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Should robotic limb control mimic the human body? Effect of control strategies on bionic hand skill learning

Hunter R. Schone*[1,2], Malcolm Udeozor[1], Mae Moninghoff[1], Beth Rispoli[1], James Vandersea[3], Blair Lock[4], Levi Hargrove[5,6], Grace Edwards[1], Shruti Japee[1], Tamar R Makin[2,7†] and Chris I. Baker[1†]

[1]Laboratory of Brain & Cognition, National Institute of Mental Health, National Institutes of Health, Bethesda, MD, USA, [2]Institute of Cognitive Neuroscience, University College London, London, UK, [3]Medical Center Orthotics & Prosthetics, Silver Spring, MD, USA, [4]Coapt Engineering, Chicago, IL, USA, [5]Department of Physical Medicine and Rehabilitation, Northwestern University, Chicago, IL, USA, [6]The Regenstein Foundation Center for Bionic Medicine, Shirley Ryan AbilityLab, Chicago, IL, USA, [7]MRC Cognition and Brain Sciences Unit, University of Cambridge, Cambridge, UK; [†] Equal contribution senior authors

*Building 10, Room 4C108, 10 Center Drive, Bethesda, MD, USA 20892. Email: hunter.schone@nih.gov

Introduction: A longstanding engineering ambition has been to design anthropomorphic bionic limbs: devices that look like and are controlled in the same way as the biological body (biomimetic). Biomimetic-inspired design in human-machine interfaces is built on the (untested) assumption that biomimetic devices might allow users to recruit pre-existing neural resources supporting the biological body to assist device control, thereby enhancing device learning, automaticity, generalization, and embodiment. But are these assumptions that underlie biomimetic design valid? Here, we sought to compare biomimetic and non-biomimetic control strategies when learning to operate a bionic hand. As a striking alternative to biomimetic control, we used an arbitrary (non-biomimetic) control strategy, which should, based on the neurocognitive assumptions underlying biomimetic design, provide no direct benefits.

Methods: To assess bionic hand skill learning, we trained able-bodied participants (n=40) over 4 days (2-3 hours per day) to use a wearable EMG-based myoelectric bionic hand operated by an 8-channel EMG pattern recognition system (Figure 1). We compared motor learning across days and behavioural tasks for two training groups: biomimetic (n=20; mimicking the desired bionic hand gesture with biological hand) and arbitrary (n=20; mapping an unrelated biological hand gesture with the desired bionic gesture). After training, we assessed how well the learning would generalize to a new control mapping. We also tested a control group (n=20) that received no bionic hand training. To quantify the neural embodiment of the bionic hand, participants underwent functional MRI scans before and after training (1-week apart for the controls; 120 scans total). In the scanner, participants performed a visuomotor task that assessed visual and motor aspects of bionic hand representation.

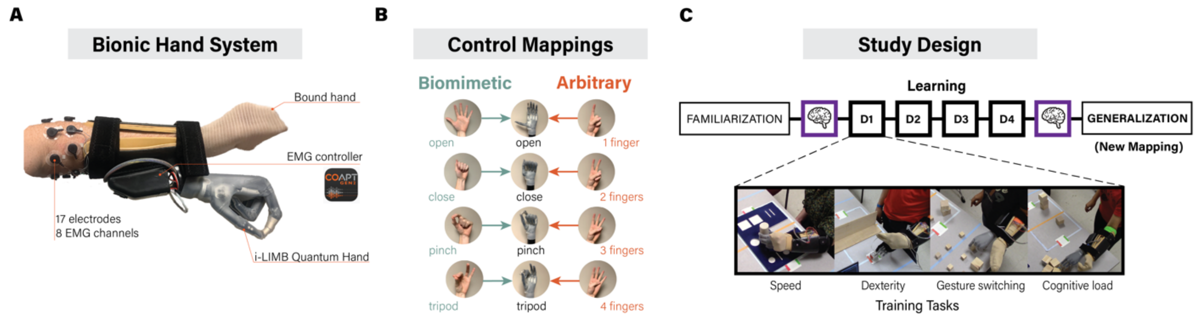

Figure 1. Experimental design of the study. (A) Bionic hand system. **(B)** The control mappings for biomimetic and arbitrary control strategies. **(C)** Experimental design each trained participant underwent. Brains denote when the fMRI scans took place pre- and post-training. D=day.

Results: Trained participants improved motor control, reduced cognitive reliance, and increase sense of embodiment over the bionic hand. Biomimetic control provided more intuitive and faster performance in the early stages of learning. However, when task difficulty was increased (complex gestures, dexterous grasping and gesture switching tasks), biomimetic users performed the same as arbitrary users. Further, arbitrary users showed increased generalization compared to biomimetic users. In the neuroimaging, trained participants showed training-dependent changes in visual and sensorimotor cortex related to different aspects of bionic limb control.

Discussion: It is a widely held assumption that control strategies designed to mimic the biological body might provide unique benefits to the user in terms of device learning, sense of embodiment, automaticity, and generalization. Contrary to this view, across a multitude of tasks, we observed few task advantages for biomimetic control. In summary, our findings suggest that biomimetic and arbitrary control strategies provide different benefits. The optimal strategy likely depends on training opportunities and user requirements.

Significance: Our findings provide a more balanced perspective of the cognitive advantages and limitations of biomimetic motor control. By challenging some of the core assumptions underlying biomimetic inspired design, our findings open up the potential for non-biomimetic control solutions for users.