CSE599E Brain-Computer Interfaces, Spring 2006

Development of a neural prosthesis for motor rehabilitation

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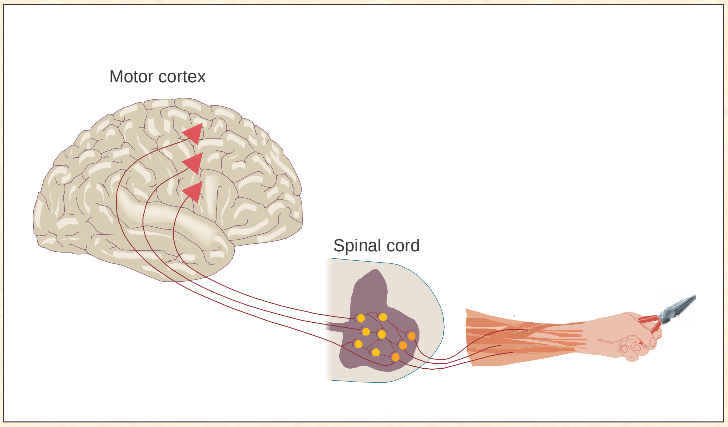
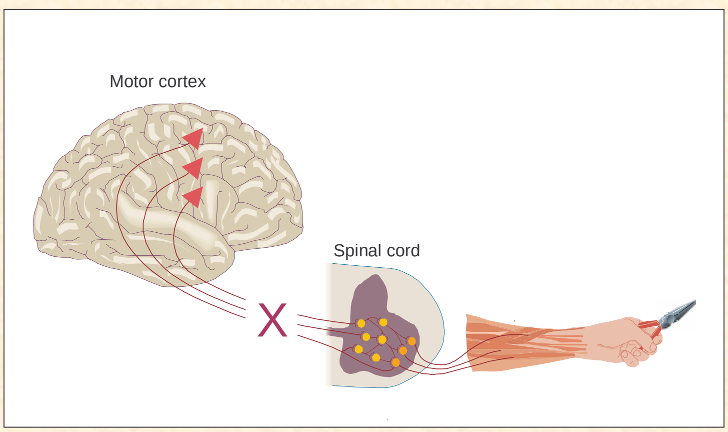
Spinal Cord Injury (SCI) statistics:

- 250,000 patients in the US.
- 11,000 new cases per year.
- Over half of new cases involve partial or complete quadriplegia.
- Causes: vehicle accidents (47%), falls (23%), violence (14%), sports injuries (9%).
- Highest rate of injury between 16 – 30 y/o.
- Life expectancy 55 – 70 y/o.
- Lifetime cost of care $1 – 3 million per patient.
- Regaining arm and hand function considered the highest priority amongst quadriplegic patients (Anderson, 2004).

A neural prosthesis for SCI:



A neural prosthesis for SCI:



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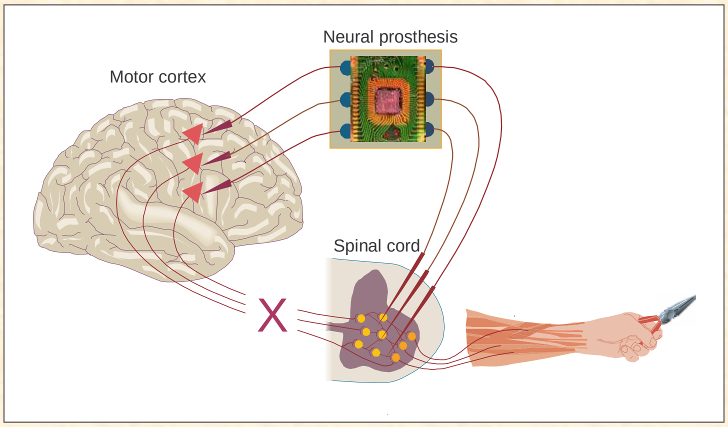

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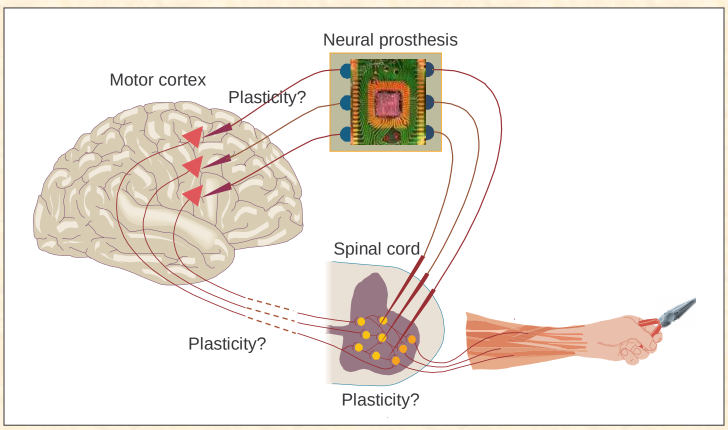

Overview:

1. Description of Neurochip BCI technology (Jaideep Mavoori)
2. Recording motor cortex activity during free behavior
3. Movements elicited by microstimulation of the spinal cord (Chet Moritz)
4. Motor cortex plasticity induced by the Neurochip BCI
5. Future directions

Neurophysiological experiments on unrestrained primates:

Photo courtesy of UW PWB program

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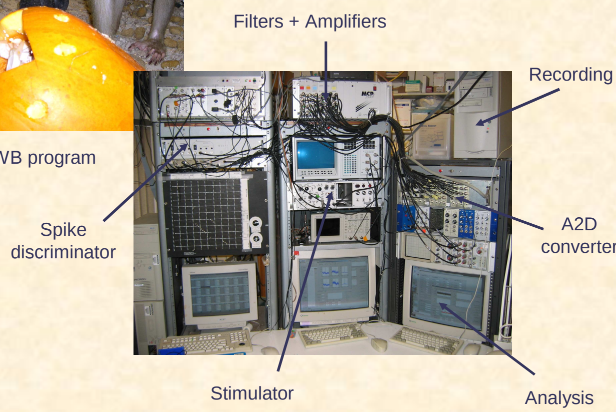
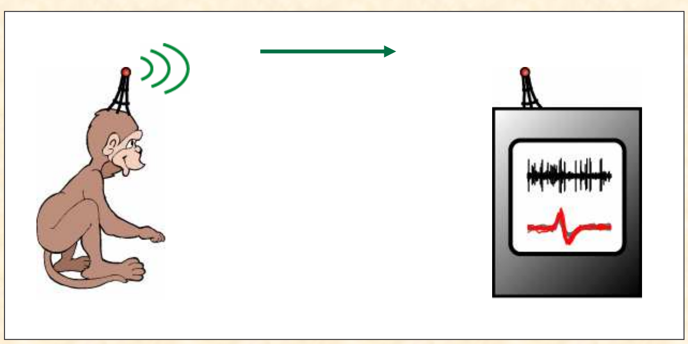
Photo courtesy of UW PWB program



Option 1 - Telemetry systems:



- high power consumption
- limited range

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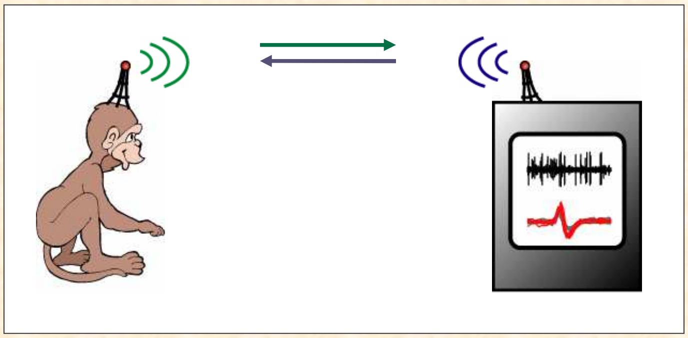
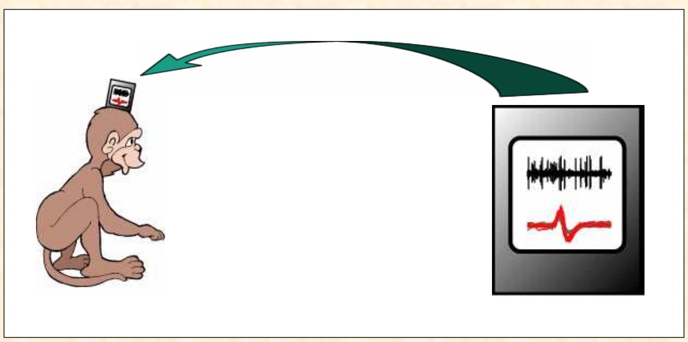


- high power consumption
- limited range
- transmission delays

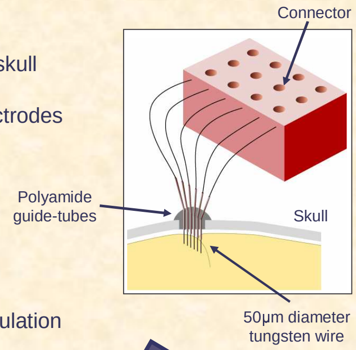
Option 2 - Implantable microelectronics:

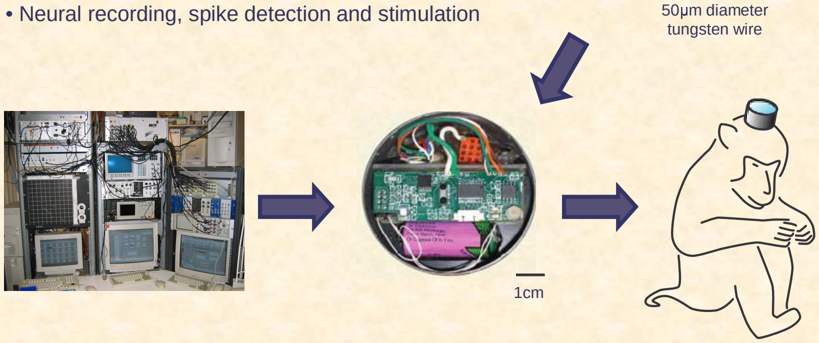


- autonomous operation
- low power
- limited processing capability

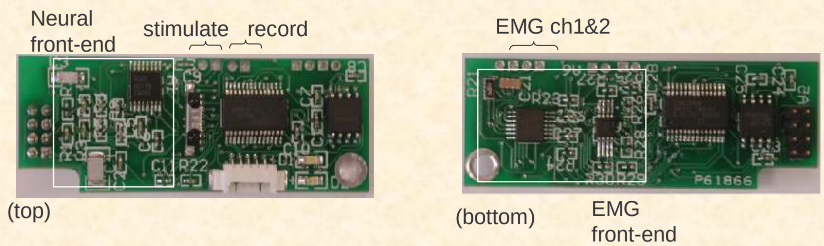
Neurochip BCI:

- 6cm diameter titanium casing fixed to the skull
- 12 independently moveable microwire electrodes
- Battery lifetime approx. 40hrs
- 16 Mb onboard memory
- IR communication with PC or PDA
- Neural recording, spike detection and stimulation



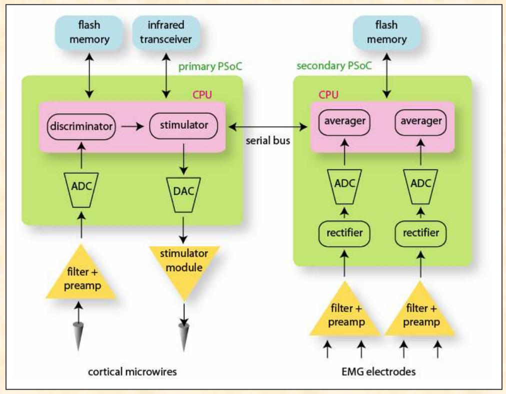


Neurochip BCI electronics:



