

Goal-Directed Quasi-Movements Based on Natural Hand Actions: EEG Correlates and Relevance for Rehabilitation BCI

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ABSTRACT: Quasi-movements (QMs) are movements minimized to the point that they produce no visible movement or detectable muscle activation. Unlike kinesthetic motor imagery (MI), they are closer to actual movement in the sense of intention and may therefore provide a more natural basis for sensorimotor BCI control. However, previous QM research has been largely limited to thumb abduction. Here we investigated, for the first time, QMs based on more natural goal-directed hand actions, pressing and pointing. Healthy participants performed kinesthetic MI, non-goal-directed QMs, goal-directed QMs, and real movements while EEG and a custom force-sensor signal were recorded. Both QM conditions elicited stronger contralateral μ -rhythm desynchronization than MI, whereas ipsilateral μ -ERD did not differ reliably between conditions. Goal-directed instruction did not produce an additional detectable effect, and residual movement did not account for the EEG differences. These preliminary findings suggest that natural-action QMs are feasible and may represent a promising alternative to MI for non-invasive BCI applications.

INTRODUCTION

Kinesthetic motor imagery (MI) is one of the most widely used control strategies in non-invasive brain-computer interfaces (BCIs) [1]. However, MI is an internally directed task and may compete with the processing of external information, including visual feedback, as well as with oculomotor control and visual attention [2,3]. In addition, MI requires the user to perform a relatively abstract mental task rather than to prepare an actual action. This motivates the search for alternative motor-related tasks that would preserve informative EEG correlates while being closer to natural action.

A promising candidate is quasi-movement (QM), a phenomenon described by Nikulin et al., in which movement amplitude is reduced until no visible movement and no detectable muscle activation remain, while EEG patterns similar to those of actual movement are preserved [4,5]. QMs were previously proposed as a model of movement attempts, which had previously been discussed as a more natural alternative to MI for BCI, particularly in clinical and rehabilitation applications [6,7]. MI-based training is difficult to teach reliably within the limited time available in clinical settings [7]. Overt attempts are more natural for patients but carry their own risks in paresis and plegia: repeated effortful

contractions can aggravate spasticity and recruit pathological synergies. QMs, as movement attempts intentionally minimized to the point of no overt output, may avoid both problems: they preserve the natural feel of an action attempt while removing the peripheral output that drives the side effects of overt attempts. Recent work also indicates that residual muscle activation, when present, does not fully account for QM-related EEG effects [8], and that QMs are experienced as more similar to actual movement than MI, which may support the sense of control during BCI use [9]. In healthy participants, QMs additionally allow direct verification of the absence of overt output through force or EMG measurements, which is not feasible in patient studies of attempted movement. At present, however, QM research remains limited largely to a single movement, thumb abduction [4,8]. This leaves open the question of whether QMs can be extended to more natural, goal-directed actions that are closer to everyday control. This question is important because goal-directed movements have specific neural correlates and may be especially relevant for BCI applications [10,11].

Here we examined whether new goal-directed hand actions can be implemented as QMs and whether they retain the sensorimotor-rhythm modulation that makes QMs promising for BCI applications. Specifically, we developed, for the first time, task instructions for QM performance based on pressing and pointing actions, and compared the resulting QMs with kinesthetic MI of the same actions. We also assessed the effects of instruction and residual movement. We expected that these new QMs would be feasible in healthy participants and would produce sensorimotor-rhythm changes at least as strong as, and potentially stronger than, those observed during kinesthetic MI.

MATERIALS AND METHODS

Participants: 11 healthy volunteers (5 females, aged 21-32 years, median age 28 years) participated in the study after providing their written informed consent. Two of them had prior experience with MI and QM.

Signal acquisition: EEG (64 electrodes) was recorded at 1000 Hz using an NVX136 DC EEG amplifier (Medical Computer Systems, Moscow, Russia). The ground electrode was placed at Fpz. Electrode impedance was kept below 20 k Ω .

