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Measuring evoked responses in forearm muscles using high density surface electromyography (HDsEMG)

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We use this protocol and it's working.

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Abstract

Surface electromyography (*sEMG*) is useful for studying muscle function and controlling prosthetics, but crosstalk from nearby muscles often limits its effectiveness. High-density *sEMG* (*HD-sEMG*) improves spatial resolution, allowing for the isolation of compound muscle action potentials (CMAPs), including M-waves, in the densely packed forearm muscles. This study assessed *HD-sEMG* for localizing M-waves and evaluated the impact of spatial filters on crosstalk reduction. We administered peripheral nerve stimulation to activate forearm muscles in five participants. We analyzed crosstalk by correlating the shape of M-waves between electrodes and used ultrasound to confirm muscle identity and location. At low stimulation intensities, we successfully isolated M-waves with minimal crosstalk and without spatial filtering. Higher recruitment levels produced significant crosstalk, which was reduced by applying bipolar or tripolar spatial filters. M-waves from a monopolar *HD-sEMG* montage showed high correlations between electrodes ($r = 0.97$ transversely; $r = 0.95$ longitudinally), while bipolar and tripolar montages showed lower correlations (bipolar: $r = 0.41$ transversely; $r = 0.19$ longitudinally; tripolar: $r = 0.17$ transversely; $r = 0.01$ longitudinally). The tripolar filter significantly reduced crosstalk (51.10% amplitude decay one electrode away) compared to no filter (10.32% amplitude decay one electrode away), effectively reducing crosstalk to negligible levels at distances ≥ 2.55 cm. Ultrasound was crucial for distinguishing true activation from artifacts caused by signals converging along muscle boundaries. Spatially-filtered *HD-sEMG* accurately detects and isolates M-waves in the forearm, and ultrasound imaging is useful for verifying the location and identity of the muscles underlying the *HD-sEMG* grids.



Materials

HD-sEMG

SAGA 64+ Bioamplifier (TMSi, Oldenzaal, Netherlands)

3-4 64-electrode HD-sEMG grids per subject (diameter = 4.5 mm; interelectrode distance = 8.75 mm; TMSi, Oldenzaal, Netherlands)

2 reference electrodes per subject (24 mm diameter, Bio-Medical, Clinton Township, MI)

2 ground electrodes per subject (24 mm diameter, Bio-Medical, Clinton Township, MI)

Abrasive gel (Lemon Prep, Mavidon, Flat Rock, NC)

Conductive gel (Signa Gel, Parker, NJ)

Stimulator

DS8R constant current stimulator (Digitimer Ltd, Welwyn Garden City, Hertfordshire, UK)

6 electrodes per subject for stimulation (24 mm diameter, Bio-Medical, Clinton Township, MI)

Ultrasound

Portable ultrasound probe (Butterfly IQ, Matamoros, Mexico)

Ultrasound gel (Pro Advantage, Portland, TN)

Software

MATLAB (MathWorks, Natick, MA)

Electrode Placement

1 HD-sEMG electrodes

Clean the forearm, ankle, and wrist with abrasive gel (Lemon Prep, Mavidon, Flat Rock, NC). Apply conductive gel (Signa Gel, Parker, NJ) to each electrode. Place the HD-sEMG grids on the forearm, with ground electrodes on the ankle and reference electrodes on the wrists.

2 Peripheral nerve stimulation electrodes

Clean the elbow crease, lateral and medial upper arm, and the area between the medial epicondyle and olecranon, using an abrasive gel (Lemon Prep, Mavidon, Flat Rock, NC). Place two disposable Ag|AgCl surface electrodes (24 mm diameter, Bio-Medical, Clinton Township, MI) over the stimulation site.

2.1 Median nerve

Place electrodes along the elbow crease, with the cathode 2 cm medial to the biceps tendon and the anode 2.5 cm medial to the cathode.

2.2 Radial nerve

Place electrodes on the upper arm with the cathode positioned 7 cm proximal to the lateral epicondyle, and the anode on the inner arm opposite to the cathode.

2.3 Ulnar nerve

Place electrodes near the elbow with the cathode between the medial epicondyle and olecranon, and the anode positioned proximal-medial to the cathode.

Instrumentation

3 HD-sEMG recording

Record from the right forearm at 4000 Hz using HD-sEMG electrode grids (SAGA 64+, TMSi, Oldenzaal, Netherlands) comprising 64 Ag|AgCl electrodes (diameter = 4.5 mm; interelectrode distance = 8.75 mm).

