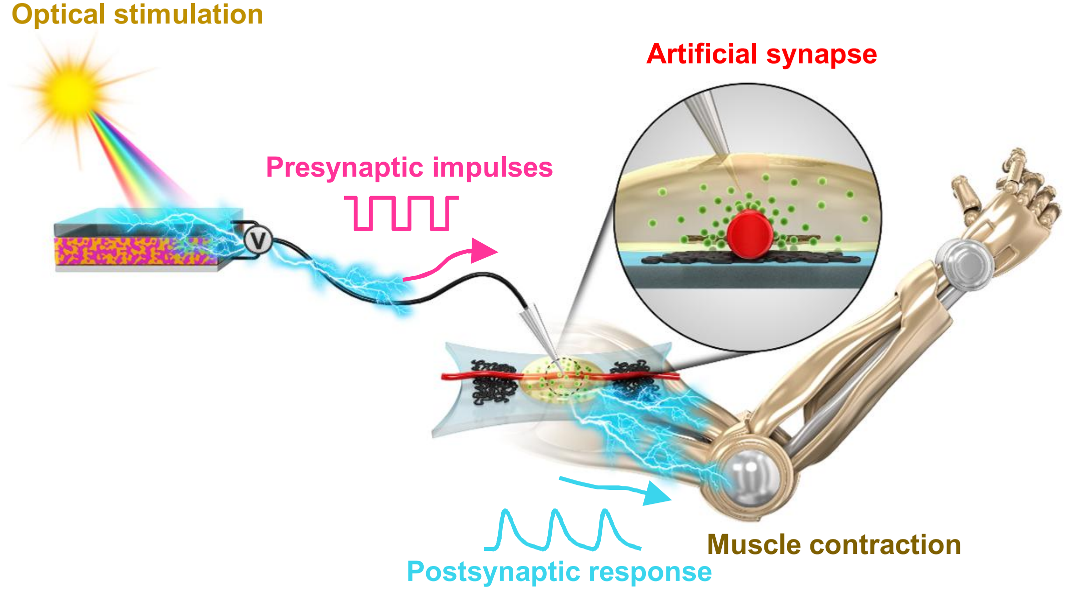


genetically-modified
motor neurons

mimicking this optogenetic neuromuscular system

- **Stretchable artificial synapse** is necessary for artificial motor system of neuro-inspired soft robots with various motions.
- **Optogenetics**
  Photosensitive protein = Photodetector
- **Neuromuscular junction**
  Synaptic cleft = Ion-gel electrolyte
  Neurotransmitter = Anion
- **Skeletal muscle**
  Postsynaptic membrane = OSC NW
  Postsynaptic potential = Drain current
  Muscle fiber = Polymer actuator

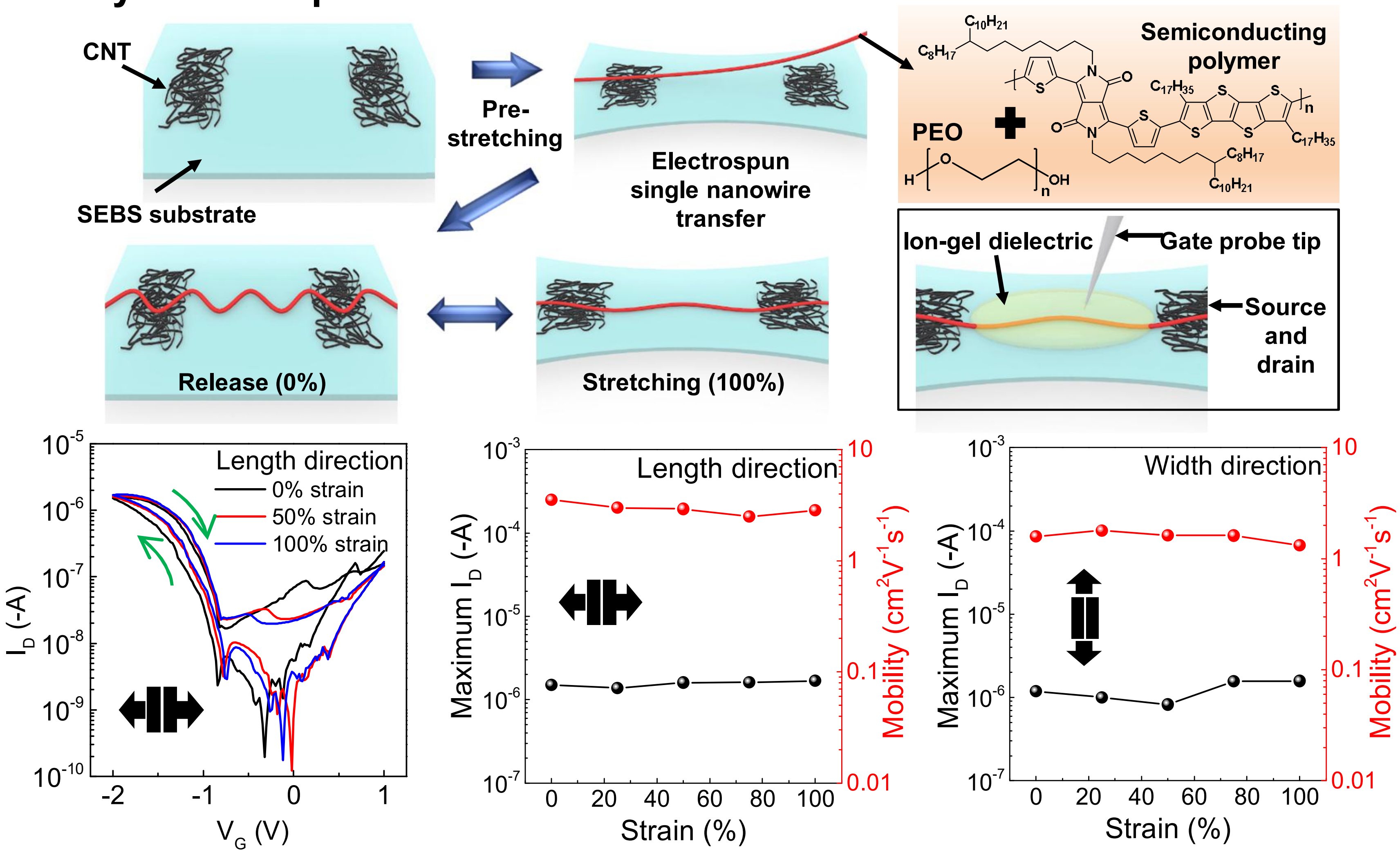
This approach is promising to restore the motor function of defective neuromuscular systems



