Studying octopus motor control using a computerized dynamic model

Yekutieli Y.[1,2], Sagiv R.[1], Hochner B[1,2] and Flash T.[3]
[1]Dept. of Neurobiology, Institute of Life Science and [2]Interdisciplinary Center for Neural Computation, Hebrew University of Jerusalem, Jerusalem 91904, Israel; [3]Dept. of Applied Mathematics, Weizmann Institute of Science, Rehovot 76100, Israel

Octopus arms are extraordinary organs; they are highly flexible, move with a wide range of velocities, are able to exert great force and grip, and can delicately manipulate objects. Octopus arms belong to a group of organs termed muscular hydrostats, which are built almost entirely of muscles with no rigid skeletal support. The basic biomechanical principles that govern the movement of muscular hydrostats are relatively well understood (Kier and Smith, 1985). However, how this hyper-redundant arm with its virtually infinite number of degrees of freedom is controlled, is largely unknown.

Several studies by our group described the reaching movement of the octopus arm towards an external object. Gutfreund et al. (1996) showed that the arm extension is performed by a stereotypical forward propagation of a bend along the arm. Gutfruend et al. (1998) described the muscles activation pattern during a reaching movement, whereas Sumbre et al. (2001) described the autonomous ability of the octopus arm, when electrically stimulated, to perform extension movement even when it is disconnected from the octopus brain.

Here we describe a dynamic model of the octopus arm that is used to study possible control strategies of the reaching movement where a bend in the arm travels towards the tip.

The model includes both external forces (gravity, buoyancy and water drag forces) and internal forces (muscle forces and constant volume constraint forces) and it is controlled by an activation signal (a simplified neuronal command) that travels along the arm.
The main findings are:

1. A simple activation wave, which moves at a constant velocity, is sufficient for the model to replicate the natural reaching movement with similar kinematic characteristics.
2. The biomechanical mechanism that produced the reaching movement is a stiffening wave – a wave of muscle contraction that pushes forward a bend along the arm. We show that during the simulated reaching movement the fully activated muscles proximal to the bend point work mainly in an isometric manner, whereas the muscles distal to the bend point are predominantly passive.
3. A comparison between two muscle models, with linear and non-linear force-length curves, has led to similar results for the simulated reaching movements. Therefore, it is justified to use the much faster linear muscle model (10 times lower computation time) for reaching movement simulations.
4. We investigated the possibility that the control of only two parameters might fully specify the extension movement: the amplitude of the activation pulse (that leads to the generation of muscle force) and the activation time (the time it takes the activation wave to travel along the arm). We show that the same kinematics can be achieved by applying different activation amplitudes above some threshold. The minimal amplitudes (just above the threshold) generate minimal muscle forces that are needed to produce the desired kinematics, while larger amplitudes generate larger forces that increase the arm's stability against perturbations without changing the kinematic characteristics.

References:

Gutfreund Y, Flash T, Yarom Y, Fiorito G, Segev I and Hochner B. (1996) Organization of octopus arm movements: a model system for studying the control of flexible arms. ***The Journal of Neuroscience*** **16(22)**: 7297-7307.

Gutfreund Y, Flash T, Fiorito G and Hochner B. (1998) Patterns of arm activation involved in octopus reaching movements. ***The Journal of Neuroscience*** **18(15)**: 5976-5987.

Kier W M and Smith K K. (1985) Tongues, tentacles and trunks: the biomechanics of movement in muscular – hydrostats. ***Zoological Journal of the linnean society*** **83**, 307-324.

Sumbre G, Gutfreund Y, Fiorito G, Flash T and Hochner B. (2001) Control of Octopus Arm Extension by a Peripheral Motor Program. ***Science***, **293**, 1845-1848.