

Single case study of Spatiotemporal Dynamics of Cortical Preparation and Motor Execution Across Lower-Limb Movements of Varying Complexity

S. Pathak¹, L. von der Linde¹, J.J. Hernández-Gloria^{1,2}, P. Ofner¹, N. Mrachacz-Kersting^{1,3}

1. Institute of Sport and Sport Science, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany

2. Department of Microsystems Engineering-IMTEK, University of Freiburg, Freiburg, Germany

3. BrainLinks-BrainTools Center, IMBIT, Albert-Ludwigs University of Freiburg, Freiburg, Germany

E-mail: shreyansh.pathak@email.uni-freiburg.de

ABSTRACT: Most lower-limb brain-computer interface (BCI) studies focus on either isolated single-joint movements or complex movements like gait initiation and walking, leaving an unexplored gap between the transition from one movement type to another. As part of the REWIRING project, we aim to investigate the spatiotemporal relationship between cortical signals and muscle activation across various motor tasks of increasing biomechanical complexity and different volition types. To accomplish this, in an ongoing pilot study, electroencephalographic and electromyographic data were recorded and analysed from a single participant during three self-paced movements of varying complexity: dorsiflexion, plantar flexion, and gait initiation. A preliminary analysis of the spatially-filtered data extracted from Cz indicates identifiable movement related cortical potential (MRCP) patterns among all investigated tasks, with differences in peak-negativity and waveform morphology. Our findings demonstrate the feasibility of the proposed setup for investigating and understanding the differences of MRCPs across various lower-limb movements in future studies.

INTRODUCTION

Motor impairments following stroke or spinal cord injury (SCI) often result from disruption of descending efferent pathways, while cortical motor intent is preserved [1]. Non-invasive BCIs aim to decode movement intention using methods such as electroencephalography (EEG) to trigger external assistive devices [2–4]. When the decoded movement intention is synchronized with peripheral sensory feedback, it promotes plasticity, leading to reorganization of the central nervous system and functional recovery [5, 6].

One prominent neural marker for endogenous movement intention is the Movement-Related Cortical Potential (MRCP) [7–9]. MRCPs are slow negative shifts in EEG (typically 0.1-3 Hz), primarily originating from pre-motor cortical areas and primary motor cortex (M1), that accompany voluntary movement and reflect cortical processes of motor preparation, planning,

execution, and feedback processing [7, 10–12]. Some foundational studies have demonstrated the significance of precisely pairing the peak-negativity (PN) of MRCPs with peripheral afferent feedback in inducing associative cortical plasticity, making MRCPs an ideal trigger signal for BCIs in rehabilitation scenarios [5, 6]. Previous BCI studies that use the MRCP as the control signal have used cue-based movements [13]. However, natural body movements are predominantly self-paced. Studies have investigated the morphological disparities in MRCPs between self-paced and cue-based movements, noting that self-paced movements exhibit a distinct readiness potential (Bereitschaftspotential, BP), whereas cue-based movements are dominated by the Contingent Negative Variation (CNV) [7, 9, 14, 15]. Our upcoming study, for the REWIRING project [16], will include tasks such as seated plantar flexion (PF) and dorsiflexion (DF) of the dominant foot, gait initiation (GI), and continuous walking (WA) during both self-paced (SP) and cue-based (CB) conditions, measured across more than 20 able-bodied individuals. As an initial step toward this investigation, a pilot experiment was conducted to evaluate the technical feasibility of the experimental setup and to investigate the MRCP morphology across self-paced lower-limb movements of varying complexity. Here, we present a preliminary comparison of MRCP morphology obtained from a single participant from this ongoing pilot study.

MATERIALS AND METHODS

Participants: The current preliminary analysis involved one able-bodied subject aged 25 years, with written informed consent. The study protocol was conducted according to the Declaration of Helsinki. The protocol was structured as a 4x2 factorial design, consisting of eight randomized experimental blocks. Only three (DF, PF, and GI) of these eight blocks were analysed here. Each experimental block comprised 40 trials, yielding a total of 120 trials.

