Synchrony in the motor system and control of skilled hand movements

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THE HAND: culture, amusement, craft, technology, medicine….  

Stroke: UK: 100,000 new cases per year, 50% have hand disabilities  

Cerebral Palsy: UK: 1800 new cases per year
Corticospinal System

- Corticospinal tract originates from widespread sensorimotor cortical areas
- Corticospinal neurons make direct monosynaptic connections with motoneurons, especially digit muscles
- These neurons are particularly active during skilled hand tasks
What does the cortico-motoneuronal (CM) system contribute to skilled hand control?

Focused control of muscles

- CM cells facilitate EMG activity in a focused group of muscles: the “muscle field”
- Probably reflects terminal arborisation of single CM axons
- CM cells can also exert profound post-spike suppression: suppressing unwanted muscular activity
What does the cortico-motoneuronal (CM) system contribute to skilled hand control?

CM cell muscle fields reflect functional synergies

- First dorsal interosseous (1DI)
- Flexor digit. profundis (FDP) (tendon)
- Adductor pollicis (AdP)

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Why study synchrony in the motor system?

- Oscillatory activity is widespread in the CNS

- In motor cortex oscillations occur at different frequencies
  
  alpha 8-12 Hz

  beta 15-30 Hz

  [gamma 40-80 Hz]

- Oscillations occur in task-related manner

- Effect of oscillations measurable in motor output

- Oscillations can encode specific motor parameters

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Transmission of synchronous activity through cortical networks

- convergence and divergence within a network
- weak synaptic connections between individual neurons
- this reduces probability of transmission of asynchronous activity, but enhances transmission of synchronous activity
- thus although synchrony may not increase the information content in the brain, it may be an important mechanism for transmitting information in a cortical network

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The precision grip task: humans and monkeys

- initial grip movement
- steady hold for ~ 1s
- release

Digit position

Digit muscle EMG

CM cell spikes: single unit

Local Field Potential: population activity
Evidence for different types of synchrony in the motor cortex

• short-term synchrony (‘synfire’)
  correlation peaks < 3 ms

• medium-term synchrony
  correlation peaks > 3 ms
  (typically 10-20 ms)
  occurs in at least two forms:

  Non-oscillatory
  (stochastic)

  Oscillatory

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Synchronous activity across a population of macaque motor cortex output neurons

16 electrode recording probe

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Baker et al JNP 2001
Getspike: a sophisticated means of converting analogue action potential spikes into digital events……

Extracellular action potentials

Interspike interval histograms

Principle component analysis

200 µV

1 ms

10 ms

100 ms

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Antidromic activation/activity patterns of CM cells

CM neuron 1

CM neuron 2

Spikes

Collision test

Interval histogram

Activity during task
Synchronous interactions between corticospinal neurons

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Baker et al JNP 2001
Cross-correlations must be corrected for task-related coactivation

Baker et al. 2000

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Population data: firing rate and synchrony show different task relationships during precision grip

- Most M1 neurons show a phasic burst (digit movement) followed by a tonic discharge (steady grip)

- Synchrony between neuron pairs is highest during the steady hold period

Baker et al JNP 2001

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Which cortical cells are synchronised together?
Correlation between pairs of CM cells

positive

negative

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Jackson et al
Neuron 2003
CM cells with positive synchrony have *similar* muscle fields

CM cells with negative synchrony have *opposing* post-spike effects
Type and strength of synchrony is related to the similarity of muscle field

- 114 CM cell pairs
- muscle divergence calculated from multidimensional vector:
  0°: perfect match
  90°: no overlap
  180°: opposite effect (facilitation vs suppression)
- neurones with heavily overlapping fields are strongly synchronised
- neurones with non-overlapping fields or exerting opposite actions do not discharge together
Double spike-triggered averaging: effects in STAs of the same muscle are not due to synchrony per se

Jackson et al., Neuron 2003

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Thus synchrony is greater between CM cells with similar muscles fields (A & B): these CM cells are actively recruited together.