Y. Lee+, J. Y. Oh+, Z. Bao*, T.-W.Lee* *et al, Sci. Adv.*, 4, eaat7387 (**2018**)

Stretchable Synaptic Transistors

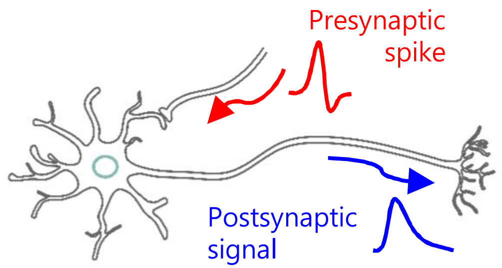
❖ **Wavy ONW on pre-strained substrate**

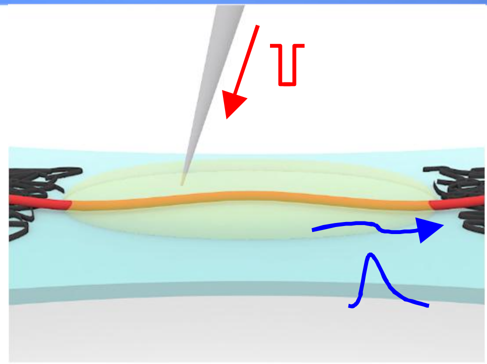


Stretchable synaptic transistors showed stable mobility and drain current during ~100% stretching without significant electrical loss.

Y. Lee+, J. Y. Oh+, Z. Bao*, T.-W.Lee* *et al, Sci. Adv.*, 4, eaat7387 (**2018**)

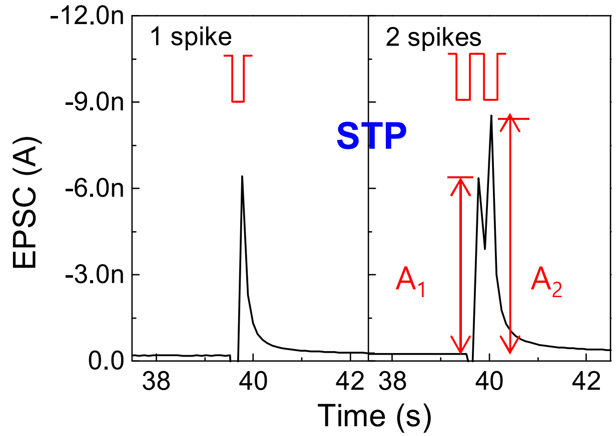
Stretchable Synaptic Transistors

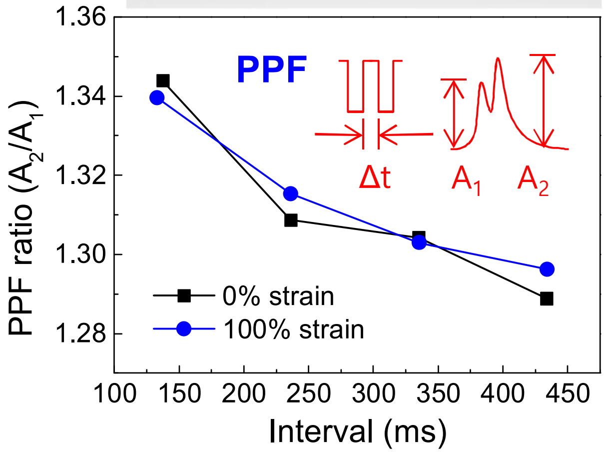


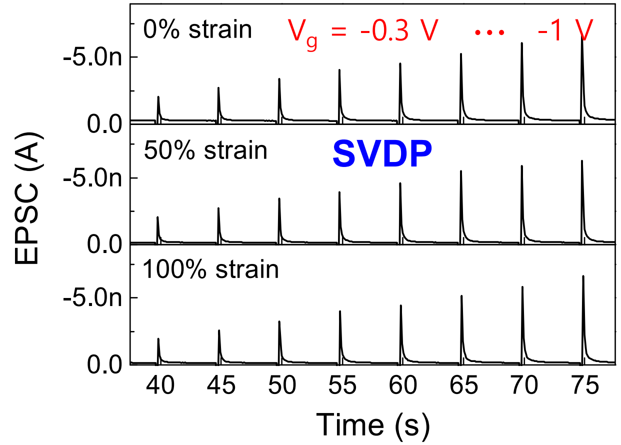


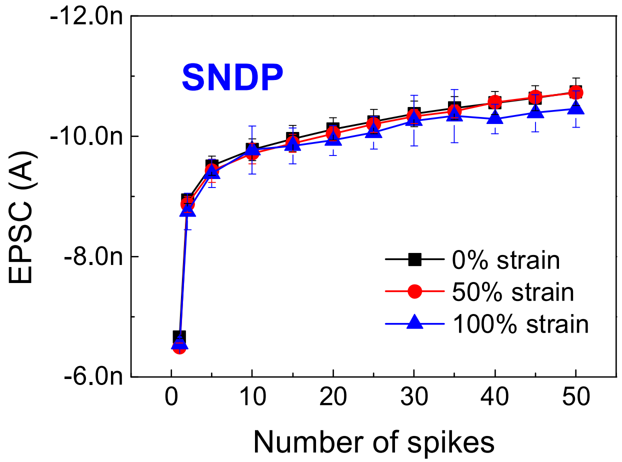
- Long alkyl chain and high crystallinity of polymer protect permeation of electrolyte to conjugated segments.
  → Low doping effect

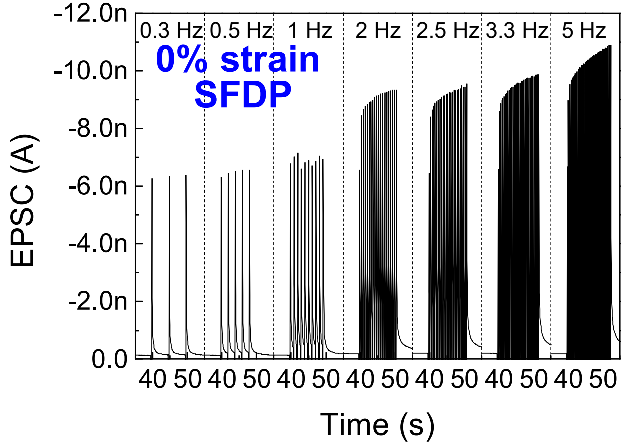
Organic Electronics, 15, 2126 (2014)