Data Acquisition: During each experimental block, EEG and electromyographic (EMG) data were recorded with two g.USBamps (g.tec Medical Engineering GmbH, Austria).

EEG data were acquired using a 28-channel active electrode system positioned according to the international 10–20 system. Particular emphasis was placed on the electrodes over the motor cortex and midline regions (Fz, FCz, Cz, CPz, Pz, C3, C4). Signals were recorded in a monopolar configuration referenced to the earlobe ipsilateral to the dominant leg, with a ground electrode placed at FPz.

For recording muscle activity, unipolar surface EMG electrodes were placed on the Tibialis Anterior (TA) and Soleus muscles of both the dominant and non-dominant legs. The reference and ground electrodes were placed on the electrically neutral bony prominence of the dominant knee. All signals were sampled at 1200Hz.

Additionally, an unimotor pedal system was used to measure the force exertion and foot positioning during dorsiflexion and plantar flexion tasks while sitting, as well as for gait initiation while standing. A force platform was used to measure ground reaction forces during the walking trials. Throughout the session, a goniometer and an accelerometer were placed on the dominant ankle foot to record ankle rotation angle and foot acceleration. This additional data was not included in this preliminary analysis.

after the last trial. For cue-based trials, the participant performed the movements by following a cursor on a screen. Each cursor screen was followed by a ‘REST’ and preceded by a ‘FOCUS’ screen, each of approximately 4-second duration [5]. All data was acquired using a previously developed MATLAB-based application. Here, the data from self-paced dorsiflexion, plantar flexion, and gait initiation were analysed for our preliminary analysis.

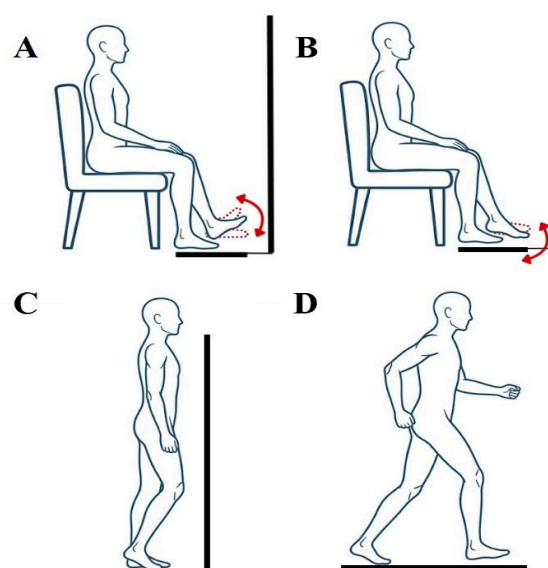


Figure 2: Movement Types; A: Dorsiflexion, B: Plantar Flexion, C: Gait Initiation, D: Walking. Only A, B, and C were evaluated in our preliminary analysis of our pilot study.

		Factor B: Volition types	
		Self-paced	Cue-based
Factor A: Movement types	Planter flexion	Self-paced plantar flexion 40 trials Condition: SP-PF	Cue-based plantar flexion 40 trials Condition: CB-PF
	Dorse-flexion	Self-paced dorsiflexion 40 trials Condition: SP-DF	Cue-based dorsiflexion 40 trials Condition: CB-DF
	Gait initiation	Self-paced gait initiation 40 trials Condition: SP-GI	Cue-based gait initiation 40 trials Condition: SP-GI
	Walking	Self-paced walking 40 trials Condition: SP-WA	Cue-based walking 40 trials Condition: CB-WA

Figure 1: Experimental protocol: 4x2 factorial design.

