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Bimanual BCI: Combining a Brain-Controlled Hand Exoskeleton with the Functional Limb

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Introduction: Brain-controlled robotic systems have demonstrated promise as personalized assistive tools [1]. Yet current BCIs largely focus on unilateral exoskeletons for basic functions [2], offering limited utility in real-world tasks demanding bilateral coordination. This is critical for individuals with unilateral motor impairments, who could combine a BCI-controlled exoskeleton for the affected limb with overt motor actions of the healthy limb. Although the motor cortex supports simultaneous movements, non-invasive electroencephalogram (EEG)-based BCIs remain understudied in this context [3]. Here we show that a BCI decoder trained on a unimanual task can be reliably transferred to more complex bimanual tasks without requiring bimanual-specific calibration.

Material, Methods, and Results: The study involved 7 subjects completing 6 sessions, beginning with a calibration session to build a motor imagery (MI) BCI for right-hand flexion versus rest that controls a hand exoskeleton [4]. In the first two online sessions, subjects performed unimanual MI tasks (rest vs right-hand flexion imagery) with closed-loop feedback, while in the last three sessions, they performed bimanual tasks combining MI-BCI of the right hand with functional tasks of the left hand. Bimanual trials included combinations of left-hand rest/force application in a prespecified range and right-hand rest/exoskeleton control. We used a Riemannian approach [5] to cope with non-stationarities in feature distributions for robust decoder transfer across tasks and over multiple sessions. Figure 1(a) shows subject-level BCI decoding performance, with a significant improvement from U1 (0.301 ± 0.199) to U2 (0.440 ± 0.232, $p < 0.01$), a decline from U2 to B1 ($p = 0.0185$), and subsequent improvement from B1 (0.217 ± 0.157) to B3 (0.368 ± 0.201, $p < 0.01$). Figures 1(b) and 1(c) reveal that this improvement is guided with increased feature separability, as quantified by the Riemannian distinctiveness metric, improving from U1 (0.125 ± 0.046) to U2 (0.168 ± 0.084, $p = 0.039$) and from B1 (0.104 ± 0.041) to B3 (0.150 ± 0.069, $p < 0.01$).

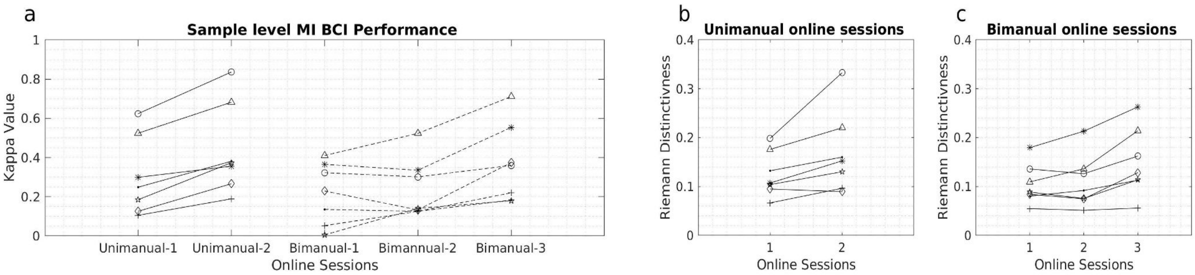

***Figure 1. Bimanual BCI control** a) Kappa value of BCI performance for unimanual (U) and bimanual (B) online sessions. b, c) Riemann Distinctiveness for unimanual and bimanual online sessions, respectively. Each marker represents an individual participant's data point, with lines connecting values across unimanual sessions U1, U2 and bimanual sessions B1, B2, B3.*

Conclusion: Our findings demonstrate that unimanual-trained BCIs can successfully transfer to bimanual tasks, with participants achieving better feature distinctiveness and decoding performance through multi-day training, despite initial performance drops during the unimanual-to-bimanual transition. Our analysis highlights the importance of longitudinal training for robust bimanual BCI control. Our study highlights the viability of transferring unimanual BCI decoders to bimanual tasks, paving the way for more natural and efficient assistive control that enhances real-world functional independence for individuals with motor impairments.

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