For mechanical registration of minimal residual movement, we developed a custom sensor based on a

DKFFF-6AA-120 strain gauge mounted on a 3D-printed compliant mechanical structure. Resistance changes were measured using a Wheatstone bridge circuit, and the midpoint voltage difference was amplified by a differential amplifier based on an LM358 operational amplifier. For comfortable hand placement, the sensor was installed in a housing that allowed the participant to rest the hand palm-down in a natural relaxed posture while the distal phalanx of the target finger was positioned on a circular plate (20 mm diameter) flush with the surrounding surface. The sensor was powered by an NVX136 amplifier AUX port, and the data was acquired using the analog input on the same port. Because the strain gauge registered deformation of the elastic sensor structure rather than force along a single separately calibrated axis, the sensor could detect very small changes in finger-applied force irrespective of direction. Surface EMG was not considered suitable for this study because pressing and pointing depend on multiple, partly deep muscle groups, so the minimal residual activation expected during quasi-movements would be difficult to detect and interpret reliably from surface recordings.

Software: Signal acquisition and real-time processing were performed using the Resonance platform [12]. The stimulus presentation sequence was delivered using a custom PyGame-based presentation script. Primary offline data processing was conducted in MNE-Python. Statistical analysis was performed in R using the lmerTest package, and post hoc comparisons were carried out with emmeans.

Experiment design: Participants sat in a chair in front of a computer screen. The right forearm rested comfortably on a support, and the right hand was placed palm-down on the force sensor so that the index finger contacted its sensitive plate. Stimuli were presented in blocks, each consisting of two motor-task sequences and one visual control sequence, with inter-sequence intervals varying randomly from 2 to 4 s.

In each motor sequence, an image of a right hand performing the corresponding action was presented for 3.2 s. One second after image onset, three brief auditory clicks were delivered with an inter-click interval of 600 ms. In response to each click, the participant performed one repetition of the task required in the current condition. In the visual control sequence, a figure with complex geometric elements was shown for 4 s, and the participant silently counted elements of a selected type at a comfortable pace, as described elsewhere [8]. Each condition comprised 20 blocks, yielding 40 motor sequences and 20 visual sequences; before each condition, participants completed 5–10 training blocks. For each of the two actions, four task types were recorded: overt movement (**OM**), kinesthetic imagery movements (**IM**), non-goal-directed quasi-movement (**nQM**), and goal-directed quasi-movement (**gQM**). OM condition was always performed first, IM and nQM were presented in random order, and gQM was always performed last for the given action. This was done because goal-directedness was introduced by instruction,

and earlier presentation of gQM could have induced premature association of the movement with its goal-directed meaning. Accordingly, before the gQM condition the experimenter avoided action-related keywords such as “press”, “button”, or “point”, describing the movement only in joint-motion terms. Immediately before gQM, the same movement was reintroduced in explicitly goal-directed terms.

Training: QM training was adapted from the procedure of Nikulin et al. and our previous work [4,8]. Participants were first shown the processed force-sensor signal on the screen and could verify that it changed with index-finger movement. To facilitate user comprehension, the Sum of Absolute Differences (SAD) between the current and lagged sensor force signals was displayed. This representation allows for the clear identification of force change regions and reduces the noise visually apparent in the graph [13]. Participants were then instructed to perform the target movement in a self-paced manner while gradually reducing its amplitude and the sensor output. After an individually determined threshold was reached, visual feedback was removed and the participant continued producing the movement in response to isolated auditory cues while further minimizing its amplitude if it remained distinguishable from sensor noise. Once stable QM performance was achieved, the experimenter asked control questions to verify that the participant had not switched to motor imagery or to another unintended movement. Finally, participants practiced responding to the triplets of auditory cues used in the main experiment. IM training was conducted immediately before each IM condition. Participants first performed the corresponding movement several times with full amplitude while attending to the sensations arising in the hand. They were then asked to describe these sensations, after which non-visual sensations such as tension, weight, stretching, or warmth were selected and used as the basis for kinesthetic imagery. Participants were instructed to imagine these sensations as localized in the hand, as if they were performing the actual movement. Training continued with auditory triplets until the participant reported being able to perform the imagery task confidently at the required pace.

Data processing: Offline processing was performed in MNE-Python. Bad EEG channels were detected automatically with PyPREP [14], using its noisy-channel detection procedures, and were then interpolated; the data were subsequently transformed into current source density (CSD). Residual movement was quantified from the force-sensor signal by robust peak amplitude (RPA), defined as the difference between the 95th and 5th percentiles within each epoch. We used this measure because it provides an estimate of overall movement-related force variation while being less affected than the conventional peak-to-peak range by isolated artifacts and extreme values. It was therefore well suited for detecting small and irregular residual movements during quasi-movements.

