Patterns in stroke patients' submovements support a paired adaptive forward/inverse learning model

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Submovements, a hypothesized basis set for human movement, have been recorded in healthy subjects' ballistic movements, eye saccades, accurate positioning movements, attempted constant-curvature movements, and attempted constant-velocity movements. Submovements have also been identified in the arm movements of infants' and recovering stroke patients [Krebs et al., 1999 *Proc. Natl. Acad. Sci.* 96:4645-4649] and in both the kinematic data and the EMG patterns generated during slow finger movements. Recently, we studied the smoothness of the arm movements of 31 stroke patients (12 acute and 19 chronic patients) and showed evidence that their submovements changed systematically during recovery [Rohrer et al., 2002 *Journal of Neuroscience* 22:8297-8304]. We then analyzed the submovement characteristics of the movements more directly; we extracted submovements from the kinematic data using an optimization algorithm that seeks a global minimum in the error of the fit.

We found that patients' submovements tended to become **1)** significantly fewer, **2)** longer in duration, **3)** higher in peak velocity, and **4)** more completely blended together. The data also demonstrated that **5)** the inter-peak interval (the time interval between adjacent submovement peaks) decreased for acute patients, but not for the others. Changes were considered significant at $p < 0.05$. This last finding suggests that different aspects of sensory-motor recovery take place on different schedules and that this progression may hint at the underlying neurological processes.

Based on the observed changes during recovery, we hypothesize a motor controller consisting of paired adaptive forward and inverse models, employing discrete rather than continuous motor commands. Our model is similar in structure to that proposed by Bhushan and Shadmehr [1999 *Biological Cybernetics* 81:39-60], especially in that it incorporates time delays.

The expected behavior of a discrete-input forward/inverse model is consistent with the changes observed in the submovement characteristics of stroke patients. Training of the forward model would allow the motor control system to predict the result of a move in progress based on sensory information, and hence would allow corrective submovements to be initiated earlier, decreasing the inter-peak interval**(5)**. Analysis results of acute patients' kinematics are consistent with this prediction. Additionally, training of the inverse model would allow the motor control system to predict the results of an attempted submovement and hence allow submovements of longer duration**(2)** and higher peak speed**(3)** to be made without increasing the endpoint error. As this occurs, fewer submovements**(1)** would be required to complete a given movement. Improvements in both the forward and inverse models would contribute to increasing submovement overlap**(4)** as submovements grow closer together and longer in duration. Results from both acute and chronic patients are consistent with this model.

The model also predicts that, given limited computational resources, performance would be maximized by initially improving the forward model, then refining the inverse model [Bhushan and Shadmehr, 1999]. The fact that the inter-peak interval, a quantity closely associated with the quality of the forward model, improves for acute but not chronic patients shows that the time-course of recovery reflected in the data is consistent with the model.