Experimental Procedure: The first factor shown in Fig. 1, ranges over four levels of movement complexity, focusing on the dominant leg. During dorsiflexion and plantar flexion, the participant was instructed to perform a ballistic movement with the dominant leg while maintaining the rest of the body steady. Gait initiation was performed while standing on the pedal system and transitioning from a quiet stance to the first step of the dominant leg without lifting off. During walking trials, the participant was instructed to walk for 2-3 steps across a force platform and return to the start position. The second factor shown in Fig. 1, was related to the volition type. For self-paced trials, the participant was given a start cue before each run, upon which they could start the trials at their will, spacing each trial by roughly 8 to 10 seconds. A stop cue was given 5-10 seconds

Signal Preprocessing: Continuous EEG data for DF, PF, and GI were recorded. The data was filtered using a 0.1 Hz high pass filter. Due to high noise level, channel P4 was removed after visual inspection. Subsequently, Independent Component Analysis (ICA) was performed to identify and remove artifacts, specifically eye movements and blinks. One component associated with eye blinks was removed and the components were projected back to EEG. A notch filter at 50 Hz was used to eliminate power-line noise. A zero-phase 2nd-order Butterworth band-pass filter (0.1 - 3 Hz) was applied to isolate the MRCPs. The data was then segmented into epochs of -4 to +6 seconds relative to movement onsets.

Epoching: To prevent temporal smearing of the grand-averaged MRCP, precise alignment of "Time Zero" is vital. For all discrete conditions (dorsiflexion, plantarflexion, gait initiation), $t=0$ was defined as the onset of the primary agonistic EMG burst (TA for dorsiflexion, Soleus for plantar flexion and gait initiation). The onset was detected using a

Teager-Kaiser Energy Operator (TKEO) thresholding method [17]. Epochs were extracted from $t = -4.0$ s to $t = +6.0$ s relative to EMG onset.

MRCP Alignment and Averaging: To enhance the spatial specificity of cortical activity over the motor cortex, a large Laplacian spatial filter centered at Cz was computed for each epoch. To reduce temporal variability across trials, the peak-negativities (PN) were aligned. For each epoch, the local minimum of the Laplacian Cz signal was identified within a window of -0.5 s to $+0.5$ s around the EMG onset. Trials were then realigned and cut to a duration of -3.0 s to $+5.0$ s based on PN before averaging. Each epoch was then individually baseline corrected. The mean signal value during the first second of the epoch (-3 to -2 s relative to PN) was calculated and subtracted from the entire trial to remove slow drifts and inter-trial offsets.

For each movement condition, the aligned trials were averaged to obtain the mean MRCP waveform. The standard error of the mean (SEM) was computed across trials to quantify variability. The resulting mean MRCPs for dorsiflexion, plantar flexion, and gait initiation were then superimposed to allow visual comparison of waveform morphology across the three tasks.

MRCP Feature Extraction: To further characterize task-dependent differences in MRCP morphology, several temporal and amplitude-based features were extracted from the averaged Laplacian Cz waveforms after peak-negativity (PN) alignment and baseline correction. The early Bereitschaftspotential (BP) slope (NS1) was calculated within the interval from -2.0 s to -0.5 s relative to PN, while the late BP slope (NS2) was calculated from -0.5 s to 0 s. A post-movement recovery slope was additionally computed from 0 s to $+1.0$ s. For each interval, a first-order linear fit was applied to each trial, and the resulting slopes were averaged across trials for each movement condition. The peak-to-peak (P2P) amplitude was calculated as the difference between the most negative deflection and the maximum positive deflection observed within the interval of ± 2 s around the PN. All quantitative features are reported as mean $\pm$ standard error of the mean (SEM) across trials.

RESULTS

Fig. 3 shows the averaged MRCPs at the Cz electrode for the three self-paced tasks: dorsiflexion (DF), plantar flexion (PF), and gait initiation (GI), time-locked to peak negativity (PN) ($t = 0$). All conditions exhibit the characteristic MRCP morphology consisting of a gradual negative potential preceding movement onset, followed by a return toward baseline after movement initiation.