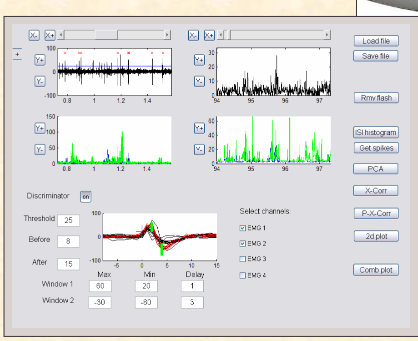
Neurochip BCI architecture:

- Two Cypress Programmable System-on-Chips (PSoCs)
- Front-end signal processing (filtering, DC offset + amplification)
- Neural signal sampled at 12ksp/s
- 2 EMG signals sampled at 2.7ksp/s
- Real-time spike discrimination
- Spike rate and mean rectified EMG compiled for user-defined timebins
- 2 x 8Mb non-volatile FLASH memory
- Biphasic, constant-current stimulator (±15V, ~100μA)
- Infra-red RS232 link to PC or PDA



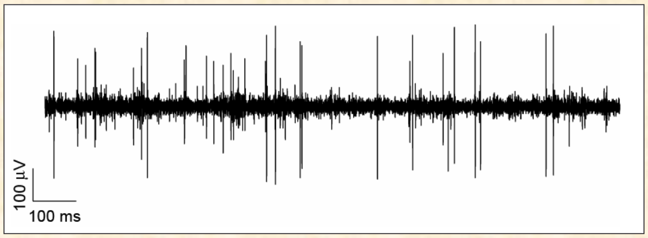
Neurochip BCI interfaces:

PDA (Lyme) ⟶



⟵ PC (MatLab)

Spiking activity recorded from M1:



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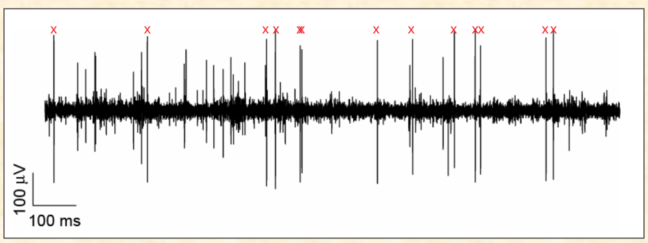
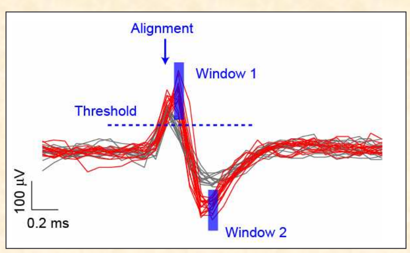
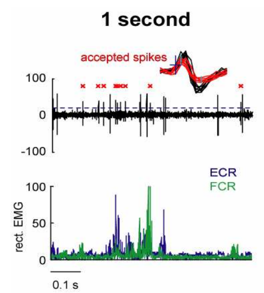


Dual time-amplitude window discriminator



M1 and muscle activity during natural behaviour:



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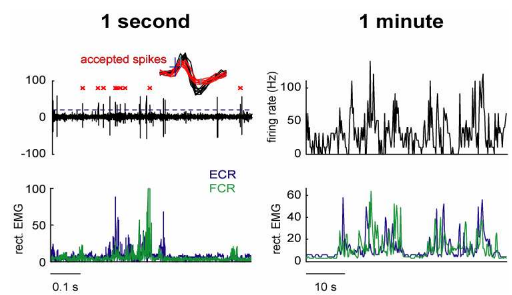

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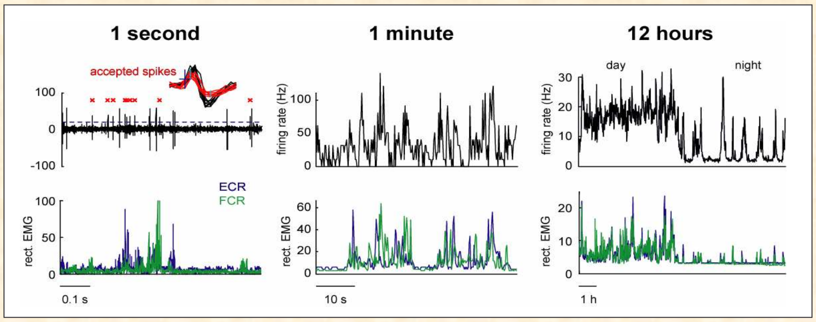
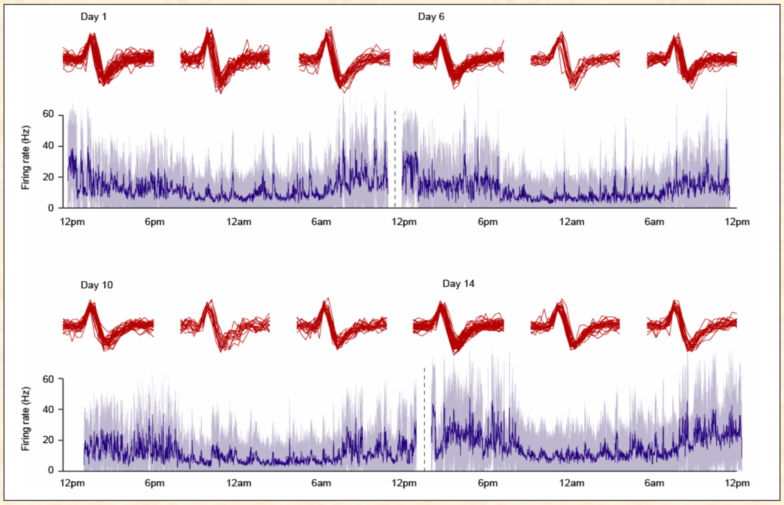


Long-term recording of cell activity:



Continuous recording of a single M1 neuron for 2 weeks.

