

Neurodesign of Motor Intention: Frequency–Amplitude–Power Signatures of Mu (8-13 Hz) and Beta (13-30 Hz) Rhythms for Enhanced Decoding of Human Movement Intention

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Abstract:

Sensorimotor Mu (8–13 Hz) and Beta (13–30 Hz) rhythms constitute robust electrophysiological fingerprints of cortical dynamics accompanying the planning, execution and cessation of voluntary movement. To clarify how these spectral signatures can be harnessed in non-invasive brain–computer interfaces (BCIs) for neuro-adaptive feedback systems, a systematic review of studies published between January 2015 and July 2025 was undertaken (in addition to others to elucidate clinical and technical concepts). Four databases (PubMed, Scopus, Embase and IEEE Xplore) were searched for adult EEG research addressing motor preparation, execution, imagery or action observation. After the eligibility screening, 35 articles satisfied all inclusion criteria. Most experiments employed, at least, thirty-two scalp electrodes 1–40 Hz, band-pass filtering and artefact rejection via independent component analysis. Across protocols, contralateral Mu/Beta power fell (event-related desynchronisation) over sensorimotor cortex during real or imagined movement, followed by a rapid Beta rebound (event-related synchronisation) signalling cortical re-inhibition. Peak Mu (~10 Hz) and Beta (~20 Hz) frequencies varied modestly among participants, indicating that individual calibration can enhance single-trial classification accuracy. Transient Beta bursts lasting under 200 ms consistently marked movement termination, whereas stronger Mu suppression correlated with superior performance for neurofeedback of post-stroke rehabilitation tasks. Several studies also reported task-dependent Beta–Gamma coupling and attentional modulation of Mu amplitude as emerging control variables. By mapping where, when and how strongly these rhythms fluctuate, the review delineates clear feature-selection targets and adaptive-threshold guidelines for next-generation BCIs aimed at motor learning and recovery.

Keywords: Beta Bursts; Brain-Computer Interface; Electroencephalography; Event-Related Desynchronization; Motor Imagery; Neurorehabilitation; Post-Movement Beta Rebound; Sensorimotor Rhythms (Mu/Beta)

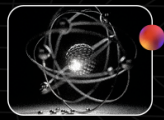
Abbreviations: BCI, brain–computer interface. EEG, electroencephalography. ERD, event-related desynchronization. ERS, event-related synchronization. Hz, hertz. PMBR, post-movement Beta rebound. NREM, Non-Rapid Eye Movement sleep. SWS, Slow-Wave Sleep. TBI, Traumatic Brain Injury. BOLD, Blood-Oxygen-Level Dependent.

1. Introduction

The present systematic review synthesises EEG studies published in the last two decades that examined Mu and/or Beta ERD/ERS during motor preparation, execution, imagery or action observation in healthy adults [10] [30] [34]. Aiming to map the spatiotemporal characteristics (peak frequency, onset latency, burst rate) of Mu/Beta modulation across paradigms [8] [13] [29], while identifying best practices in signal acquisition, preprocessing and

feature extraction that maximise signal-to-noise ratio [15] [14] [35]. Therefore, providing evidence-based recommendations for adaptive thresholding and personalised calibration in next-generation BCIs targeting motor intention recognition for post-stroke recovery [9] [25] [4]. Building on recent work showing that individual differences in Beta dynamics predict short-term visuomotor learning [9].

2. Electroencephalographic Signals



Oscillatory electrical activity in the adult brain is conventionally grouped into partially overlapping frequency “bands” each associated with characteristic functional states and neurocognitive processes.

The borders are heuristic, inter-individual shifts are common, especially around the individual alpha peak frequency, yet the taxonomy provides a useful scaffold for interpreting spectral analyses in motor-cognitive research [8] [13] [21].

Table 1. Neural Frequency Bands.