EEG analysis focused on the sensorimotor ROI

comprising FC5, FC3, C3, C1, CP3, CP1 and FC6, FC4, C4, C2, CP4, CP2. Single-trial Morlet time-frequency power was computed for each ROI channel and manually baseline-normalized in dB as $10\log_{10}(\text{power} / \text{PRE})$, where PRE was the mean baseline power in the selected pre-stimulus interval. μ -band ERD (8–13 Hz) was then derived from the band-limited ROI power time course using the selected post-stimulus interval relative to the first auditory cue. For each participant and condition, the electrode showing the maximal effect within the ROI was selected for analysis.

Statistical analysis: μ -band ERD was analysed with linear mixed-effects models fitted separately for contralateral μ ERD and ipsilateral μ ERD. The model included movement type, condition, epoch number, preceding task, prestimulus desynchronization level, and RPA, with subject as a random intercept. The interaction between RPA and task type was included to estimate the contribution of residual movement separately for different task types. Statistical analysis was performed in R using *lmerTest*, with post hoc comparisons conducted using *emmeans*.

RESULTS

Analysis of the force-sensor signal – Empirical cumulative distribution functions of RPA for different movements and conditions are shown in Fig. 1.

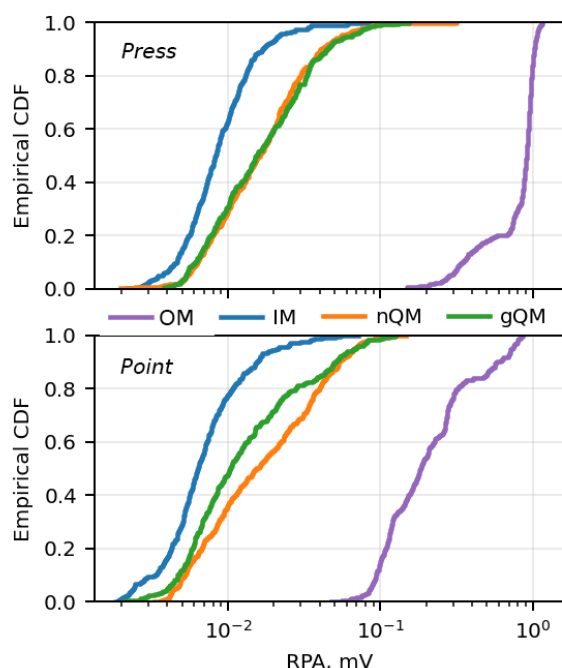


Figure 1. Cumulative distribution functions (CDFs) for the trial RPA values computed for different movements and conditions.

Table 1 shows the percentages of nQM and gQM epochs containing elevated residual movement, defined for each participant and movement separately as epochs whose RPA exceeded the 97.5th percentile of the RPA distribution observed in the corresponding IM condition. Participants varied highly in the percentage of trials

without elevated residual movement, and only four participants were able to refrain from producing elevated RPA in all the conditions. Still, no participants produced RPA stronger than minimal RPA observed during OM in the QM conditions.

Table 1. Percentages of epochs with elevated residual movement in QM conditions.

Participant	Press		Point	
	nQM	gQM	nQM	gQM
1	5	10	90	52.5
2	0	0	22.5	0
3	17.5	15	15	35
4	10	67.5	0	2.5
5	85	65	70	97.5
6	17.5	—	30	—
7	52.5	27.5	97.5	27.5
8	90	80	40	30
9	77.5	100	67.5	92.5
10	12.5	45	10	2.5
Mean	36.75	45.6	44.25	37.8

Repeated measures ANOVA with condition as a within-subject factor showed that movement magnitude, quantified by RPA, differed significantly across conditions for both *press* and *point* ($p < 0.001$ in both cases). For *press*, RPA was markedly higher in OM than in IM, nQM, and gQM (all $p < 0.001$). Among the non-overt conditions, nQM showed slightly higher RPA than IM ($p = 0.008$), whereas the difference between gQM and IM did not reach significance ($p = 0.064$). nQM and gQM did not differ from each other ($p = 0.941$).