The MRCP features differed across the three movement conditions. The Peak-to-peak amplitudes were comparable for DF ($11.68 \mu\text{V}$) and PF ($11.10 \mu\text{V}$), whereas GI exhibited a smaller overall peak-to-peak excursion ($7.85 \mu\text{V}$).

Differences were also observed in the temporal evolution of the readiness potential. GI exhibited the steepest early BP slope (NS1: $-5.69 \pm 1.68 \mu\text{V/s}$), whereas DF demonstrated the strongest late BP slope (NS2: $-16.51 \pm 2.33 \mu\text{V/s}$). PF showed comparatively smaller negative slopes during both preparatory phases. In the post-movement interval (NS3), all conditions exhibited positive recovery slopes, with DF showing the largest recovery rate.

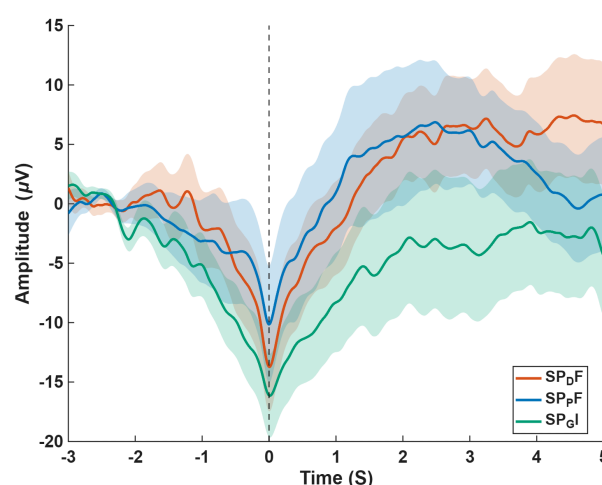


Figure 3: Mean MRCPs at electrode Cz for self-paced (SP) DF (SPDF), PF (SPPF), and GI (SPGI). Shaded regions represent $\pm$ SEM across trials. The dashed line indicates peak negativity (PN) ($t=0$).

DISCUSSION

The framework presented in this study addresses a critical bottleneck in the translation of BCI-based neuro-rehabilitation: the transition from simple, isolated motor intentions to the control of complex locomotor actions. By characterizing the MRCPs across a spectrum of movement complexities, we intend to establish a comprehensive “morphological library” of motor intention.

The present work represents an exploratory pilot analysis based on data from a single participant ($N = 1$). Consequently, statistical comparisons between movement conditions on a group-level were not feasible. In addition, only three self-paced movement conditions were evaluated, limiting the generalizability of the findings to broader motor tasks or clinical rehabilitation populations.

Nevertheless, the quantified MRCP features revealed distinct waveform characteristics across dorsiflexion,

plantar flexion, and gait initiation. In particular, gait initiation exhibited the largest motor potential amplitude and the steepest early BP slope, whereas dorsiflexion demonstrated the strongest late BP slope immediately preceding movement onset. These observations suggest the possibility of task-dependent differences in cortical preparatory dynamics associated with varying movement complexity.

Importantly, the present study does not establish that these features can reliably discriminate movement classes in a classifier framework. Rather, the results serve as an initial indication that MRCP-derived features such as early and late BP slopes, motor potential amplitude, and latency may contain discriminative information worth investigating in larger cohort studies. If validated across multiple participants and sessions, such features could potentially support the development of more adaptive BCI systems capable of differentiating between simple ankle movements and more complex locomotor actions such as gait initiation [2].

Although preliminary, the results presented here provide an initial validation of the proposed experimental framework and motivate future studies involving larger participant cohorts, additional movement conditions, and clinical populations relevant to neuro-rehabilitation applications.

CONCLUSION

This study outlines the feasibility of a comprehensive, multimodal paradigm for characterizing the spatiotemporal and cortico-muscular dynamics of lower-limb movements. Building upon this pilot, we aim to map the diverse neural signatures required for asynchronous, intent-driven, closed-loop BCI rehabilitation systems that can account for variations in the interactions involved in movements of varying complexity.

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