Francesco Lacquaniti- Modular Control of Human Locomotion

Functional modules are thought to be the underlying basis of motor control. Initially considered as a way to reduce dimensionality, it has recently been suggested that they are present as a way to construct complex motions and tasks from simple patterns.

There has been literature showing that there appear to be center pattern generators (CPGs) present in rodents that are organized as flexor and extensor modules, which are regulated by interneurons in the spinal cord. However, this simple system isn't present in humans, so we need more advanced techniques to extract the hidden patterns responsible for motor control.

Indeed it is possible to approximate the motor activations by combination of temporal waveforms and weights, which we present as the so called muscle synergies. Several approaches exist for obtaining these synergies and each have different assumptions but they produce similar results, namely in the case of locomotion there are 4 components that represent 90% of all variance from 16 muscles. These muscle synergies are functional and correspond to weight acceptance, propulsion, foot lift, leg deceleration which each represent activation of ankle, knee or hip muscles.

Similarly to what was found in rats there is a connection between ipsilateral and contralateral sides that modulated by spinal inhibitory interneurons. However, there is a evidence that there must be a supraspinal component as well, since cerebellar patients do not exhibit the same adaptations to speed perturbations on split belts.

The question though is whether multiple muscles share a common neural drive or the patterns are simply due to biomechanical constraints, and each muscle has an independent neural drive. In order to rule out this possibility a previous study was performed, with data recorded in isometric conditions with HD EMG. The results showed that only 5-25% of net activity input is accounted for by a specific coherence, which emphasizes the existence of this common drive. Nevertheless, muscle synergies are task dependent. For instance, walking in different directions can lead to different muscle synergies despite kinematic similarity. Additionally, if you add more muscles you get more synergies.

The concept of modularity allows for superposition of different synergies in an additive manner, for instance we can have a walking synergy combined with a voluntary task, such as picking up an object.

Next we wanted to evaluate if we could reveal this modularity independent of statistics, and the approach that has been taken is to use spinal maps. The spinal maps represent the dynamic activation that is going on in the spinal cord, and we found four bursts of activity, which were synchronized with the synergies that we previously discussed.

Additionally, we looked at different populations to determine how synergies were affected by pathology. In the case of spinal cord injured patients, after training with the body weight support they improved in their kinematics, meaning that we found plastic spatial reorganization in the spinal cord. This leads to different spinal maps and high subject variability. Four main synergies still exist amongst this subject population, though different than for the able bodied subjects previously studied. In patients with cerebellar ataxia the synergies were not altered significantly, excepting for changes in temporal variance. In other conditions there were similar results, with some examples of compensating synergies.

Synergies are also of interest when it comes to development. It has been shown that newborns can produce automatic forward stepping motions, however this disappears after a few months, to later be replaced by volitional forward and backward stepping. This is reflected in the muscle synergy organization. In neonates we find 2 muscle synergies similar to simple sine waves, and in older children two additional synergies appear, which narrow until reaching adulthood.

Cerebral palsy was also considered, and it was found that subjects with the disorder have synergies that are much closer to those of toddlers and this difference is also represented in spinal maps.

In conclusion, modularity was revealed by different methods and shown to be task-dependent. Modules can be superimposed additively (such as with locomotion and voluntary tasks). Through learning and development modules can be added to produce more complex behaviors. On the other hand they can also be affected by impairments. But rehabilitation and training can lead to compensation for these problems. Accordingly training whole limbs instead of single joints may lead to better improvements.