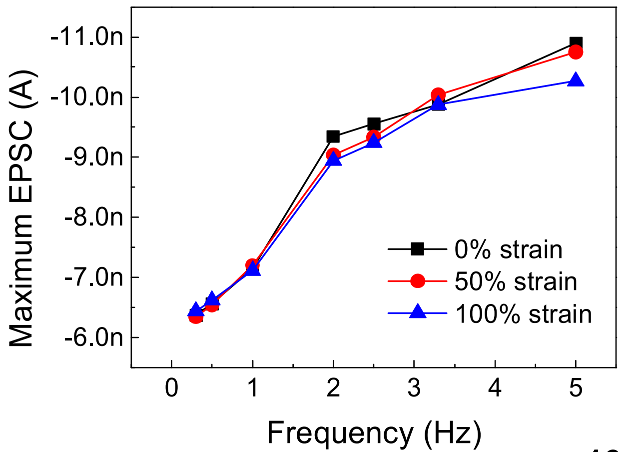






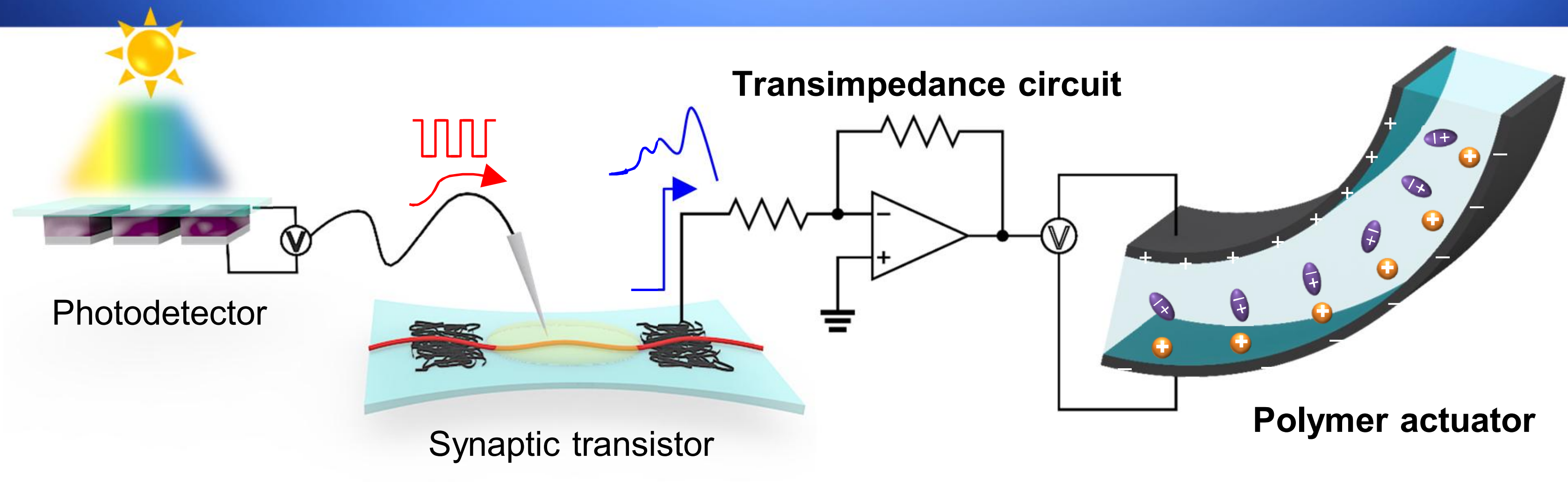




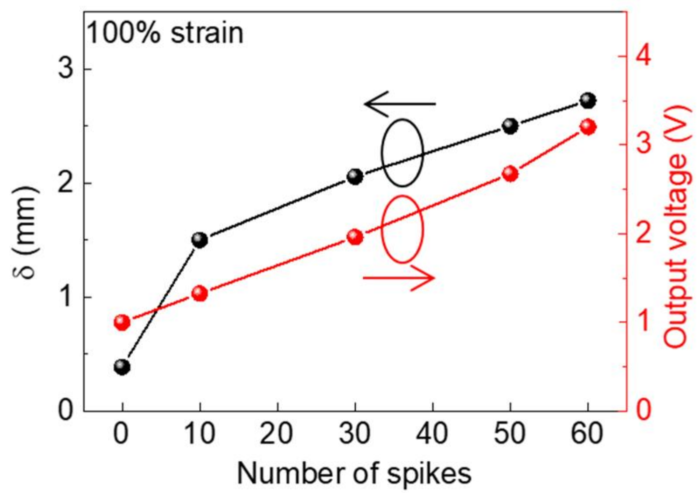


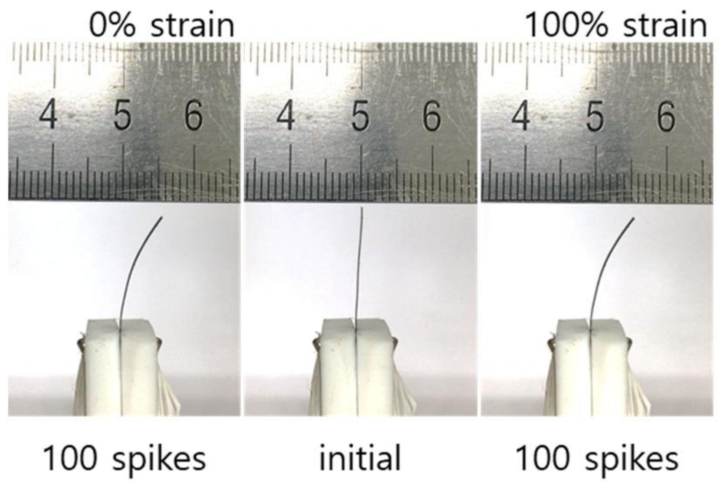
Y. Lee+, J. Y. Oh+, Z. Bao*, T.-W.Lee* *et al, Sci. Adv.*, 4, eaat7387 (**2018**)

Artificial Optoelectronic Neuromuscular System



EPSCs from the organic optoelectronic synapse were converted to voltage signals to operate our *fabricated polymer actuator*.



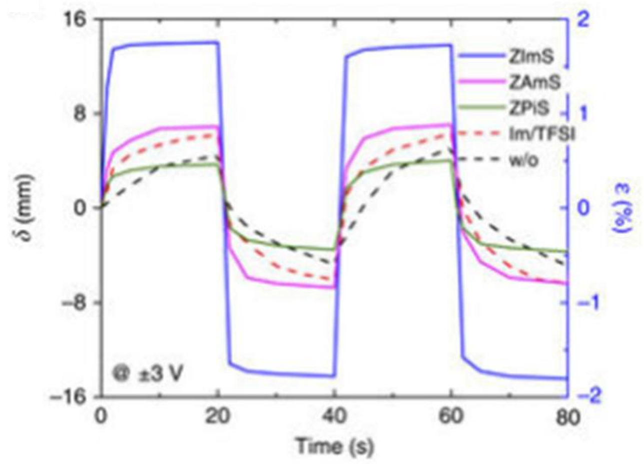


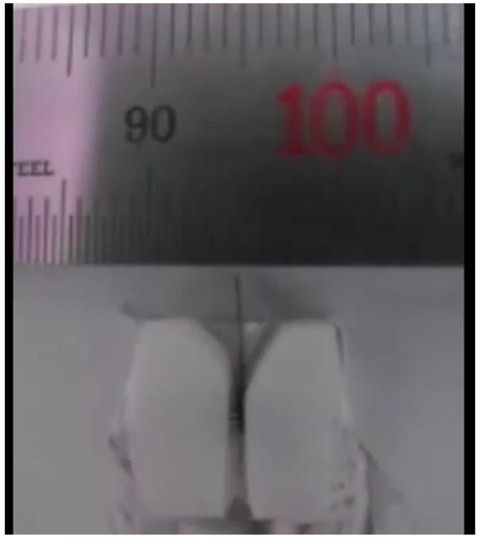
→ A novel bio-inspired somatic sensorimotor system for advanced bio-inspired electronics and neurorobotics