For *point*, OM again showed higher RPA than IM, nQM, and gQM ($p = 0.028$, $p = 0.028$, and $p = 0.027$, respectively). By contrast, no significant differences were found among the non-overt conditions after correction for multiple comparisons: the contrast between IM and nQM was marginal ($p = 0.050$), whereas IM and gQM ($p = 0.163$) and nQM and gQM ($p = 0.599$) did not differ.

Overall, these results indicate that overt movement was associated with the largest mechanical signal, as expected, whereas the residual movement observed during quasi-movements was small and generally comparable to that observed during imagery, especially for the *point* movement.

Sensorimotor-rhythm modulation in the new tasks – The contralateral μ -band ERDs are shown in Fig. 2, and the corresponding grand average timecourses are shown in Fig 3. As far as the main goal of this preliminary study was to compare new QMs with corresponding IMs, the OM condition was excluded from this analysis. The analysis with linear mixed-effects models showed significant effects of movement type, task type, previous task, and prestimulus amplitude ($p = 0.001$, $p = 0.024$, $p < 0.001$, and $p < 0.001$, respectively). By contrast, neither RPA nor its interaction with task type reached significance ($p = 0.967$ and $p = 0.820$, respectively). Overall, contralateral μ -ERD was stronger for *press* than for *point* movements. With respect to task type, both quasi-movement conditions were associated with

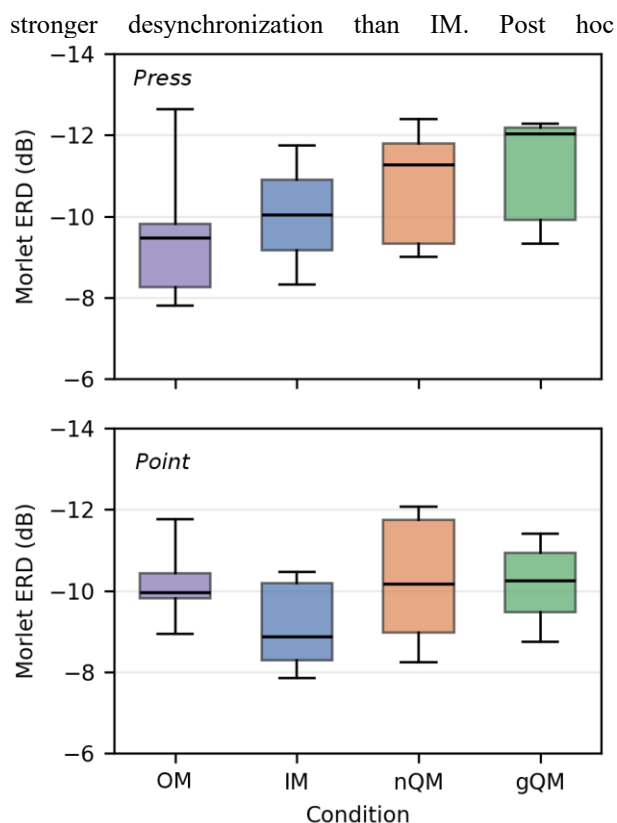


Figure 2. Desynchronization of contralateral sensorimotor rhythms in different conditions.