CM cells with different muscle fields provide task-specific substrates for a wide repertoire of grasp types.
Oscillatory synchrony between cell pairs is pronounced during steady grip (hold phase)
15-30 Hz Local Field Potential activity in hold phase of precision grip task

Baker et al., 1997

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Does oscillatory activity include corticospinal neurons?

- Spike-triggered averages of the Local Field Potential from identified Pyramidal Tract Neurons (PTNs) shows that PTNs are phase-locked to the LFP oscillations.

- Activating many PTNs simultaneously can reset the phase of the ongoing oscillations.

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Can stimulation of the corticospinal tract reset the rhythm?

**Case A:** If the network generating 15-30 Hz oscillatory activity in the motor cortex involves corticospinal neurons, the LFP oscillations should be reset when the pyramidal tract is stimulated.

**Case B:** no reset occurs because corticospinal neurons are not part of the generating network.
A

movement onset

start of hold period

hold period stimulus

target limits

5 mm

finger

200 ms

thumb

B

1DI

LFP

C

Power Spectrogram of LFP

frequency (Hz)

power (µV^2)

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Corticospinal tract stimulus resets cortical rhythm

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15-30 Hz Local Field Potential activity in hold period of precision grip task

- LFP shows clear oscillatory activity in hold period, but not in movement phases (grip, release)

- LFP and EMG from contralateral hand muscles are phase-locked during the hold period
Coherence between cortex and muscle during steady grip

• “coherence” measures degree of phase-locking between oscillations in LFP and EMG

• Coherence in the 15-30 Hz frequency band is pronounced

• This coherence is present during steady grip, but abolished during movement

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Baker et al. 1997
Coherence in the beta frequency band

- between LFP and EMG
- between EMGs of different muscles

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Baker et al. 1997
Precision grip of a compliant/solid object in humans

Kilner et al., 1999
Coherence between cortical (MEG) and muscular activity during precision grip is also present in humans.
MEG-EMG coherence is related to the degree of object compliance

- coherence in the 15-30 Hz bandwidth shows no clear changes with force or displacement
- coherence in the 15-30 Hz bandwidth is most pronounced during grip of compliant objects
- coherence is least when solid objects are gripped

Influence of sensory inputs from the hand

• 15-30 Hz oscillations are generated centrally

• however, the variation in coherence with compliance suggests that sensory feedback from the hand can modulate the central rhythm

• cutaneous inputs from the finger tips (important for detecting level of grip force) are critical for handling compliant objects

• tested by examining effects on EMG-EMG coherence in volunteers with lignocaine block of digital nerves in the index finger and thumb
Digital nerve block reduces EMG-EMG coherence in the 15-30 Hz bandwidth

- pooled data (10 subjects)
- digital nerve block significantly reduces but does not abolish coherence
- suggests that during gripping tasks cutaneous feedback can boost centrally-generated oscillatory activity
15-30 Hz coherence is absent in a deafferented subject (GL)
CONCLUSIONS I

There is widespread synchrony in the 15-30 Hz range at the level of CELL POPULATIONS. This synchrony

• is coherent with contralateral EMG activity
• pronounced during periods of steady holding
• disappears during digit movement
• does not encode simple parameters: grip force/ displacement
• encodes control of more complex object properties such as compliance
• requires sensory input from the hand. Object “parameterisation”?
• could represent a ‘sensorimotor working memory’ important for maintaining steady grasp of everyday objects (food, tools etc)
CONCLUSIONS II

• during steady grasp populations of CM cells with similar muscle fields are *synchronised* together; this helps to sustain the ‘sensorimotor memory’ until a new manipulation is required

• CM cells with different muscle fields are the substrate of the many different possible types of grasp

• CM cells which exert opposite effects on a target muscle are actively de-synchronised

*Synchrony in the motor system plays a useful functional role during grasp and manipulation*