A little detour …
Other Biological Models

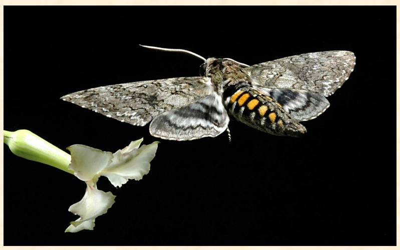


Photo courtesy of Armin Hinterwirth

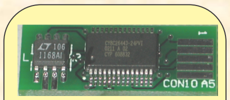
Daniel lab

Photo courtesy of UW PWB program

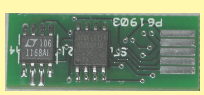
Fetz lab

Moth-chip Prototypes

1st Generation



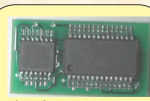
(top) 1cm



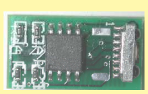
(bottom)

1cm x 3cm x 0.5cm
1.47g (without battery)

2nd Generation



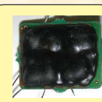
(top) 1cm



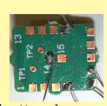
(bottom)

1cm x 1.9cm x 0.4cm
0.85g (without battery)

3rd Generation



(top)



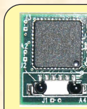
(bottom)

1cm x 1.25cm x 0.25cm
0.25g (without battery)

4th Generation

0.9cm x 1cm
0.6g (no battery)

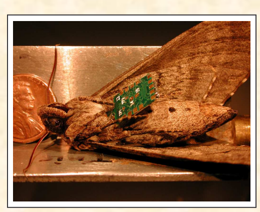
5th Generation

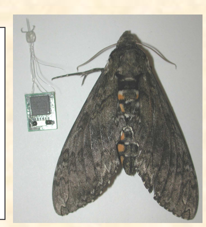


(top)

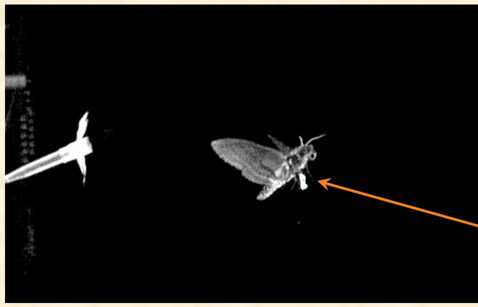
(bottom)

1cm x 1.27cm
0.42g (no battery)



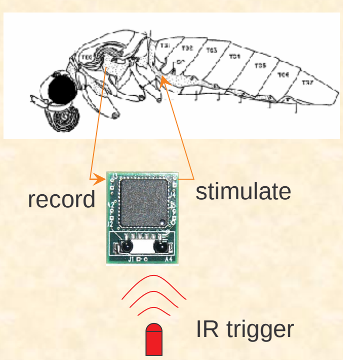


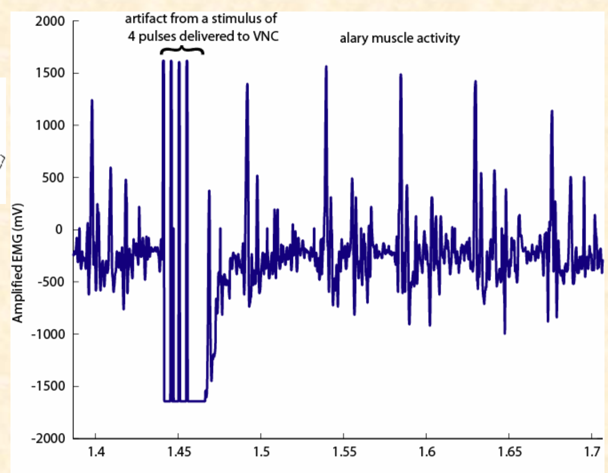
A Moth-portable Chip



Generation 3
moth chip

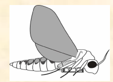
A Multi-tasking Chip



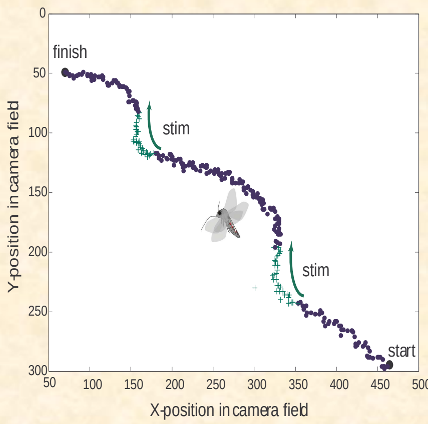


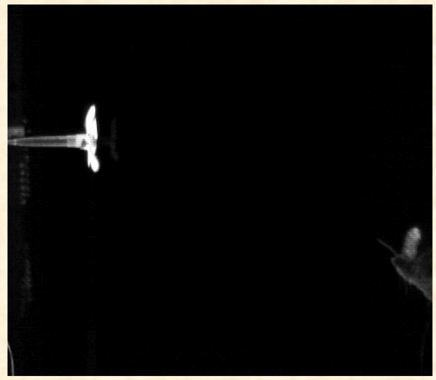
Mavoori, Millard, et al
IEEE BioCAS 2004