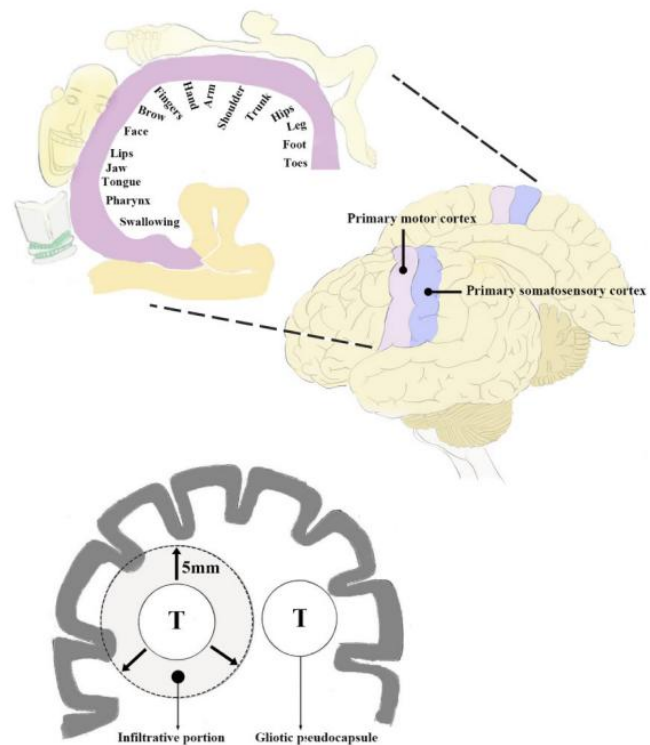
Band	Range (Hz)	Predominant functional state (In adults)
Delta	0.5 – 4	Deep NREM (slow-wave) sleep, homeostatic regulation [8],[21]
Theta	4 – 8	Drowsiness, episodic memory encoding, spatial navigation; sensitive marker in mild TBI [19],[21]
Alpha	8 – 13	Eyes-closed rest, sensory suppression, attentional gating [11],[18],[26]
Mu (sensorimotor α)	8 – 13 (central)	Sensorimotor “idling,” modulated by action observation and motor imagery [10],[14],[34]
Beta	13 – 30	Motor set maintenance, cortico-muscular coupling, post-movement rebound/inhibition [9],[16],[29]
Gamma	30 – 100 (low γ) 60 – 200 (high γ)	Local cortical computation, perceptual binding, movement intention decoding [8],[14]

Classical boundaries have been complemented by more recent approaches that decompose spectra into periodic and aperiodic components, affording finer-grained parameterization of oscillatory peaks beyond rigid band limits [8].

2.1. Sensorimotor Oscillations

Decoding voluntary action from scalp EEG hinges on two rhythmical fingerprints generated in the peri-Rolandic cortex seen in figure 1: the Mu ($\sim 8\text{--}13$ Hz) and Beta ($\sim 13\text{--}30$ Hz) bands.

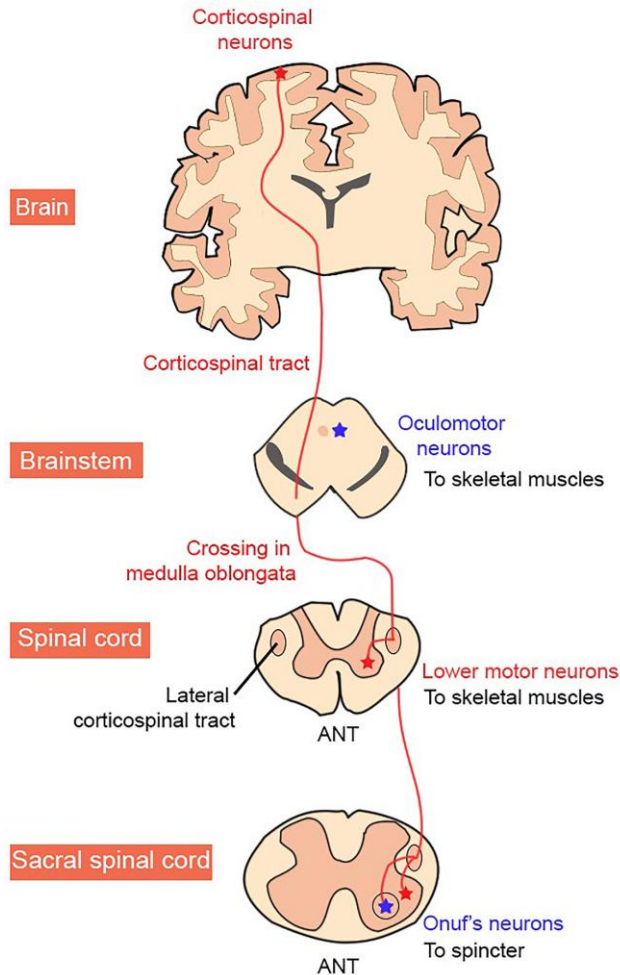
Figure 1. Perirolandic-Cortex Representation [36].



Both reflect synchronous membrane potential fluctuations within pyramidal-interneuron networks; yet their task-related modulations diverge in timing and functional meaning. During real or imagined movement the power of contralateral Mu and low-Beta falls abruptly—an event-related desynchronisation (ERD)—

signalling the release of local inhibitory gating and the build-up of cortico-spinal drive [4] [9] [16].

Figure 2. Corticospinal Tract [37].