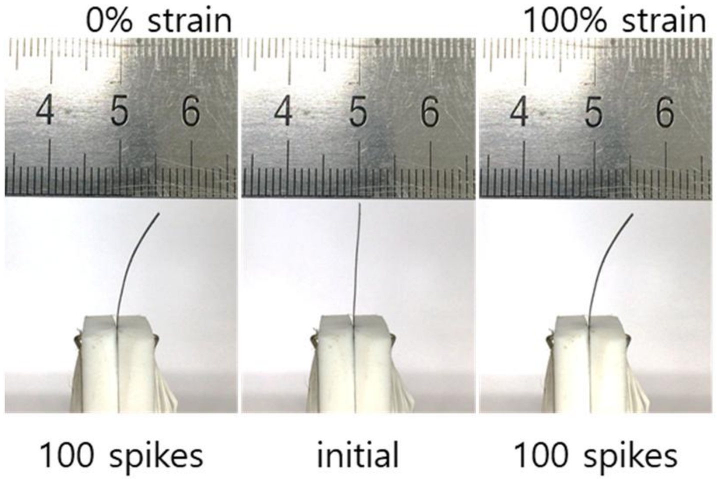
Y. Lee+, J. Y. Oh+, Z. Bao*, T.-W.Lee* *et al, Sci. Adv.*, 4, eaat7387 (**2018**)

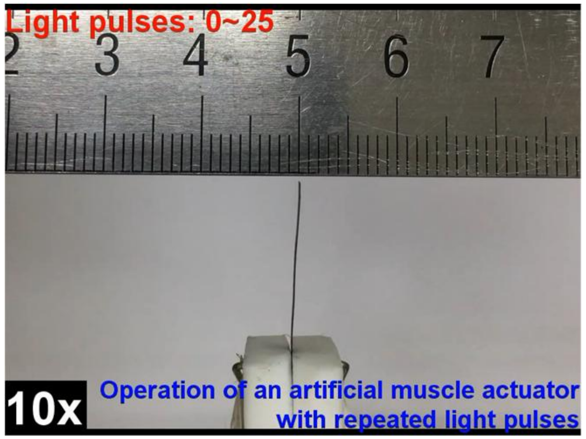
Artificial Optoelectronic Neuromuscular System

✔ **Without artificial synapse (Constant displacement with constant voltage)**









→ **Neuromorphic Soft Robotics**

Y. Lee+, J. Y. Oh+, Z. Bao*, T.-W.Lee* *et al, Sci. Adv.*, 4, eaat7387 (**2018**)

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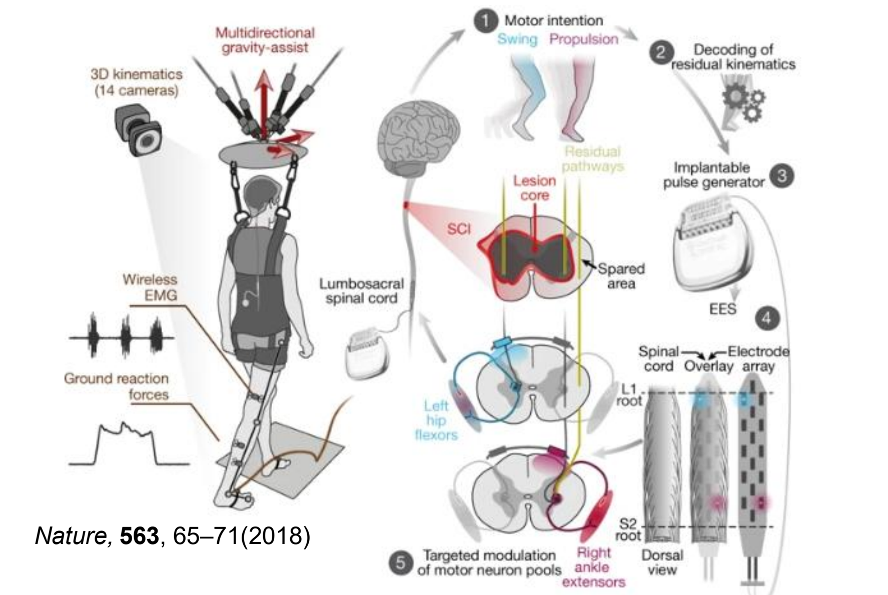
Problems of Conventional Way to SCI

Absence of a method to emulate biological nerve signal transduction

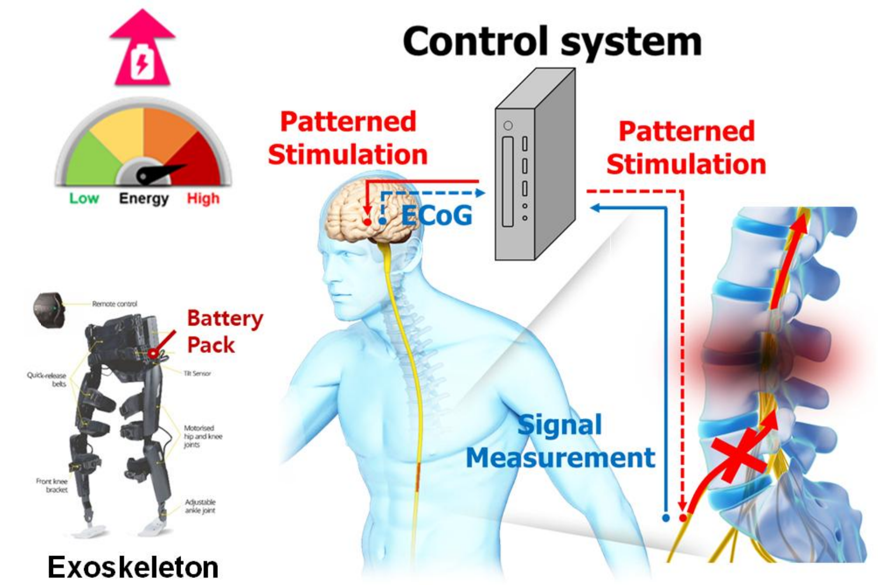


Nature, **563**, 65–71(2018)