In-Flight Stimulation



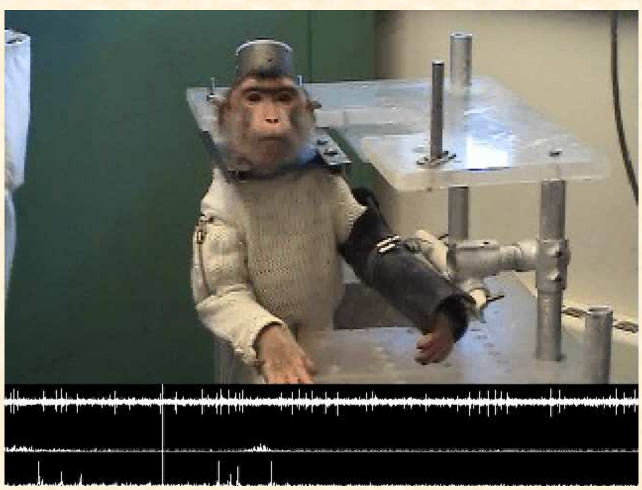
Stimuli: 1ms pulse @ 100Hz





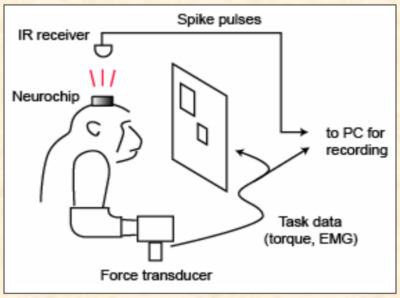
Mavoori, Millard, et al
IEEE BioCAS 2004

Back to primates …

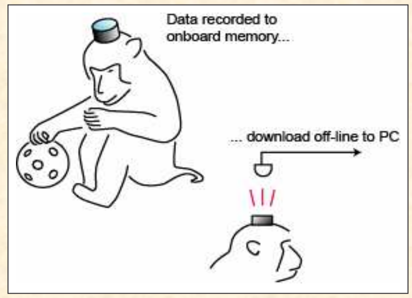


Two paradigms for studying the neural control of movement:

Trained task



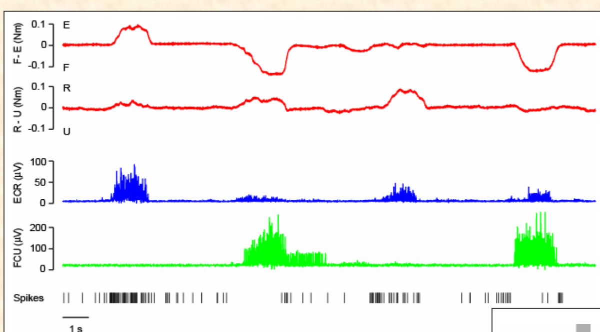
Free behavior



- Controlled, repeated behavior
- Decoupling of muscle synergies (methodologically advantageous)
- Unnatural movements
- Artificial restraint
- Limited relevance for neuromotor prosthesis

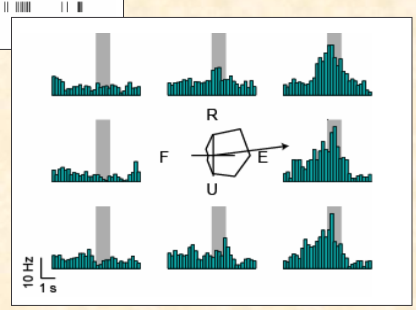
- Uncontrolled behavior
- Synergistic muscle use (methodologically problematic)
- Natural movements
- No restraint
- Relevant for neuromotor prosthesis to restore full range of movements

Conventional task-based experiment:

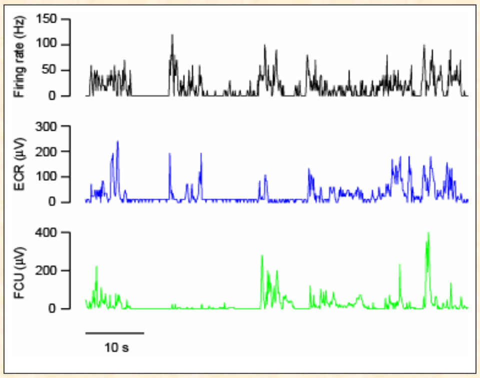


Torque traces, EMG and cell activity during a center-out wrist tracking task.

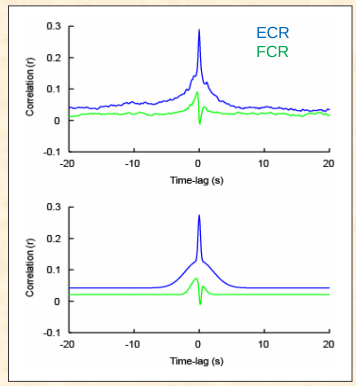
Peri-event time histograms for each target direction can be used to determine the preferred direction of a cortical cell (in this case extension).



Free behavior experiment:

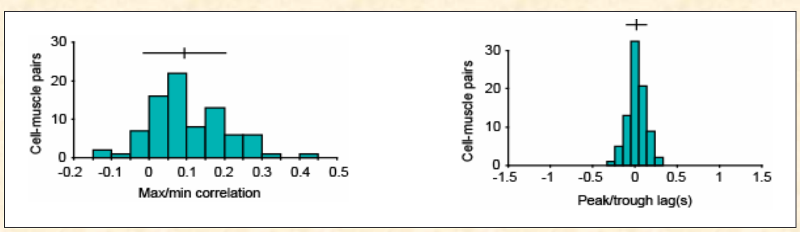


Spike rate and EMG activity during free behavior captured by the Neurochip BCI.

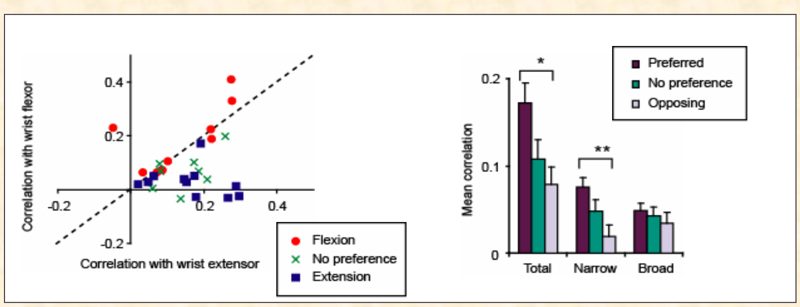


Cross-correlation functions reveal positive and negative relationships between cell firing rate and muscle activity over a range of time-scales.