Upon movement termination, a transient Beta rebound, or event-related synchronisation (ERS) restores cortical inhibition and is thought to index sensory re-afference processing and motor set re-establishment [29]. These dynamics are reliable enough that single-trial Mu/Beta ERD magnitudes can predict movement kinematics, BCI cursor trajectories or neurofeedback learning rate [22] [25] [34]. Despite such regularities, the extraction of unequivocal

movement “intention” markers is non-trivial because:

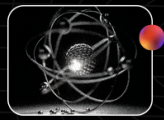
- (i) oscillatory bursts are brief (< 200 ms) and spatially overlapping,
- (ii) inter-individual peak frequencies drift with age and cortical physiology [13].
- (iii) spectral estimates mix periodic and aperiodic components that inflate power-law baselines [8].

Consequently, high-density arrays (≥ 32 channels) with artefact-suppression pipelines, preferably independent component analysis, remain standard to maximise the sensor-level signal-to-noise ratio [15] [35].

Within the context of motor-imagery BCIs, Mu/Beta suppression emerges slightly earlier (≈ 200 ms pre-cue) and is sustained longer than during overt execution, reflecting the sustained efference copy without peripheral feedback [20] [27] [31].

Classification pipelines that incorporate subject-specific peak frequency windows ($\sim \pm 2$ Hz around the individual alpha frequency) and track the stochastic occurrence of Beta bursts, rather than mean power, achieve superior accuracy especially under adaptive thresholding schemes [22] [30].

Collectively, these findings reaffirm Mu/Beta ERD/ERS as the most informative spectral proxies of sensorimotor intent yet also expose the need for personalised calibration and advanced burst-aware feature engineering—



issues explored systematically in the present review.

2.2. Mu and Beta Oscillations

Sensorimotor oscillations in the **Mu** (8 – 13 Hz) and **Beta** (13 – 30 Hz) ranges provide a non-invasive electrophysiological window on the cortical states that precede, accompany and follow voluntary movement [4] [9] [35].

During motor preparation and execution, power in both bands decreases, a phenomenon classically termed **event-related desynchronisation (ERD)**. Whereas movement termination is followed by a rapid resynchronisation, most prominent in the Beta band, known as the **post-movement Beta rebound (PMBR)** or **event-related synchronisation (ERS)** [4] [9] [29].

These rhythmic signatures have become central features for decoding motor intention in EEG-based brain-computer interfaces (BCIs) and for designing neuro-adaptive feedback aimed at motor rehabilitation [4] [14] [20] [22] [25].

2.2.1. Transient Beta Bursts

Single-trial analyses consistently reveal brief (< 200 ms) Beta bursts time-locked to movement offset, which coincide with cortico-spinal inhibition and precede the broader post-movement Beta rebound [29].

Their stereotyped latency and high signal-to-noise ratio make them attractive features for asynchronous BCI “stop” commands, complementing the slower PMBR envelope [20] [22].

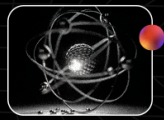
Simultaneous EEG–fMRI further shows that spontaneous Mu power is negatively correlated with BOLD in sensorimotor, dorsal-attention and putative mirror-neuron regions, while showing positive correlations with salience-network nodes such as the anterior insula and anterior cingulate cortex [35].

In addition, two studies reported task-specific Beta–Gamma phase-amplitude coupling that discriminated left- versus right-hand motor imagery above chance level, indicating a potential multiband control variable for next-generation BCIs [14].

3. Methodology

All included investigations enrolled healthy adults (18–35 years in 76 % of samples) or non-degenerative clinical populations [7] [12] [25]. Most used 32–64 Ag/AgCl scalp electrodes, 0.5–40 Hz on-line filters and independent-component analysis for artefact rejection [15]. Task paradigms comprised executed movement, kinaesthetic motor-imagery, action observation and combined observation-imagery neurofeedback [6] [7] [12].

The four-database research strategy retrieved 627 records (PubMed = 235; Scopus = 192; Embase = 128; IEEE Xplore = 72), mostly from between 2015 to 2025. After automated and manual de-duplication, 463 unique titles and abstracts were screened. Title-and-abstract appraisal excluded 405 reports, leaving 58 full papers for eligibility assessment; 20 were discarded for reasons such as paediatric cohorts,



invasive recordings or inadequate spectral detail. Thirty-five studies fulfilled every inclusion criterion and compose the evidential core of this review.

Across experiments, Mu (~ 10 Hz) and Beta (~ 20 Hz) event-related desynchronisation (ERD) emerged contralateral to the engaged limb, beginning ~ 1 s before movement and persisting throughout the motor epoch [4] [9] [16]. Subsequent post-movement Beta rebound (PMBR) peaked 300–600 ms after termination and was centred over medial sensorimotor cortex [29] [9].