Recent approaches for treating spinal cord injury

- Dozens of cameras and computing systems are used to detect motor intentions and stimulate with the pre-stored signals
- Mechanically transmits neural signals stored in an external device according to a predetermined exercise

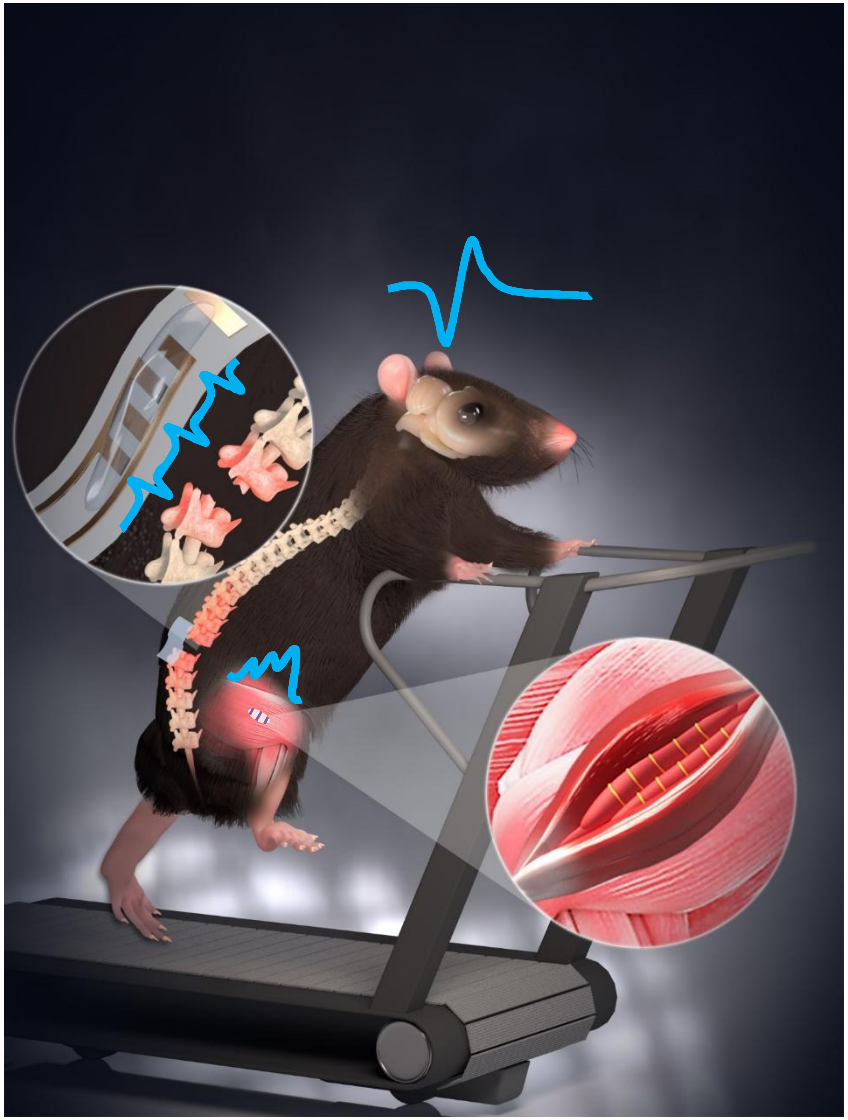
Requires bulky and complex external computer



Existing Bionics Device Flow Chart

- In the existing Bionics system, biological information is connected to and transmitted to an external computer.
- Mechanically connecting the living body and the system.
- **High energy consumption and plasticity of biological nerves cannot be emulated**

Neuromorphic prosthetic nerve for SCI

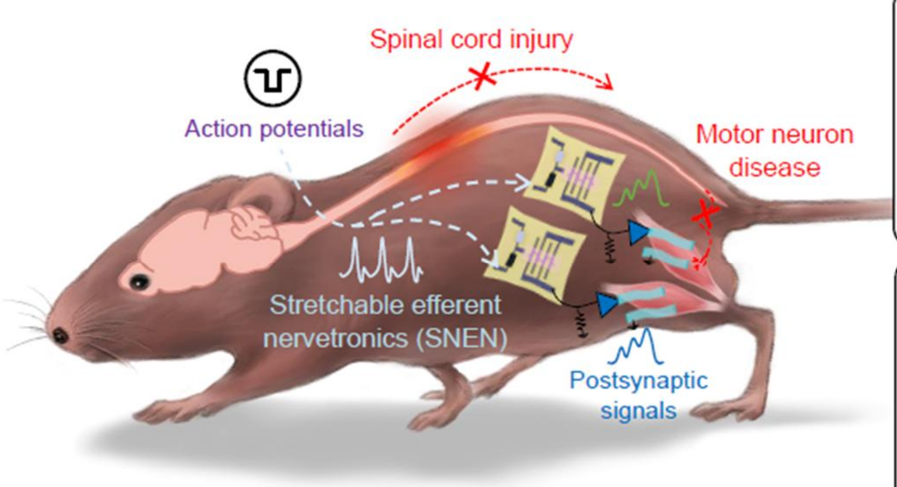


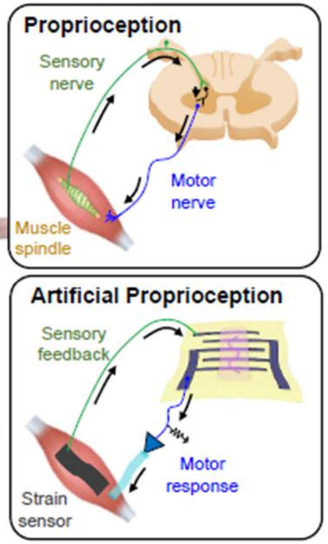
Moving of hind limb of mouse with spinal cord injury

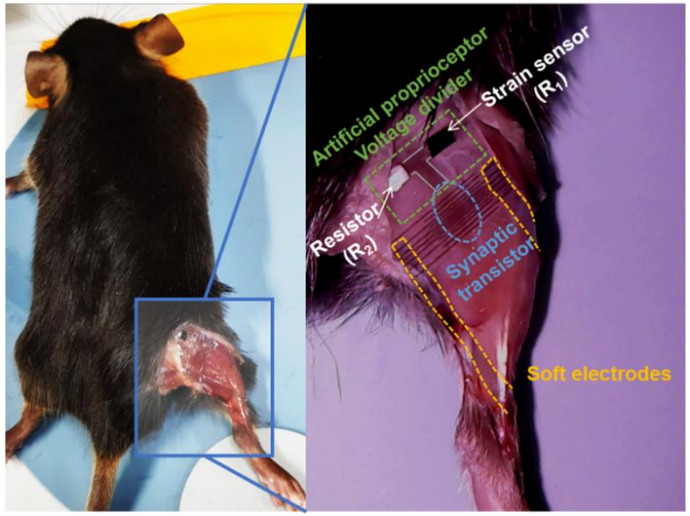
Y. Lee+, Y. Liu+, D.-G. Seo+, Z. Bao*, T.-W. Lee* *et al, Nat. Biomed. Eng.*, ***2022,*** doi:10.1038/s41551-022-00918-x