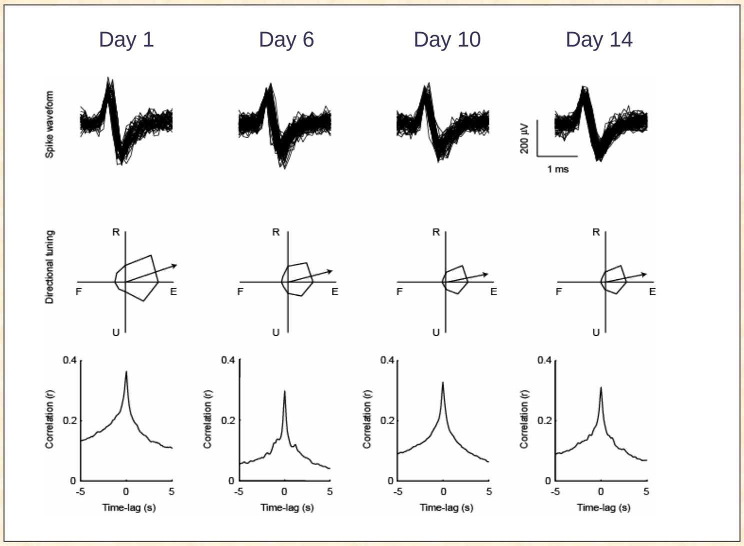
Summary of cross-correlation peaks/troughs:



Relationship between task and free behavior:



Long-term stability of cell recordings:



Summary (1):

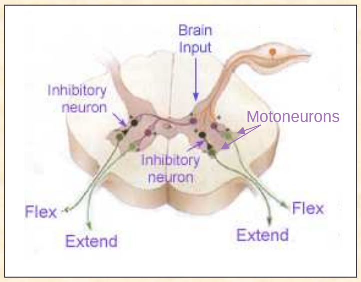
• Using the Neurochip BCI we recorded the activity of motor cortex neurons and muscles during a trained task and free behavior.

• During the trained task many cells exhibited directional tuning, firing maximally for torque responses in the preferred direction.

• During free behavior, motor cortex cell activity was robustly correlated with muscle activity across the repertoire of natural movements. Correlations were stronger with muscles which acted in the preferred direction of the cell as defined by task activity.

• The strength and stability of cell – muscle correlations suggests that neural prosthetics approaches may be successful in restoring a wide range of natural movements.

Intraspinal microstimulation (ISMS)



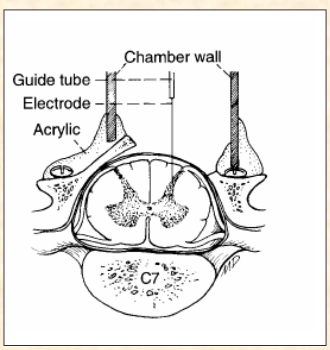
• Trains of low current, biphasic current pulses delivered to motoneurons in the intermediate zone and ventral horn of the spinal cord can activate muscles and elicit movements.

• Techniques for implanting electrodes for chronic stimulation have been developed in the cat lumbar cord by a group in Alberta (Mushahwar and Prochazka).

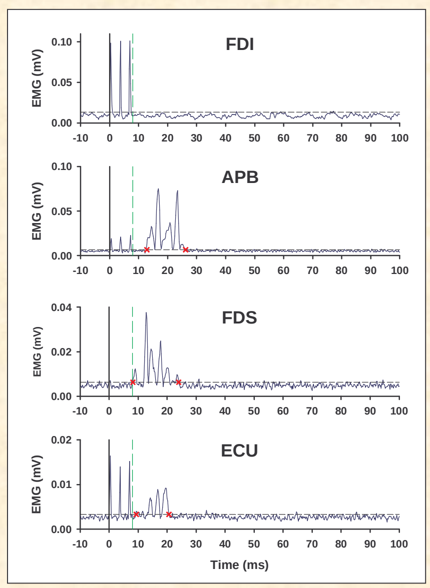
• The responses to cervical spinal cord stimulation are less well studied. The Old World Macaque monkey is a good model for the human upper-limb function.

• The cervical spinal cord may be a good target for functional electrical stimulation to restore upper limb movements due to it's small size and mechanical stability. Recruitment of local spinal networks may elicit coordinated muscle synergies.

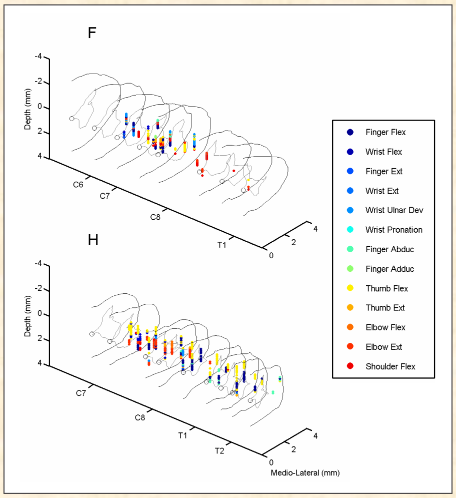
Mapping responses to cervical ISMS:



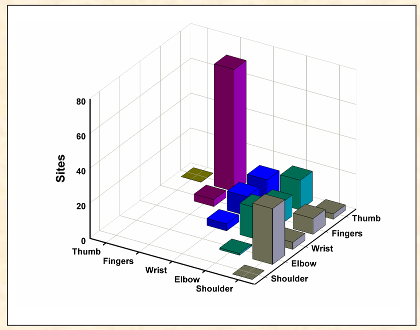
Responses to three pulses of ISMS were mapped in anesthetized monkeys using a recording chamber covering a C4 - C7 laminectomy. EMG profiles were documented at movement threshold (10 – 80 μA).



