How to average movement data? Decoupling spatial and temporal variability to extract salient features in time series

Aleksei Krotov, Reza Sharif Razavian, Mohsen Sadeghi, Dagmar Sternad

Motor neuroscience research examines a wide spectrum of actions, ranging from finger tapping to cracking a whip. Even the simplest of such actions show variability arising from various sources in the sensorimotor loop. To extract interpretable features from the measured spatiotemporal profiles, the multiple repetitions of movement are typically summarized by calculating the mean and variance in the spatial domain, typically after time normalization, resampling, and binning of the sampled data. The resulting mean profile aims to highlight the essential characteristics of the ensemble to provide a basis for insights into control priorities. The band of standard deviations around the mean is interpreted as reflection of exploration, performance refinement, and learning. However, such extraction of summary statistics is far from straightforward, as every single movement is affected by potentially different variability in the spatial and temporal domains that cannot easily be dissociated. Due to such coupling, simple averaging across repeated timeseries can lose information in both spatial and temporal dimensions of the movement. This issue has been recognized in the motor control literature but has rarely been accounted for in a systematic way.

This work explored and discussed several techniques to decouple variability into spatial and temporal components and to extract salient characteristics separately for these two domains. In particular, we present a powerful method, called elastic functional analysis, which has been successfully applied in statistics, animation, and shape analysis, but only very rarely in motor neuroscience. This method uses optimization procedures to rescale the temporal evolution in a nonlinear fashion to align salient features, such as peaks, valleys, and slopes of an ensemble of time-series. This technique was compared with conventional time-normalization and time-padding, using synthesized signals with controlled levels of induced variability, as well as real hand kinematics of a three-dimensional unconstrained reaching task. Systematic analysis of these data demonstrates that the elastic functional analysis method can be successfully applied to movement signals. It teases apart temporal and spatial variability and can substantially mitigate the potential biases in movement features when using conventional methods. Other application examples are presented and implications of this method in motor neuroscience are discussed and may inform the research when extracting subtle and otherwise covert features of movement kinematics.