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Limb Movement: Getting a Handle on Grasp

Dispatch

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The mechanical complexity of the hand is indisputable, but there is increasing evidence that its control is simplified in many tasks around synergic groups of muscles that effectively decrease the number of controlled degrees of freedom.

In 1982, Georgopoulos and colleagues [1] reported a study that created a paradigm shift in the manner in which we think about the way the brain controls limb movement. Their work showed that it is possible to reduce much of the complexity of control at the level of the primary motor cortex to a set of neurons with 'preferred directions', which simply specify the direction of hand motion. The complex control of grasping would appear to be another matter entirely. The human hand contains 27 bones which give it roughly 25 degrees of freedom, or ways of moving. Judging from the oversized hands in the classic homunculus [2], a disproportionate amount of the cerebral cortex is devoted to controlling the roughly 40 muscles necessary to actuate the hand. Can there be any hope that control of the hand will yield to similar simplification?

An electromyographic (EMG) study reported recently by Brochier *et al.* [3] suggests that such simplification may be possible. In this study, two monkeys were trained to grasp several different objects while recordings were made of the activity of 10–12 muscles of the digits, hand and arm. The goal was to identify a grasped object based on its EMG signature, a simple measure of the activity across these muscles. The complex waveform of activity produced by each muscle during a grasp was reduced to a single value, the magnitude of normalized activity that occurred midway through the movement. This set of measurements can be thought of as representing a single point within a multi-dimensional muscle space. The authors asked whether this point would be adequate to identify the grasped object.

Data were collected during 20 different experimental sessions, in which data points were averaged across five blocks of 10 reaches to each of six objects. This yielded 30 points within the muscle space for each session. Nearest neighbors within this space were progressively combined to form clusters using a hierarchical cluster analysis. If the points resulting from grasping a particular object were significantly closer to each other than to those of other objects, they should have formed identifiable clusters. Remarkably, the analysis correctly clustered and identified all of the points for both monkeys within any given session. Similar results were obtained across sessions, using data averaged over all the reaches in a given session. Even across monkeys, most of the grasps of like objects clustered together. The precise time at which the measurement was made was not critical — points taken within the latter half of the grasp worked approximately equally well.

Brochier *et al.* [3] found that there are significant correlations among the different muscles that are active during grasping, suggesting that the dimensionality of the control signal may actually be significantly smaller than the number of muscles. The authors demonstrated this reduction by calculating a set of mutually orthogonal 'principle components' from their cloud of data points. Differing numbers of these components were used to reconstruct the points in a lower dimensional space. Objects were still identified with 98% accuracy using only five of the twelve principle components.

The idea that seemingly complex movements may be controlled by a relatively simple set of muscle synergies is also supported by results obtained in a completely different system, hindlimb kicking movements in frogs. Using a novel approach, d'Avella *et al.* [4] extracted a set of time-varying 'synergies' from the recordings made from 13 muscles during repeated kicking movements in different directions. These synergies consisted of groups of muscles whose activity was coherent in either space or time. Using just three of these synergies, it was possible to account for 65% of the variance of a novel dataset that had not been used in the original synergy estimation. According to the authors, the composition and temporal structure of the different synergies appeared to be functionally specific.

These results are consistent with another recent study [5] that examined the kinematics of grasping. Although primarily concerned with factors that determine hand shape and grip force of different objects, this study confirmed in monkeys an important observation made earlier in humans. Seventeen different positions of the wrist, hand and digits were monitored as two monkeys repeatedly grasped 16 different objects. The hand postures over many trials were subjected to a singular value decomposition analysis that serves essentially the same purpose as principle component analysis. The resultant eigenvectors — or 'eigenpostures' in this group's terminology — provide mutually orthogonal axes that can be used to represent variation in the static posture of the hand while gripping different objects.

The essential result was a tremendous reduction in the number of degrees of freedom that were actually used to grasp the different objects. In this study [5], the first eigenvector accounted for fully 93% of the different hand postures. In an earlier study with human subjects and a wider range of objects, three principle

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components accounted on average for approximately 90% of the variance [6].

Stereotypic grasping represents perhaps an extreme of dimensionality reduction. In fact, the hand is clearly capable of adopting an infinite range of postures that would not be well defined by only three to four degrees of freedom. Despite the hand's large number of degrees of freedom, however, certain finger movements cannot be made independently of one another. Some of this limitation appears to be the result of passive mechanical coupling arising from a variety of sources. In humans, this is true in particular of the index, middle and ring fingers. But independent movements of the ring and little fingers during relatively large movements are also significantly constrained by limitations of neuromuscular control [7].

It is tempting to conclude that the further dimensionality reduction during stereotypic grasping is the result of muscle synergies represented within the central nervous system that serve to simplify the control problem for certain hand movements. Some evidence for this view was demonstrated by a study [8] of the relationship between M1 discharge and the activity of groups of muscles. Multi-dimensional preferred directions in 'muscle-space', analogous to the classic preferred directions of Georgopoulos *et al.* [1], represented the set of muscles that were consistently activated with a given neuron. A cluster analysis was performed on a set of these vectors derived from data collected while monkeys reached toward and pressed a series of different buttons. Rather than being distributed uniformly within this space, these vectors were found to be grouped into a small number of clusters, several of which represented functionally distinct groups of muscles [8]. The vectors for individual neurons proved to be quite stable across time, and were reasonably well preserved across several different grasping tasks as well as button pressing [9].

There is abundant evidence that the complex muscle activity mediating limb withdrawal, scratching and locomotion can be generated by spinal circuitry, at least in animals such as frogs and cats, and possibly in primates, including humans [10]. The grasp reflex, evident in infants, and sometimes expressed with abnormal intensity following spinal cord injury, may also have a spinal origin [11]. The results described here support the idea that the normal control of grasping, as well as other stereotypic movements, is based on branched descending projections and spinal circuits that define an underlying basis set of muscle synergies. These synergies can be combined in various ways that may potentially simplify the control of a range of complex movements.

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