ISMS elicits muscle and movement synergies:

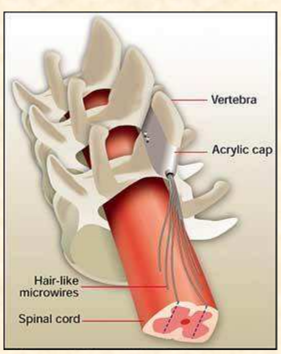


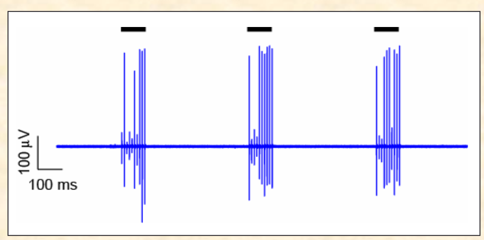
Multiple muscles and movement synergies are activated by low current stimulation at sites distributed through a small region of cervical spinal cord. No apparent topography is evident.



ISMS with chronically implanted microwire electrodes:

Method for chronically implanting microwires in the monkey cervical spinal cord adapted work on cat lumbar cord in Alberta.





EMG responses in muscle AbPB to trains of stimuli through chronically implanted cervical microwire electrode eliciting a thumb twitch.

Prochazka, Mushahwar & McCreery, *J Physiol* (2001)

Summary (2):

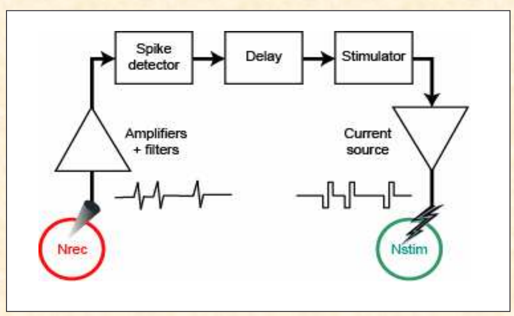
• Low current intraspinal microstimulation (ISMS) of cervical spinal cord elicits arm and hand movements involving multiple synergistic muscles.

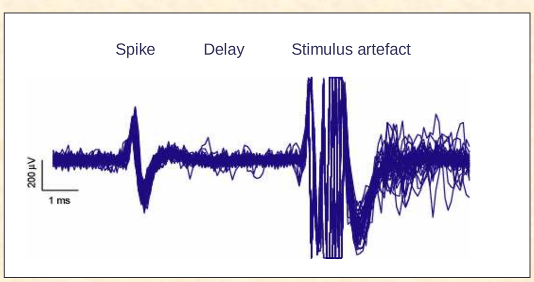
• Unlike the motor cortex, no topographic organization of output effects is evident.

• Stimulation through chronically implanted microwires may be used to restore a range of movements following SCI.

A simple Prosthetic Neural Connection:

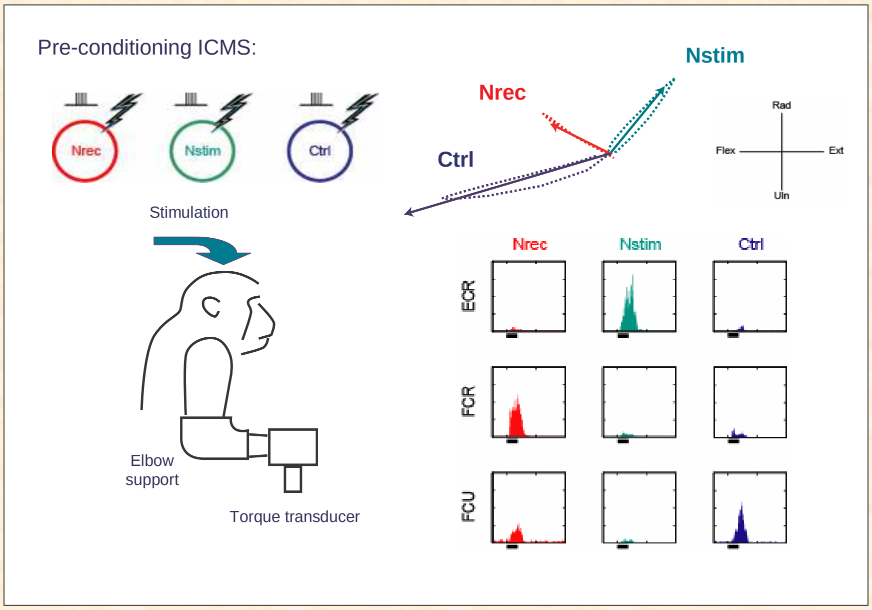
Spikes recorded at the Nrec electrode trigger stimuli delivered to the Nstim electrode after a pre-defined delay.



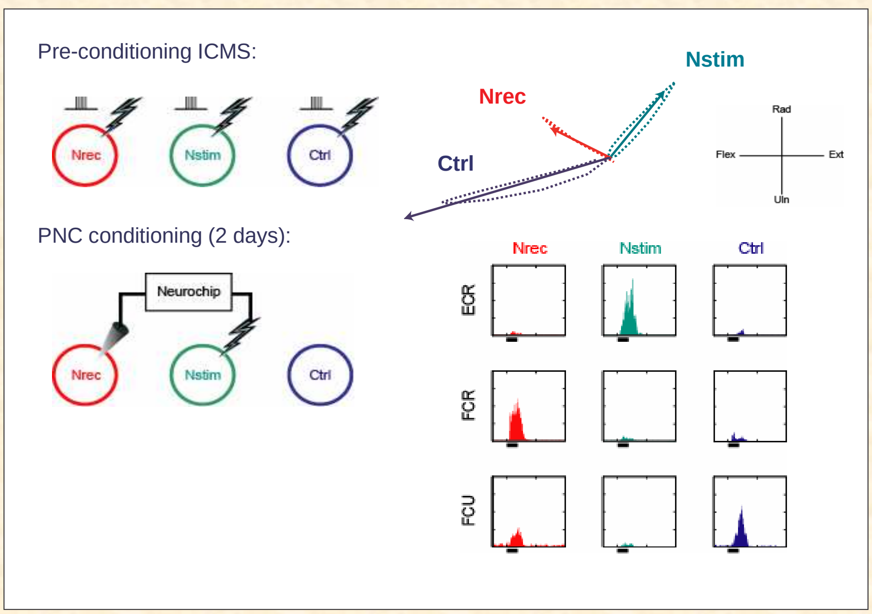


Recording from Nrec electrode shows spike and stimulus artifact.

