Closed-Loop Cortical Control of Intraspinal Microstimulation to Restore Volitional Upper-Limb Function

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Targeting Recovery: Priorities of the Spinal Cord-Injured Population

KIM D. ANDERSON
The importance of non-human primates

Neural recording using a Neurochip

1 second

Jackson et al., *JNP* (2007)
Towards an artificial neural implant for spinal cord injury

An autonomous electronic implant such as the Neurochip could act as an artificial pathway from the cortex to the spinal cord in order to restore upper-limb function after injury.
**Intraspinal microstimulation (ISMS)**

*While BMIs have been used to control robotic limbs, spinal cord injury patients want control of their own limbs! However, restoring movements to the human arm and hand remains a considerable challenge…*

- 34 muscles act synergistically on the human hand. Many are small and inaccessible. Neighbouring muscles often have very different actions on the hand.

- Functional Electrical Stimulation (FES) of many hand muscles would require extensive, difficult surgery and implants would be at risk of mechanical failure.

- Intraspinal microstimulation below the injury may provide a means to activate all upper-limb muscles from a single implant site in the cervical enlargement (Moritz et al. *J Neurophysiol* 2007).


*Can ISMS generate functional movements of the primate upper-limb?*
Open-loop ISMS produces functional reach and grasp

Stimulation delivered to just two spinal electrodes the cervical spinal cord of an anesthetised monkey can to produce functional reach and grasp movements.
Open-loop ISMS produces functional reach and grasp

Stimulation delivered to just two spinal electrodes the cervical spinal cord of an anesthetised monkey can to produce functional reach and grasp movements.
Graded sinusoidal grip force produced by open-loop ISMS

Zimmermann, Seki & Jackson, JNE (2011)
Towards a chronic spinal microelectrode implant

Floating Microelectrode Array (Microprobe Inc.)

FMA implant in monkey cervical enlargement.
Towards a chronic spinal microelectrode implant

<table>
<thead>
<tr>
<th>Channel</th>
<th>Current (µA)</th>
</tr>
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<tbody>
<tr>
<td>Ch 3</td>
<td>10</td>
</tr>
<tr>
<td>Ch 4</td>
<td>5</td>
</tr>
<tr>
<td>Ch 6</td>
<td>5</td>
</tr>
</tbody>
</table>

- 1DI
- APB
- FDS
- FDP
- FCU
- ECR

3 µV

10 ms

Threshold current (µA)

Working electrodes (%)

Days post-implant
Testing a neural prosthesis for closed-loop cortical control of ISMS

Ventral premotor cortex (PMv) → Primary motor cortex (M1) → Spinal cord

Neural prosthesis

Muscimol

Graphs:
- Lift (cm) vs. Time (s)
- Trial Number vs. Time (s)
- Rate (Hz) vs. Time (s)

Legend:
- hand/fingers
- arm/elbow
- mouth/face
- no response

Scale: 1 cm

Diagram:
- PMv
- AS
- CS

Muscimol injection site

X1
Closed-loop cortical control of ISMS

Restoring Hand Function
Using Spinal Cord Microstimulation

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Closed-loop cortical control of ISMS (Monkey 1)

Stimulation at 30µA controlled by a single PMv neuron.

Bursts of PMv activity in absence of stimulation indicate the monkey’s unsuccessful efforts.

However, even without stimulation the monkey can sometimes perform task successfully.
Closed-loop cortical control of ISMS (Monkey 2)

Stimulation at 50µA controlled by a single PMd neuron.

Bursts of PMv activity in absence of stimulation indicate the monkey’s unsuccessful efforts.

However, even without stimulation the monkey can sometimes perform task successfully.
Improved task-related EMG activity

Monkey 1

- APB
- FDS
- FCU

EMG
50μV

1 DI

EMG
2 μV

FDP

ECR

1 s

With Stimulation

Without Stimulation

Normal

Monkey 2

- APB
- FDS
- FCU

EMG
2 μV

1 DI

EMG
2 μV

FDP

ECR

1 s
Summary

1. Cervical intraspinal microstimulation elicits co-ordinated patterns of muscle activity and can produce functional movements of the upper-limb including reaching and grasping.

2. Closed-loop cortical control of intraspinal microstimulation can restore volitional modulation of EMG patterns and improve performance of a simple grasp task.

3. These simple closed-loop intraspinal microstimulation algorithms could be implemented by an autonomous electronic implant (Neurochip). Such a system could act as an effective neural prosthesis for patients with spinal cord injury but...

4. ...there are still many issues yet to resolve:
   - Long-term stability of electrodes
   - Range of movements that can be restored
   - Efficacy with absent/altered proprioceptive feedback
   - Utility of ISMS in chronic injury model
   - Beneficial or adverse plasticity arising from long-term use
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