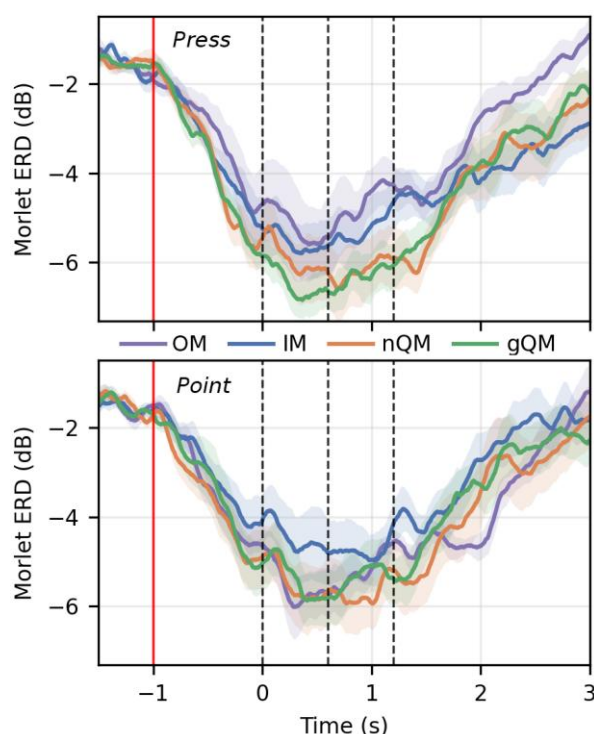


Figure 3. Group grand average time courses for ERD in sensorimotor rhythm band (8-14 Hz). Vertical red line corresponds to the moment of visual cue appearing on the screen. Vertical dashed lines correspond to the sound stimuli onset.

comparisons confirmed that μ -ERD was significantly stronger in nQM than in IM ($p=0.027$) and in gQM than in IM ($p=0.042$), whereas nQM and gQM did not differ ($p=0.792$).

Thus, both QM conditions elicited stronger contralateral μ -rhythm desynchronization than IM, while the goal-directed instruction did not produce an additional effect. The absence of significant RPA-related effects further indicates that residual movement was unlikely to account for these differences.

For ipsilateral μ -ERD, the analysis revealed significant effects of previous task and prestimulus amplitude ($p<0.001$ and $p=0.008$, respectively). By contrast, the effects of movement type and RPA were not significant ($p=0.236$ and $p=0.798$, respectively), and the main effect of task type did not reach significance ($p=0.086$). The RPA $\times$ task type interaction was also non-significant ($p=0.788$).

None of the pairwise comparisons between task types reached significance ($p=0.203$ for IM vs nQM, $p=0.955$ for IM vs gQM, and $p=0.135$ for nQM vs gQM). Thus, unlike contralateral μ -ERD, ipsilateral μ -ERD did not show reliable differences between imagery and quasi-movement conditions.

The absence of significant RPA-related effects further suggests that residual movement did not make a detectable contribution to ipsilateral μ -ERD.

DISCUSSION

These results are preliminary, given the small sample. Nevertheless, they suggest that quasi-movements can be extended beyond the “classical” thumb-abduction paradigm [4] to more natural hand actions such as pressing and pointing. The main result was that both nQM and gQM were associated with stronger contralateral μ -rhythm desynchronization than IM, whereas ipsilateral μ -ERD did not differ reliably between conditions. In addition, the contribution of residual movement, quantified by RPA, was not significant in either hemisphere. Overall, this pattern indicates that the advantage of the new quasi-movements over imagery was expressed primarily in contralateral sensorimotor activation and was unlikely to be explained simply by peripheral motor leakage.

In this respect, the present findings are broadly consistent with the original study of quasi-movements by Nikulin et al. [4], in which α -band ERD was strongest for overt movement, weaker for quasi-movement, and weakest for motor imagery, with the QM-IM difference being especially clear in the contralateral hemisphere. They are also in line with the later analysis of Vasilyev et al. [8], which showed that stronger contralateral ERD in QM than in imagery could not be explained by residual muscle activation alone. Thus, the present data extend the earlier QM literature by indicating that this advantage over imagery may also be obtained for more natural hand actions than thumb abduction.

At the same time, the absence of an additional effect of goal-directed instruction should be interpreted

cautiously. Existing evidence suggests that goal-directedness may be expressed less as larger mean ERD over central sensorimotor sites than as earlier onset, broader spatial distribution, and stronger parietal involvement, particularly in the upper alpha range [10,11,15–17]. However, the available direct comparisons are few, based on small samples, and partly confounded by movement complexity. Therefore, the lack of a clear gQM vs. nQM effect in the present study does not necessarily argue against goal-directedness-related neural differences. Rather, it may reflect the fact that the present analysis focused on mean amplitude within a central sensorimotor ROI, whereas the most specific effects of goal-directedness may lie in parietal recruitment, upper- μ dynamics, and temporal characteristics of ERD.

A further reason for caution is that the two actions used here, pressing and pointing, are themselves highly familiar and naturally associated with external objects and outcomes. Thus, even the nominally non-goal-directed variants may have retained part of their habitual action meaning. In addition, the gQM condition had to be presented last for each movement in order to avoid contaminating the neutral conditions, which was methodologically justified but may also have reduced the possibility of isolating a pure goal-directedness effect. Under these circumstances, the present data are better interpreted as showing that goal-directed instruction did not produce an additional detectable effect in the current design, rather than as evidence against the relevance of goal-directedness per se.