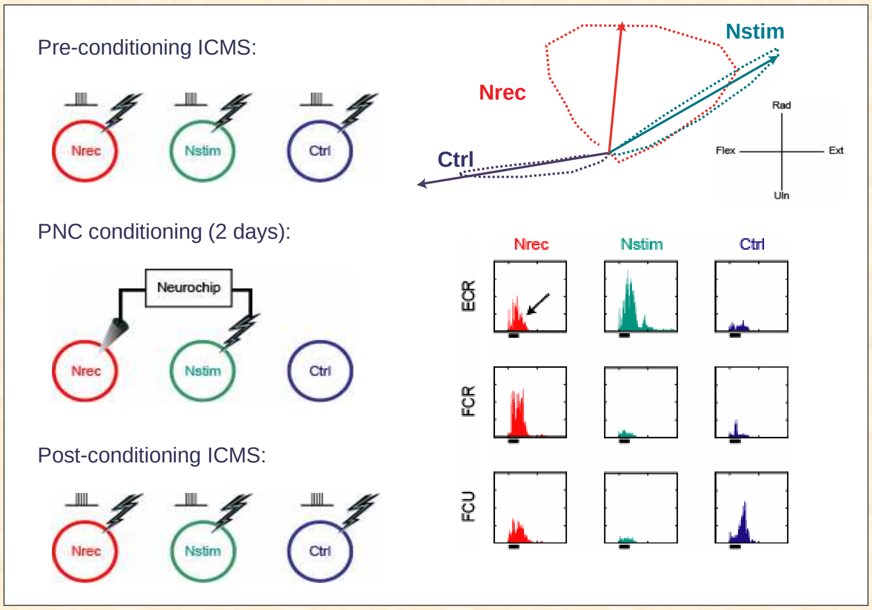
Intracortical microstimulation (ICMS) mapping of motor output:



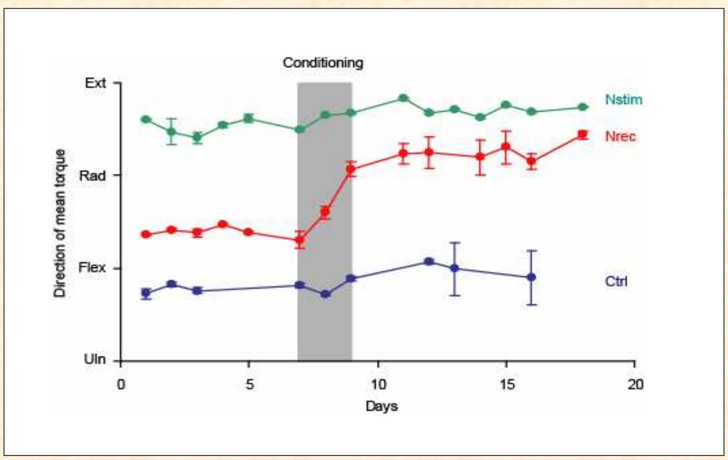
Conditioning with an artificial connection:



Post-conditioning ICMS mapping:



Long-term stability of conditioning effects:



Modified cortical output persists for over 1 week post-conditioning

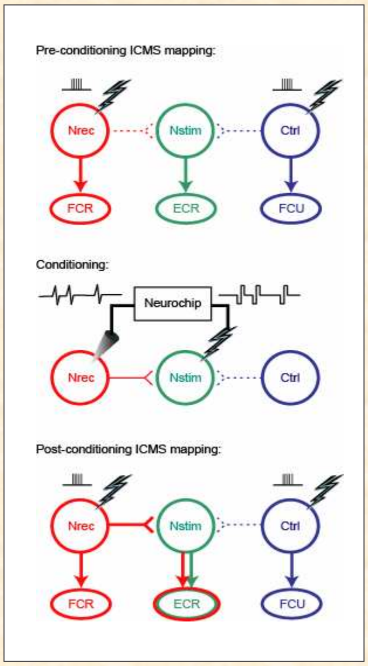
Hebbian plasticity:

When an axon of cell A is near enough to excite B and repeatedly or persistently takes part in firing it, some growth process or metabolic change takes place in one or both cells such that A's efficiency, as one of the cells firing B, is increased.

(Hebb, 1949)

Motor remapping caused by Neurochip conditioning can be explained by a timing-dependent Hebbian strengthening of pathways between Nrec and Nstim or downstream sites.

Plasticity mechanism may be related to spike-timing dependent plasticity (STDP) described in cortical slices, but here between populations of synchronously active neurons.



Summary (3):

Using spiking activity at one electrode to trigger stimuli delivered to another, the Neurochip can act as a simple artificial connection between sites.

• Continuous operation of artificial connections induces a stable reorganization of motor cortex, with the motor output at recording sites shifting towards the output at stimulation sites.

• Remapping is consistent with a timing-dependent Hebbian plasticity mechanism. Plasticity induced by a neural prosthetic may have application for rehabilitation following motor injuries such as stroke and incomplete spinal cord injury.

Future directions:

• Further development of the Neurochip BCI for multiple channels of recording and stimulation.

• Investigate neural activity in other motor areas (premotor cortex, supplementary motor area) during free behavior.

• Control of intraspinal microstimulation by cortical recordings using the Neurochip BCI.