HOW TO SET UP A MOVEMENT CNP LAB

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DISCLOSURES

Financial Disclosures

- No financial relationships or conflicts of interest with any of the companies discussed
- Multiple companies were contacted for description of their hardware and software options, price estimates

Intellectual Disclosures

- Quantification > qualitative observation
- Splitting > lumping
- Invested time and resources learning to do movement CNP studies

OUTLINE

- Basic principles of movement CNP: terms, phenotypes, features
- Movement CNP components: hardware, signal processing, analysis
- Movement CNP system options

MOVEMENT CNP BASICS: TERMS

Basic terms

- ***Movement disorders***: abnormalities involving increased (hyperkinetic) and/or decreased (hypokinetic) movement which arise from disorders of the central nervous system, especially the basal ganglia, cerebellum, thalamus, and cortex
  - Impaired movement due to disorders limited to the peripheral nerves, muscle, or spinal cord are generally classified as neuromuscular disorders
- ***Clinical neurophysiology (CNP)***: a subspecialty of neurology focused on measuring bioelectric signals (both spontaneous and stimulated) to aid clinical evaluation
  - Neuromuscular CNP: needle electromyography (EMG), nerve conduction studies
  - Seizures/epilepsy CNP: electroencephalography (EEG)
  - Movement CNP: also termed movement disorders CNP, mCNP, movement electrophysiology (ephys), kinematics, instrumented evaluation, or movement studies

MOVEMENT CNP BASICS: PHENOTYPES

Clinical Goal: **phenotype** abnormal movements for the purpose of supporting diagnosis, treatment planning, and/or response monitoring.

Key features of well-established phenotypes include:

- **Tremor**: rhythmicity, distribution, setting
- **Myoclonus**: EMG burst morphology, distribution, setting, cortical origin
- **Functional movement symptoms**: positive signs of voluntary motor involvement, including distractibility, inconsistency, pre-movement voluntary cortical activity
- **Stiff person syndrome**: enhanced startle, exteroceptive reflexes

MOVEMENT CNP BASICS: PHENOTYPES

Features of additional phenotypes needing further investigation:

- **Dystonia**: patterned EMG morphology (limited, especially in fixed dystonia). Abnormal excitability
- **Chorea**: EMG morphology (complex and limited), entropy, motor impersistence
- **Tics**: EMG resembles voluntary movement. Consistency, pre-movement cortical activity (also overlaps with voluntary movement)
- **Ataxia**: impaired accuracy, rhythmicity of voluntary limb movements (developing)
- **Bradykinesia**: impaired speed, amplitude, rhythmicity of voluntary movements. (developing: quantitative digitography (QDG))
- **Gait, Eye movements**: well-developed fields, but beyond the scope of this course

MOVEMENT CNP BASICS: FEATURES

Practical Goal: capture **actionable** CNP data to enable quantitative analysis and phenotyping of abnormal movements.

Major features of abnormal movements:

- Movement **kinematics:**
  - Position in space (meters, x, y, z)
  - Velocity (meters / second, speed and direction)
  - Acceleration (meters / second^2, rate of change in speed and/or direction)
- Movement **effectors**: activation pattern of muscle**s**
- Movement **control**: brain activity, neuroaxis excitability
- Abnormal movement **response** to stimulation and tasks

MOVEMENT CNP TOOLS

Key tools for quantifying abnormal movement features:

- Muscle activation patterns: **multi-channel EMG**, wired or wireless
  - Surface EMG: noninvasive, painless, record target muscle and neighbors
  - Needle / fine wire EMG: isolate specific muscles, mainly for botulinum planning/injection
- Movement: inertial measurement units (**IMUs**: require power supply)
  - Linear acceleration: accelerometers, often tri-axial x, y, z
  - Angular velocity: gyroscopes, often tri-axial pitch, roll, yaw
  - Position in space: motion capture. Multiple options, gets complicated fast
- **Tasks**: structured protocol, live annotation, video recording

MOVEMENT CNP TOOLS

Additional tools:

- **Brain activity**: EEG, mainly EMG-EEG back-averaging, coherence. No clinical applications for MEG, fMRI in movement disorders (yet)
- **Stimulation**: sound, tactile, electrical. Allows evaluation of neuroaxis excitability. Common methods:
  - Somatosensory evoked potential (SSEP)
  - Long latency reflex (LLR, aka C-reflex)
  - Auditory startle reflex
  - Exteroceptive reflex
  - Blink reflex recovery curve (BRRC)
  - Transcranial magnetic stimulation (TMS: more for research)