Neuromorphic prosthetic nerve

✓ ***Organic neuromorphic prosthetic nerve for biomedical engineering***







anesthetized

Neural signals

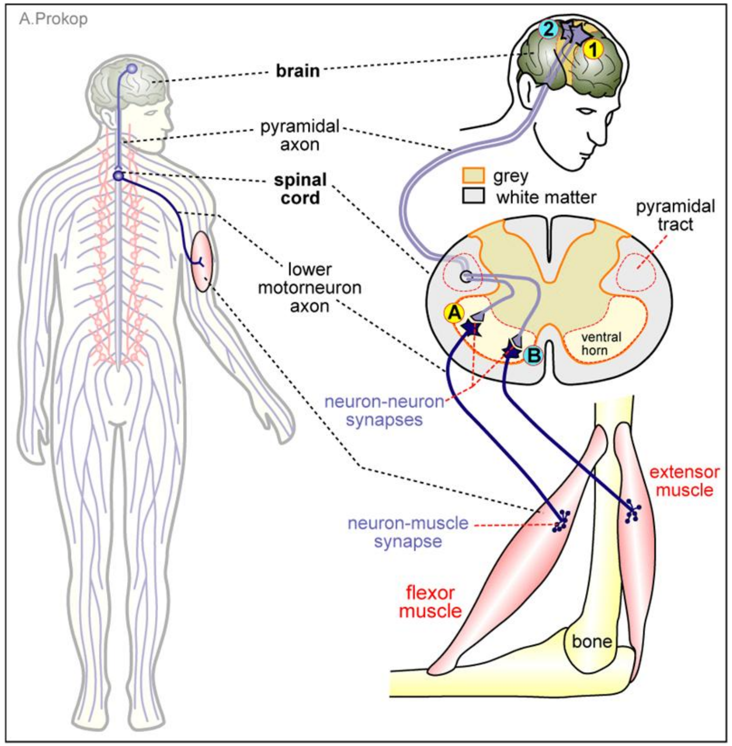
Spinal Cord Injury (SCI)
Motor Neuron Disease (MND)

Neuromorphic
Artificial Nerves

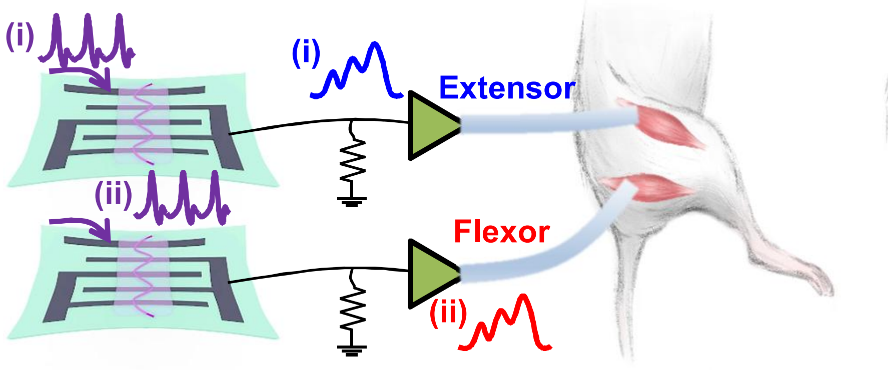
Muscle contraction

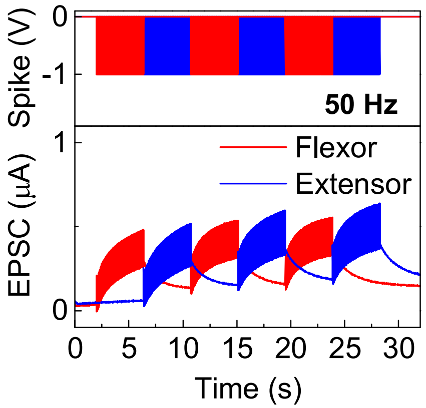
Y. Lee+, Y. Liu+, D.-G. Seo+, Z. Bao*, T.-W. Lee* *et al, Nat. Biomed. Eng.*, ***2022,*** doi:10.1038/s41551-022-00918-x

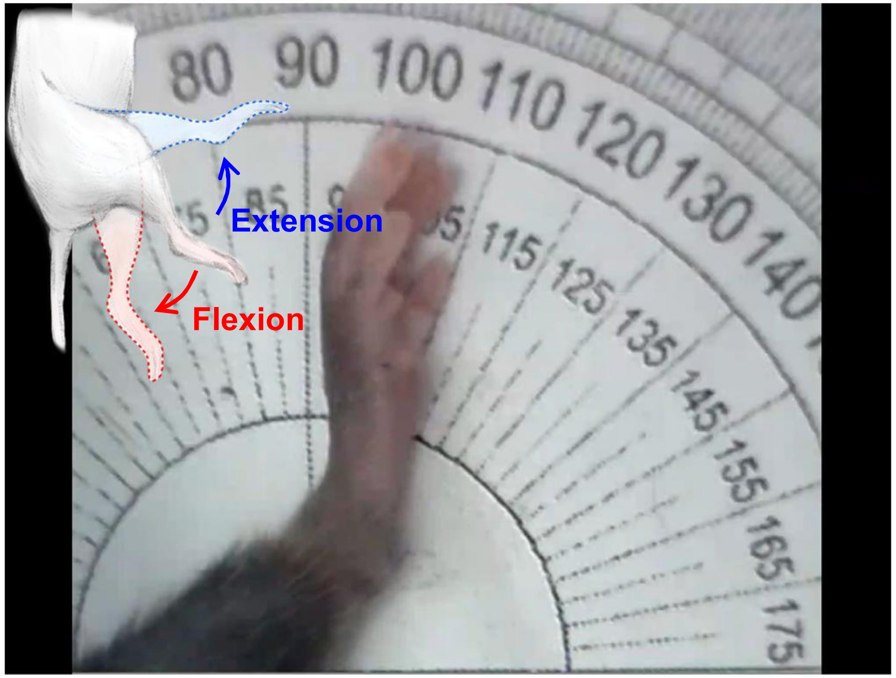
Coordinated motions – Flexion and Extension