Although participants varied in the proportion of QM epochs containing elevated residual movement, the covert conditions were much closer to one another than to OM, especially for pointing. Most importantly, neither the main effect of RPA nor its interaction with task type was significant in the mixed-model analysis of μ -ERD. This argues against the simplest explanation that the stronger desynchronization in QMs merely reflected residual movement. Instead, the present findings support the view that QMs represent a distinct motor-related state that is closer to overt movement than imagery at the cortical level while remaining behaviorally non-overt. This interpretation is also compatible with the conclusion of Vasilyev et al. [8] that occasional peripheral activation is insufficient to account for the stronger cortical effects observed in QMs. The sensor was not separately calibrated for directional sensitivity, but the absence of a strong press-point dissociation in the covert conditions argues against this as a main source of the observed effects (Fig. 1).

A particularly interesting aspect of the present data is the pattern observed for the *press* movement. Although OM was not included in the main mixed-model comparison focused on IM and QMs, inspection of the data suggested that for at least some participants contralateral ERD during overt pressing tended to be smaller than in the QM conditions. At first sight, this appears inconsistent with the classical pattern reported by Nikulin et al. [4], where overt movement produced the strongest ERD. However,

the broader literature offers a plausible interpretation. Highly familiar or automated movements may be associated with reduced, rather than increased, sensorimotor ERD, especially in the α/μ range, in line with a neural-efficiency account [18–21]. Lower movement-related α desynchronization has been reported in highly trained participants, and practice may likewise reduce desynchronization or increase sensorimotor power [18–21]. On this view, overt pressing in the present experiment may have functioned as a highly familiar and automatized action, whereas pressing in the QM mode required a less habitual and more demanding control regime, since participants had to generate an effective motor command while simultaneously suppressing overt output. If so, the tendency toward smaller ERD in OM *press* would not necessarily contradict the QM framework but might reflect an interaction between quasi-movement-related activation and movement familiarity.

This interpretation should, however, remain cautious. The available literature on familiarity and sensorimotor ERD is heterogeneous with respect to task type, expertise, and movement phase [18–21]. Likewise, the literature on goal-directedness is limited by small samples and by incomplete separation of goal-related and complexity-related factors [15,16]. Therefore, the present data do not justify a general conclusion that familiar overt actions produce weaker ERD than quasi-movements. Rather, they suggest that the unexpected *press* pattern is compatible with findings on automatization and neural efficiency and deserves direct testing in a larger study.

A methodological limitation should also be noted. Band-power ERD does not separate cortical activation from active inhibition of motor output, which is particularly relevant for QMs, since participants generate a motor command while suppressing overt execution. The stronger contralateral μ -ERD for QMs relative to IM is therefore compatible with greater activation, stronger inhibitory control, or both. Direct characterization would require methods such as TMS-derived motor-evoked potentials, paired-pulse paradigms, or corticomuscular coherence, which have not yet been applied to QMs.

From the BCI perspective, the present findings are encouraging. The stronger contralateral μ -ERD observed in nQM and gQM relative to IM is consistent with the general idea that motor-related states closer to actual movement may provide more informative control signals than classical imagery [1,22]. The extension to pressing and pointing is relevant to rehabilitation in particular, since these actions are closer to functional grasp and reach targets than the thumb abduction used in previous QM studies, and goal-directed action representations have been proposed as a basis for more naturalistic BCI control [10,11]. Real-time QM-BCI control of hand exoskeleton has recently been demonstrated in both healthy participants and chronic stroke patients (Yashin et al., this conference), supporting the feasibility of the broader approach; the present results suggest that the task repertoire available for such applications can be

expanded beyond a single minimal movement. Future work should therefore include replication in a larger sample, more explicit manipulation of action goal-directedness, and testing of these new QMs in online BCI paradigms.

CONCLUSION

Our results suggest that pressing- and pointing-based quasi-movements are feasible and may provide more informative sensorimotor EEG correlates than imagery, as reflected in stronger contralateral μ -rhythm desynchronization. These preliminary findings support further investigation of natural-action quasi-movements as a promising alternative to motor imagery for BCI applications.

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