HARDWARE INTEGRATION

A single hardware system with multi-channel EMG, accelerometers, EEG, electrical and sound stimulation, and video recording **does not currently exist**

Data streams from multiple sources can be synchronized during live acquisition or during analysis

Integration options:

- Synchronized start (ready, set, press Record button)
- Common artifact
- Transistor-Transitor Logic (TTL) or other triggers to send and receive
- Lab Streaming Layer (LSL) or other integration networks
- Analog to Digital Converter (ADC) with various inputs (EMG/EEG amplifiers, accelerometers)
- Customized inputs into clinical hardware ports

MOVEMENT CNP PRIORITIES

Hardware priorities:

- #1: **Multi-channel surface EMG**, at least 4 channels, with ability to save and export
- #2: **Accelerometers**, at least 2 for comparing movement between sides
- #3: **Video recording**, synchronized to allow visual review of "what just happened?"
- #4: **EEG**, at least 4 channels (ideally more) for EMG+EEG back-averaging, SSEP
- #5: **Electrical stimulation** for SSEP* exteroceptive response, reflex myoclonus

MOVEMENT CNP SIGNALS

Signal processing basics:

- ***Analog signal***: a continuous time-varying electrical signal representing ("analogous to") a quantity of interest
  - Audio analog signal: voltage varies continuously with sound wave pressure
  - EEG analog signal: voltage varies with cortical EPSPs and IPSPs
  - EMG analog signal: voltage varies with ion flow across muscle fiber membranes
- ***Digital signal***: computational analysis of the quantity of interest requires sampling the analog signal at a specified sampling rate to generate a digital signal (analog to digital conversion: ADC)
- ***Nyquist frequency***: the sampling rate which is at least two times the maximum frequency of interest present in the signal.
  - This is necessary to accurately reconstruct the analog signal and prevent aliasing (under-sampling causing distortion of high-frequency components)
  - For tremor around 10Hz, a minimum sampling rate of 20 Hz is required, but clinical systems typically use much higher rates (≥500Hz)

MOVEMENT CNP SIGNALS

- ***Amplifier***: physiologic electrical signals are very low voltage, and must be amplified and separated from noise to generate useful EEG/EMG signals.
  - This typically involves comparing the difference between two sites: e.g. active and reference EMG electrodes, or two EEG electrodes, or one and a reference electrode or average
- ***Dynamic range***: voltage range over which an amplifier behaves linearly, i.e. the minimum to maximum voltage that can be reliably measured
  - ***Saturation***: voltage rising above the dynamic range, preventing accurate quantification. Can occur when an EMG signal is fed into an EEG amplifier with insufficient range
- ***Bit depth***: within the dynamic range, the number of distinct voltage values that can be represented is 2^n, where n is the bit depth.
  - An 8-bit system can therefore represent $2^8 = 256$ distinct values
- ***Voltage resolution***: how precisely the signal can be quantified ("resolved")
  - Voltage resolution = dynamic range / bit depth
  - If you have a large dynamic range, you need a high bit depth to precisely measure values across the full range

MOVEMENT CNP ANALYSIS

Requires software which allows **online** (during live data acquisition) and **offline** (post-acquisition) visualization and quantification of CNP data

This may involve getting add-on software from the device maker (which may require a research ethics board (REB) / institutional review board (IRB) protocol), or acquiring data with one software, and then **exporting** to another software for offline analysis.

Analysis software options:

- Open-source movement CNP analysis tools: Tremoroton, BacAv
- Built-in movement CNP specific applications: Natus, Cadwell, CED, Noraxon
- Non-specific coding tools: Python, Matlab

MOVEMENT CNP ANALYSIS

Basic features:

- EMG burst morphology
- EMG burst duration
- Movement distribution across muscles on EMG: agonist/antagonist, regions, spread
- Movement timing on accelerometers

MOVEMENT CNP ANALYSIS

Common analysis techniques:

- **Rhythmic movement frequency**: IMU or EMG
  - Raw data visualization: count out EMG bursts, accelerometer modulation
  - Frequency power spectrum
  - Time-frequency spectrogram
- **Coherence**
  - EMG-EMG between contralateral limbs
  - EMG-EEG (myoclonus)
- **Epoching and averaging**
  - EMG-EEG (myoclonus cortical sharp, BP)
  - Stimulus-EEG (SSEP)
  - Stimulus-EMG (LLR, BRRC)

EMG FOR MOVEMENT CNP

EMG features of common phenotypes:

- **Tremor**: rhythmic bursts with synchronous agonist-antagonist co-contraction, or alternating reciprocal agonist-antagonist activation, at rest and/or with activation. Coherence between sides
- **Myoclonus**: short sharp discharge with agonist-antagonist co-contraction, distribution, at rest and/or with activation, stimulation. Long-latency reflex (LLR)
- **Functional movement symptoms**: variable burst duration, distribution, frequency, pauses at baseline and with distracting tasks
- **Dystonia**: fusing of EMG bursts, spread to adjacent muscles, inappropriate antagonist activation
- **Tasks**: muscle activation state, finger tapping, ballistic movements

ACCELEROMETERS, GYROSCOPES

Accelerometers: measure linear acceleration

- Ideal for measuring the **frequency** of an oscillating movement: each beat involves a rapid change in velocity, whether involuntary (tremor) or voluntary (rhythmic tapping to a metronome)
- Limitations on measuring the **amplitude** of an oscillating movement (or any other movement)
- Sensitive to movement anywhere in the body, so **localizing requires caution**

Gyroscopes: measure angular velocity

- Useful for **frequency** of twisting movement: pronation/supination, head turning
- Less explored than accelerometers

POSITION

Position sensors:

- **Goniometers**: measure angle.
- **Torsiometers**: measure torsion (twisting tension)
- Validated set-up for botulinum planning for upper limb tremor

Motion capture:

- **Marker-based**: optical or magnetic
- **IMU-based**: fused data from accelerometers, gyroscopes, and magnetometers (orientation in space)
- **Markerless video**: promising results for tremor amplitude. Accessible

EEG FOR MOVEMENT CNP

EEG allows correlating cortical activity with EMG activity, with utility in specific phenotypes:

- **Myoclonus**: cortical sharp transient on raw EEG (rare) or EEG-EMG back-averaging: requires 50-100 jerks for reliable results
- **FMD jerks**: Bereitschaftspotential (BP) on EEG-EMG back-averaging: requires 20+ jerks for reliable results
- **Limitations**: head movement artifacts, infrequent **or** continuous movements

STIMULATION

Stimulation modalities, utility:

- **Sound**: handclap/percussion instrument with EMG artifact, or waveform generator synchronized with recording
- **Tactile**: reflex hammer or finger flick with EMG/accelerometer artifact
- **Electrical**: SSEP for cortical myoclonus, exteroceptive reflex for stiff person syndrome

TASKS

Movement CNP studies involve various tasks from holding postures to rhythmic tapping, requiring an organized approach and annotation of recorded data. Options:

- Separate named **files** for each task: possible with any system which allows saving files, but time-consuming to start, stop, save, and analyze each file separately
- **Annotation** during data acquisition to indicate timing of voluntary and involuntary movements, task start and end times
- **Protocol structures** built in to recording software: allows consistency, efficiency, though time-consuming to create
- Synchronized **video recording**: during offline data analysis, allows checking for visible abnormal movement, patient position, activation state, potential sources of artifacts (e.g. repositioning by the clinician)

CLINICAL / RESEARCH SYSTEMS

Clinical hardware/software systems:

- Optimized to be simple and efficient in completing specific clinical studies
- Widely available, FDA approved, maintenance costs covered by other clinical uses
- May be limited in doing flexible recordings, annotate, save, analyze, or export data, or integratimg other hardware components

Research hardware/software systems:

- Optimized for flexibility, customization, integration with other systems
- More work to set up and use, may require more engineering, coding knowledge
- Costs must be covered by clinical movement studies and/or research funds
- FDA approval for clinical use gets complicated

- **Size, weight**: does it fit in a suitcase, or on a cart, or is it immobile?
- **Wired vs wireless**: wired systems are more common, but wireless can have equal data quality, allow greater freedom of movement, with similar or lower cost
- **Multi-use vs movement CNP only**: sharing a system can help with funding, but shared access must be organized

HARDWARE PRACTICALS

Clinical neuromuscular EMG systems are optimized for online EMG analysis of a single muscle (and nerve conduction studies)

Advantages:

- Widely available
- Multi-channel EMG acquisition of 4-12 channels may be possible
- Electrical stimulation included
- Some systems have movement CNP analysis tools available: Cadwell, Natus

Disadvantages:

- Recording duration, annotation, saving, offline analysis, and export may be limited
- May not be able to integrate with accelerometers, video, EEG, other inputs

OPTION: NEUROMUSCULAR EMG SYSTEM

OPTION: SEIZURE/EPILEPSY EEG SYSTEM

Clinical EEG systems are optimized for multi-channel EEG acquisition, offline review and analysis

Advantages:

- Widely available
- 4+ EMG channels common. Adding more EMG channels in bipolar pairs may be possible if EEG amplifier dynamic range goes high enough
- Video recording common
- Annotation of recording is standard, export is common

Disadvantages:

- Movement CNP analysis tools may be limited
- May be difficult to integrate with accelerometers, other inputs

OPTION: EVOKED POTENTIAL SYSTEM

Evoked potential systems are optimized for delivering stimulation and recording EEG and EMG data

Advantages:

- Common in neuromuscular CNP labs
- Mix of EMG and EEG channels, may be flexible
- May have protocols for auditory startle, exteroceptive reflex

Disadvantages:

- Recording duration, movement CNP analysis, data export may be limited
- May be difficult to integrate with accelerometers, video, other inputs

OPTION: POLYSOMNOGRAPHY SYSTEM

Clinical polysomnography systems are optimized for long-duration acquisition of EEG, other inputs

Advantages:

- 4+ EMG channels common. Adding more EMG channels in bipolar pairs may be possible if EEG amplifier dynamic range goes high enough
- Video recording common
- Annotation is standard, export is common
- May be available for daytime use

Disadvantages:

- Integrated accelerometer may not be adequate for movement CNP
- Movement CNP analysis tools may be limited
- May be difficult to integrate with other inputs

OPTION: INTRAOPERATIVE MONITORING SYSTEM

Intraoperative monitoring systems are optimized for continuous recording of EMG and EEG data

Advantages:

- Available through some neuromuscular CNP labs
- Flexible mix of EMG and EEG channels

Disadvantages:

- Systems may be complex, customized, and heavy
- Movement CNP analysis, data export may be limited
- May be difficult to integrate with accelerometers, video, other inputs

OPTION: WIRELESS EMG + IMU SYSTEM

Wireless sensor systems are optimized for flexible recording and analysis of motion

Advantages:

- No tangled wires
- Entire system often lightweight and portable
- EMG + IMU sensors are widely used in gait studies for clinical and research purposes
- Exporting, integrating with other systems is common
- Robust EMG, motion data analysis tools common

Disadvantages:

- EEG integration challenging

MOVEMENT CNP FINANCES

Movement CNP costs:

- **Equipment**: acquisition, disposables (e.g. EMG stickers), annual software licenses, upgrades, maintenance
- **Time**: planning, set-up, acquisition, analysis, and reporting time for physician, CNP technician, fellow, and/or resident
- **Space**: clinic exam room, neuromuscular/epilepsy CNP room, clinical research area

Movement CNP billing approaches:

- Research / non-clinical **protected time**: after initial set-up phase, not appropriate or sustainable for providing a clinical service
- Billing as a **clinical visit**: feasible, but generates no more revenue than seeing a new patient, so not a sustainable pathway for equipment, technician support
- **Procedural billing codes**: mostly borrowed from gait studies, as

MOVEMENT CNP BILLING CODES

Procedural billing codes:

- Ontario G266: Electrophysiological assessment of movement disorders includes multi-channel recording of **EEG** and **EMG**, rectification, averaging, **back averaging**, **frequency analysis** and **cross correlation**. Minimum of 3 hours. Physician must be physically present throughout assessment. OHIP: $279 CAD ($204 USD)
  - Created via advocacy from Drs. Robert Chen and Peter Ashby
- CPT 96002: **Dynamic surface EMG**, during walking or other **functional activities**, 1-12 muscles. Medicare: $21 USD ($29 CAD)
- CPT 96004: **Review and interpretation** by physician or other qualified health care professional of comprehensive computer-based motion analysis, dynamic plantar pressure measurements, **dynamic surface EMG** during walking or other functional activities, and dynamic fine wire EMG, with **written report**. Medicare: $106 USD ($147 CAD)
- CPT 95999: **Unlisted** neurological or neuromuscular **diagnostic procedure** [can be used to bill for accelerometer set-up and data acquisition]. Medicare: no set reimbursement
- CPT 95957: **Digital analysis of EEG** [back-averaging, coherence]. Medicare: $293 USD ($405 CAD)
- CPT 96000: Comprehensive computer-based motion analysis by **video-taping** and **3D kinematics** [accelerometers alone may not be sufficient]. Medicare: $82 USD ($114 CAD)

SUMMARY

Key points:

- If you have nothing else, 4 channels of surface EMG allows basic movement studies
- Understanding the value and limitations of EMG, accelerometers, EEG, and other inputs is vital to appropriate use and interpretation
- A perfect movement CNP system does not currently exist, but usable tools are available, and may already be present at your institution