4 Electrical stimulation

Use a DS8R constant current stimulator (Digitimer Ltd, Welwyn Garden City, Hertfordshire, UK) to deliver monophasic cathodal pulses (1 ms pulse width) at a repetition rate of 1 Hz. Control the stimulator output using a custom MATLAB (MathWorks, Natick, MA) script that generates a 5V trigger for each stimulation pulse, recorded as a digital event input on the HD-sEMG system. Determine the twitch threshold as the lowest intensity at which muscle twitches are first observed.

Stimulate across a range of amplitudes, starting 1 mA below the twitch threshold and increasing up to each participant's maximum comfort level. For lower comfort thresholds (e.g., 10–12 mA), use 2 mA increments; for higher thresholds (e.g., 18–30 mA), use 3 mA

increments. Deliver each intensity level 10 times in a randomized order, ensuring all intensities are delivered once before beginning the next repetition.

Evoked Response Measurements

- 5 Crosstalk study
Place one HD-sEMG grid on the anterior forearm, 1 cm medial to the biceps tendon, and 4cm distal to the elbow crease. Stimulate the median nerve.
- 6 Forearm musculature mapping
Place 3 HD-sEMG grids around the forearm. Use an additional grid for subjects with larger forearm circumferences. Retain the anterior grid position from the Crosstalk Study. Align the other grids adjacent to the anterior grid, with the ulnar grid over the ulnar muscles (extensor carpi ulnaris [ECU] and flexor carpi ulnaris [FCU]), and the posterior grid over the posterior forearm. If 4 grids are used, placed the 4th grid (posterior grid 2) between the posterior grid and ulnar grid. Stimulate the median, ulnar, and radial nerve individually.

HD-sEMG data processing

- 7 Bad electrodes
Excluded electrodes with excessive noise, artifacts, or no signal.
- 8 M-wave amplitude
Quantify M-wave amplitude as the peak-to-peak value within a time window that excludes late responses like H-reflexes and F-waves. We measured M-waves between 5 and 30 ms after stimulation in the monopolar montage for all subjects and in the spatially filtered montages for Subject 1 due to longer-latency M-waves. For the remaining spatially filtered montages, our measurement window for the M-waves was 5 to 16 ms.
- 9 Recruitment Curves
Used the average peak-to-peak amplitudes for each electrode across trials to build recruitment curves. We defined the activation threshold (AT) as the intensity at which amplitude exceeded 5% of the maximum amplitude, and the maximal motor response (Mmax) as the intensity where the recruitment curve saturated, with less than 2% amplitude change.
- 10 Topographic Heatmaps
Generate topographic heat maps of M-wave peak-to-peak amplitudes from all HD-sEMG electrodes at each stimulation intensity. Display the normalized amplitudes. For excluded electrodes, substitute the mean value of adjacent electrodes in the medial-lateral direction. If the excluded electrode is on the grid edge, use the value of the nearest electrode.
- 11 Crosstalk detection

Calculate linear correlation coefficients between electrode pairs along rows (transverse) and columns (longitudinal) to detect crosstalk. A correlation above 0.9 indicates crosstalk. Plot the cumulative distribution function (CDF) of the correlation coefficients for each direction.

12 Amplitude decay measurements

Calculate decay as the percent reduction in signal amplitude at one electrode distance from the source. Then measure crosstalk at increasing distances from the source. Average these values across all stimulation intensities at or above the AT, with a focus on the muscle with the lowest AT to minimize interference from adjacent muscles. Only intensities up to Mmax for the muscle with the lowest AT should be used in the calculation to further mitigate crosstalk from adjacent muscles. Guide electrode selection by the tripolar montage due to its effectiveness in isolating muscle activity. We defined the threshold for negligible crosstalk as a 15% reduction in M-wave amplitude from the source electrode.

Ultrasound imaging

- 13 After completing all measurements, apply ultrasound gel (Pro Advantage, Portland, TN) and use a portable ultrasound probe (Butterfly IQ, Matamoros, Mexico) to locate muscles beneath the HD-sEMG electrodes. The source electrodes are those within the ultrasound-defined muscle boundary and with M-wave amplitudes at least 50% of the maximum recorded for that muscle. To minimize the effect of crosstalk, limit monopolar montage localization to the highest stimulation level where correlations stayed below 0.9. For bipolar and tripolar montages, localize at Mmax, or the highest stimulation level if Mmax isn't reached.