✓ ***Alternating stimulation of muscles***



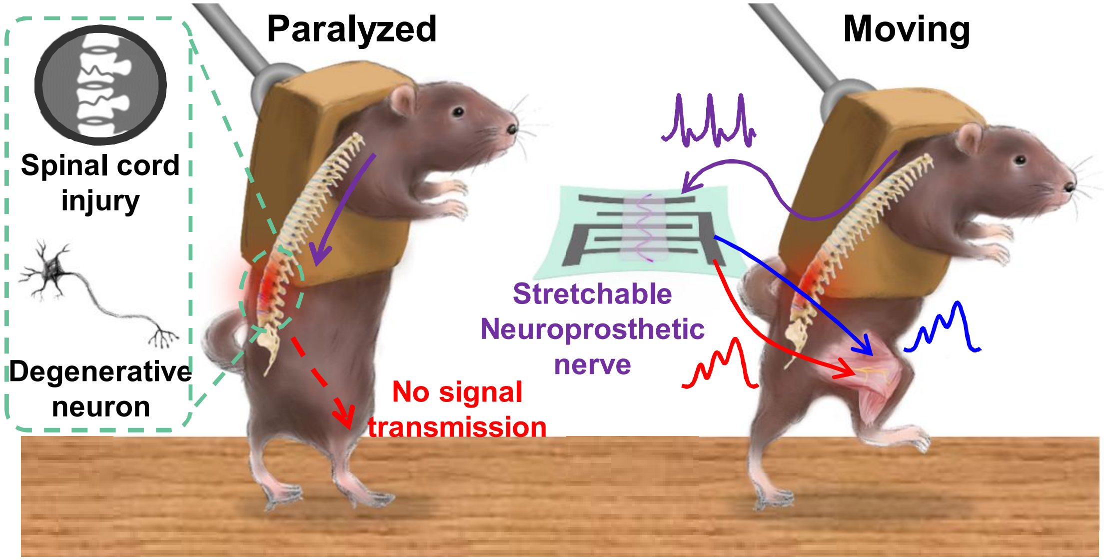


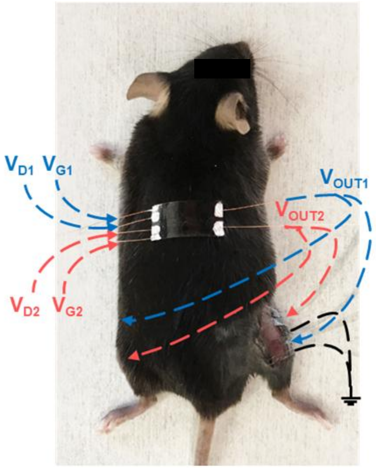


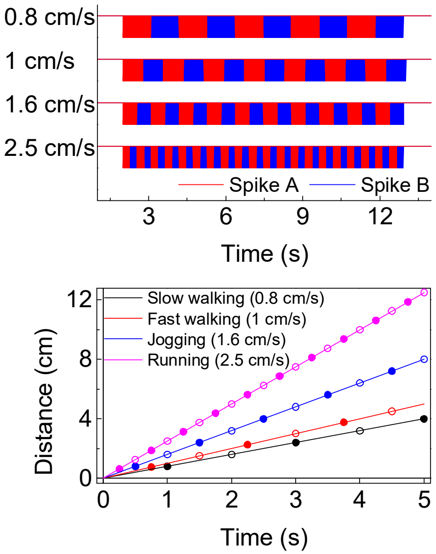
Y. Lee+, Y. Liu+, D.-G. Seo+, Z. Bao*, T.-W. Lee* *et al, Nat. Biomed. Eng.*, ***2022,*** doi:10.1038/s41551-022-00918-x

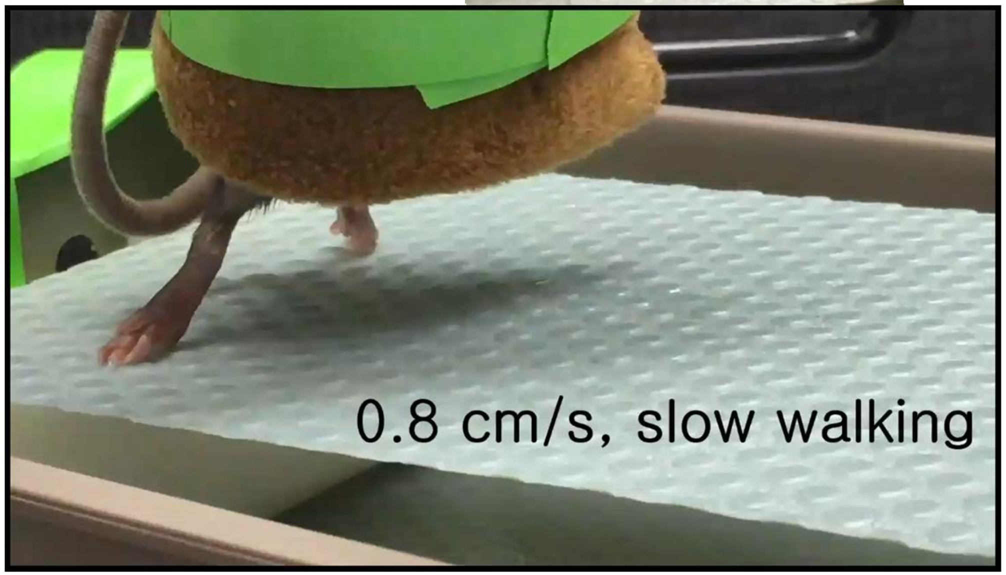
Coordinated motions – walking and running

