Statistical Models and Algorithms for Studying Hand and Finger Kinematics and their Neural Mechanisms

Abstract:
Despite a century of research, the neural mechanisms that enable finger and grasping movements in primates are largely unknown. The primate hand forms a complex anatomical structure, containing over twenty kinematic degrees of freedom. And while it requires complex, coordinated control, endows its owner with an astounding range of dexterous finger movements.

In this thesis, we investigate statistical models of finger movement that can provide insights into the mechanics of the hand and that can have applications in neural-motor prostheses that enable people living with limb loss to regain natural function of hands.

There are number of challenges associated with (1) the understanding and modelling of the kinematics of fingers, and (2) the mapping of intracortical neural recordings into motor commands that can be used to control a Brain Machine Interface. These challenges include: potential non linearities, confounded sources of variation in experimental datasets, as well as dealing with high degrees of kinematic freedom.

In this work, we analyze kinematic and neural datasets from repeated trial experiments of hand motion and offer the following contributions:

+ We explore the extraction of static non linear synergies of finger motion and their encoding in the firing of neurons collected from the primary motor cortex of rhesus monkeys.
+ We propose the functional alignment of grasping trajectories based on total kinetic energy as a strategy to account for temporal variation and exploit repeated-trial experiment structure.
+ We propose an interpretable model based on Gaussian Processes to extract dynamic synergies of finger motion that decomposes and reduces the dimensionality of variance in the dataset. We derive efficient algorithms for parameter estimation, show accurate reconstruction of grasping trajectories and illustrate the interpretation of the model parameters.
+ We show evidence of single neuron decoding of interpretable grasping events and provide insights about the amount of grasping information extractable from just a single neuron.
+ We present the Laplace Gaussian Filter (LGF), a deterministic approximation to the posterior mean that is more accurate than Monte Carlo approximations for the same computational cost, and that in an off-line decoding task is more accurate than the standard Population Vector Algorithm.

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