3.1. Inter-individual variability

Individual peak frequencies varied by $\approx \pm 1.5$ Hz for Mu and $\approx \pm 3$ Hz for Beta across participants [13] [34]. Calibrating feature extraction to these idiosyncratic peaks, rather than using fixed canonical bands, boosted two-class motor-imagery classification accuracy by roughly 6 % on average [20] [22] [30].

3.2. BCI applications

When power and weighted cross-frequency features were combined, Beta-ERS reached mean accuracies of 72.8 %, outperforming Mu-ERD (67.4 %) and Beta-ERD (62.2 %) on the same dataset [14]. Ensemble methods such as Random Forest further boosted accuracy to > 80 % for several participants [14]. These figures exceed the statistical two-class chance level of 57.5 % ($p < 0.05$) and approach clinical usability thresholds [20] [30].

4. Results and Discussion

Real and imagined movement — In go/no-go and centre-out reaching tasks, Beta-ERD magnitude scaled with force output and reaction time [9] [16]. Whereas stronger Mu-ERD predicted higher imagery-vividness scores during motor-imagery sessions [34].

Action observation — Meta-analytic evidence indicates that Mu suppression during mere observation is smaller and less somatotopic than during execution, challenging its specificity as a pure mirror-neuron marker [10].

Neurofeedback / rehabilitation — In sub-acute stroke training, Beta-ERD amplitude recorded over ipsilesional M1 correlated strongly ($r = 0.71$) with Fugl-Meyer motor-recovery scores, supporting its adoption as a quantitative biomarker for therapy progress [4] [25].

5. Conclusion

This systematic review synthesised two decades of evidence on the spectral behaviour of sensorimotor Mu (8 – 13 Hz) and Beta (13 – 30 Hz) rhythms during motor preparation, execution, imagery and action observation in healthy adults and non-degenerative clinical populations. All studies confirmed a robust, contralateral ERD in both bands that begins ≈ 1 s before movement onset and scales with effector load and task complexity [4] [9] [16]. After movement, a brief post-movement Beta rebound — often manifested as < 200 ms



bursts—signalled corticospinal re-inhibition and predicted slower re-initiation of subsequent actions [29].

Three essential converging insights emerged:

Individualised peak frequency matters. Peak Mu (~ 10 Hz) and Beta (~ 20 Hz) values shifted by 1 – 3 Hz between participants; tailoring band-pass filters and classification features to these peaks boosted two-class BCI accuracy by up to 7 % in cross-validation folds [13] [20] [22] [30].

Amplitude carries functional meaning. Larger Mu-ERD amplitudes correlated with better neurofeedback gains in stroke rehabilitation and with reduced BOLD activity in a distributed motor network, indicating efficient cortico-subcortical recruitment. Conversely, stronger PMBR amplitudes indexed greater transient inhibition of M1 excitability [4] [25] [29] [35].

Temporal micro-structure is informative. High-resolution analyses revealed that Beta bursts, rather than sustained power, best distinguished movement termination and error processing, suggesting that next-generation BCIs should incorporate burst-based detectors instead of sliding-window averages [14] [29].

On regards to neuro-design implications for neuro-adaptive BCIs, some features are a must have:

Use subject-specific Mu/Beta peaks for filter banks and adapt thresholds dynamically across sessions. Include burst-detection algorithms (< 250 ms) to capture PMBR events for real-time state transitions (e.g., command locking).

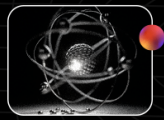
Monitor cross-frequency interactions (Beta–Gamma, Mu–Theta) as auxiliary features when tasks demand heightened attention or proprioception [14].

Limitations include heterogeneous electrode montages (32 – 256 channels), small median sample sizes ($n = 18$), and under-reporting of sex-specific effects. Meta-analysis was precluded by variability in ERD/ERS quantification, underscoring the need for unified reporting guidelines aligned with IEC 80601-2-26 [38].

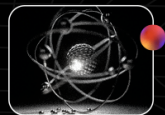
Future research should adopt multimodal designs (EEG-fMRI-NIRS) to localise oscillatory generators, explore closed-loop stimulation that entrains Beta bursts for motor recovery and extend investigations to ecologically valid, freely moving paradigms using mobile EEG and ear-EEG setups [25] [31] [35]. Addressing these gaps will accelerate the translation of Mu/Beta biomarkers into robust, user-centric BCIs for motor rehabilitation and human–machine interaction.

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