Bipedal walking with SNEN









Y. Lee+, Y. Liu+, D.-G. Seo+, Z. Bao*, T.-W. Lee* *et al, Nat. Biomed. Eng.*, ***2022,*** doi:10.1038/s41551-022-00918-x

Contents

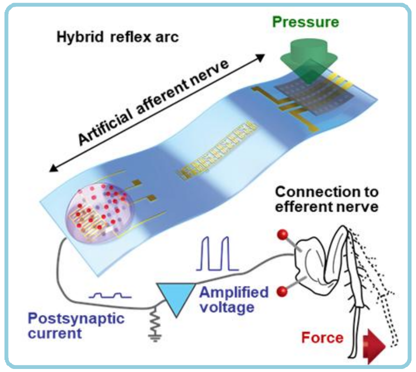
Future Plan Roadmap

2019

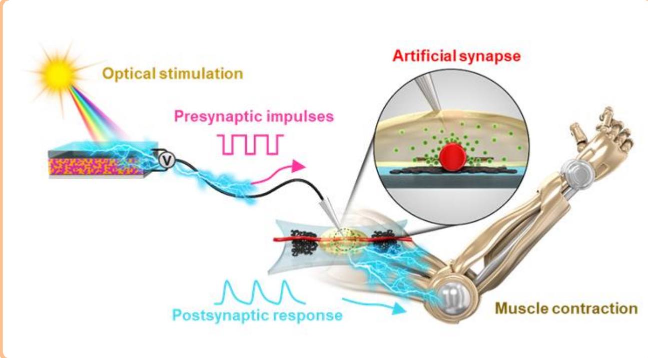
2029

2039

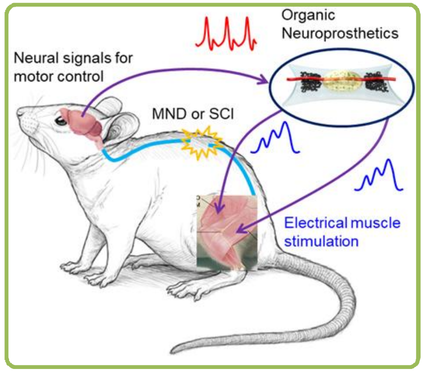
Artificial Sensory Nerves

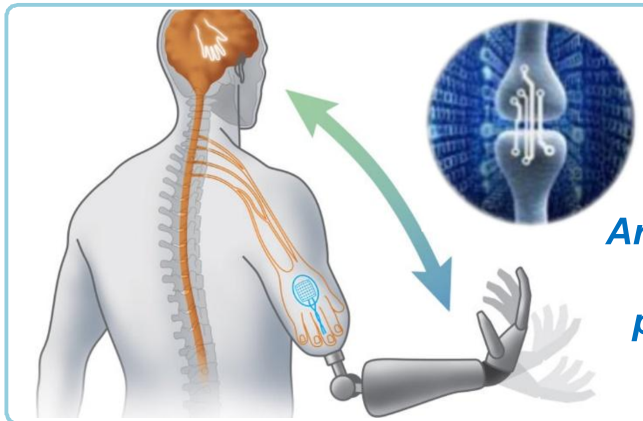


Robotic Motor Nerves



Neural prostheses



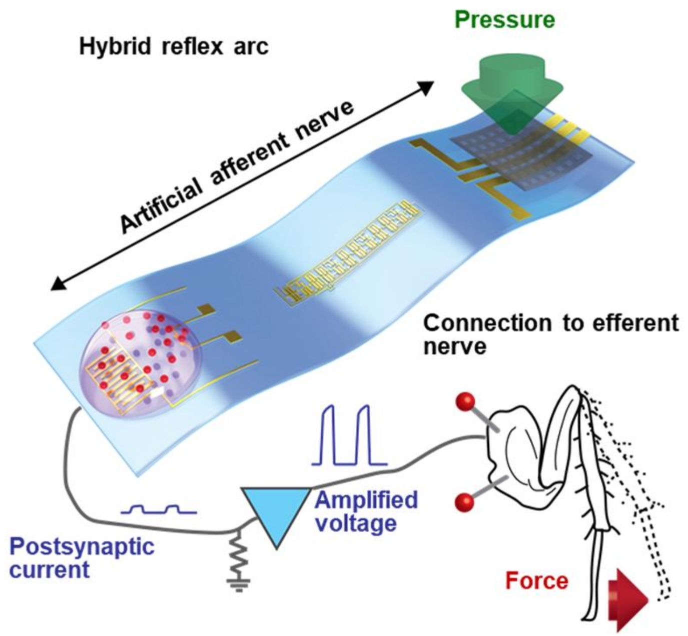


Artificial nerves for neural signals operating prosthetic sensory and motor limbs

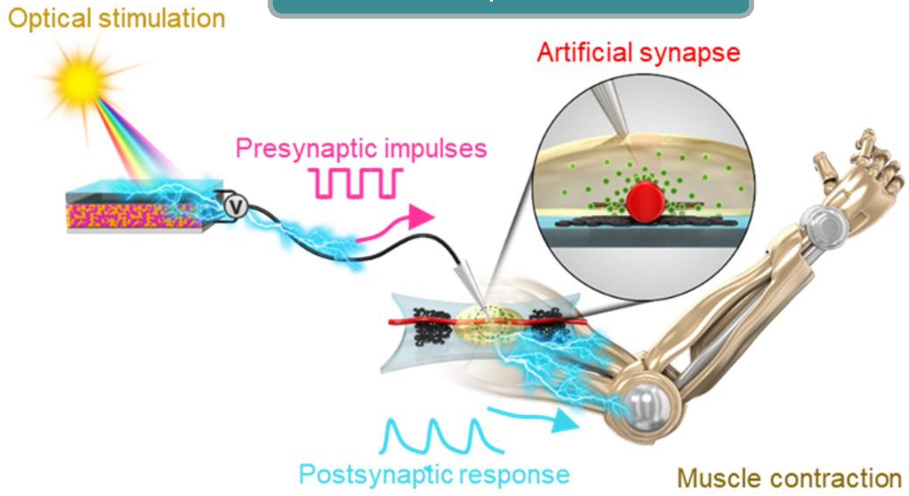
Neural bypass for degenerative neurons & synapses

Summary

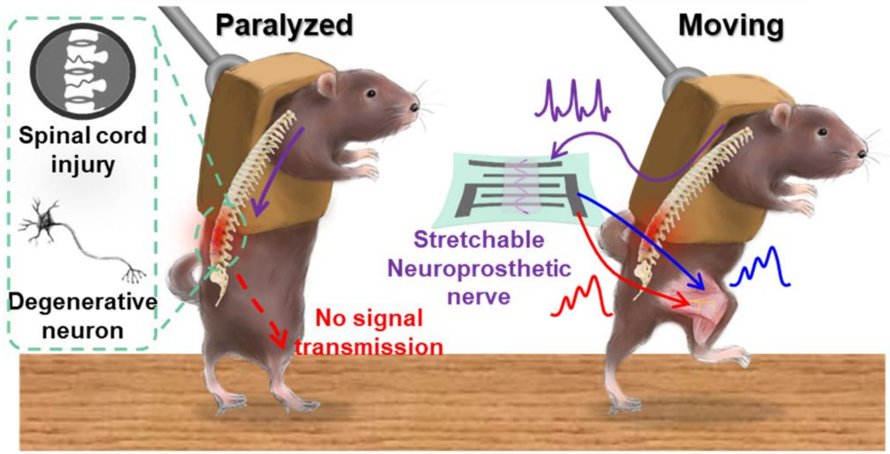
Artificial Nerve



Neuromorphic Robotics



Neuromorphic Neuroprosthetics



- **Development of a flexible/stretchable artificial synapse and a novel bio-inspired sensory nervous systems.**
- **Promising strategy to advance soft electronics, neuroprotheses, and neuro-inspired robots.**

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