Muscle memory

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Muscle memory has been used synonymously with motor learning, which is a form of procedural memory that involves consolidating a specific motor task into memory through repetition. When a movement is repeated over time, a long-term muscle memory is created for that task, eventually allowing it to be performed without conscious effort. This process decreases the need for attention and creates maximum efficiency within the motor and memory systems. Examples of muscle memory are found in many everyday activities that become automatic and improve with practice, such as riding a bicycle, typing on a keyboard, typing in a PIN, playing a musical instrument, martial arts or even dancing.

Physiology

Motor behavior

When first learning a motor task, movement is often slow, stiff and easily disrupted without attention. With practice, execution of motor task becomes smoother, there is a decrease in limb stiffness, and muscle activity necessary to the task is performed without conscious effort.

Muscle memory encoding

The neuroanatomy of memory is widespread throughout the brain; however, the pathways important to motor memory are separate from the medial temporal lobe pathways associated with declarative memory. As with declarative memory, motor memory is theorized to have two stages: a short-term memory encoding stage, which is fragile and susceptible to damage, and a long-term memory consolidation stage, which is more stable.

The memory encoding stage is often referred to as motor learning, and requires an increase in brain activity in motor areas as well as an increase in attention. Brain areas active during motor learning include the motor and somatosensory cortices; however, these areas of activation decrease once the motor skill is learned. The prefrontal and frontal cortices are also active during this stage due to the need for increased attention on the task being learned.[7]

The main area involved in motor learning is the cerebellum. Some models of cerebellar-dependent motor learning, in particular the Marr-Albus model, propose a single plasticity mechanism involving the cerebellar long-term depression (LTD) of the parallel fiber synapses onto Purkinje cells. These modifications in synapse activity would mediate motor input with motor outputs critical to inducing motor learning. However, conflicting evidence suggests that a single plasticity mechanism is not sufficient and a multiple plasticity mechanism is needed to account for the storage of motor memories over time. Regardless of the mechanism, studies of cerebellar-dependent motor tasks show that cerebral cortical plasticity is crucial for motor learning, even if not necessarily for storage.

The basal ganglia also play an important role in memory and learning, in particular in reference to stimulus-response associations and the formation of habits. The basal ganglia-cerebellar connections are thought to increase with time when learning a motor task.[12]

Muscle memory consolidation

Muscle memory consolidation involves the continuous evolution of neural processes after practicing a task has stopped. The exact mechanism of motor memory consolidation within the brain is controversial. However, most theories assume that there is a general redistribution of information across the brain from encoding to consolidation. Hebb's rule states that "synaptic connectivity changes as a function of repetitive firing." In this case, that would mean that the high amount of stimulation coming from practicing a movement would cause the repetition of firing in certain motor networks, presumably leading to an increase in the efficiency of exciting these motor networks over time.

Though the exact location of muscle memory storage is not known, studies have suggested that it is the inter-regional connections that play the most important role in advancing motor memory encoding to consolidation, rather than decreases in overall regional activity. These studies have shown a weakened connection from the cerebellum to the primary motor area with practice, it is presumed, because of a decreased need for error correction from the cerebellum. However, the connection between the basal ganglia and the primary motor area is strengthened, suggesting the basal ganglia plays an important role in the motor memory consolidation process.

Strength training and adaptations

When participating in any sport, new motor skills and movement combinations are frequently being used and repeated. All sports require some degree of strength, endurance training, and skilled reaching in order to be successful in the required tasks. Muscle memory related to strength training involves elements of both motor learning, described below, and long-lasting changes in the muscle tissue.

Evidence has shown that increases in strength occur well before muscle hypertrophy, and decreases in strength due to detraining or ceasing to repeat the exercise over an extended period of time precede muscle atrophy. To be specific, strength training enhances motor neuron excitability and induces synaptogenesis, both of which would help in enhancing communication between the nervous system and the muscles themselves.

However, neuromuscular efficacy is not altered within a two-week time period following cessation of the muscle usage; instead, it is merely the neuron's ability to excite the muscle that declines in correlation with the muscle's decrease in strength. This confirms that muscle strength is first influenced by the inner neural circuitry, rather than by external physiological changes in the muscle size.

Previously untrained muscles acquire newly formed nuclei by fusion of satellite cells preceding the hypertrophy. Subsequent detraining leads to atrophy but no loss of myo-nuclei. The elevated number of nuclei in muscle fibers that had experienced a hypertrophic episode would provide a mechanism for muscle memory, explaining the long-lasting effects of training and the ease with which previously trained individuals are more easily retrained.

On subsequent detraining, the fibers maintain an elevated number of nuclei that might provide resistance to atrophy; on retraining, a gain in size can be obtained by a moderate increase in the protein synthesis rate of each of these many nuclei, skipping the step of adding newly formed nuclei. This shortcut may contribute to the relative ease of retraining compared with the first training of individuals with no previous training history.

Reorganization of motor maps within the cortex are not altered in either strength or endurance training. However, within the motor cortex, endurance induces angiogenesis within as little as three weeks to increase blood flow to the involved regions. In addition, neurotropic factors within the motor cortex are upregulated in response to endurance training to promote neural survival.

Skilled motor tasks have been divided into two distinct phases: a fast-learning phase, in which an optimal plan for performance is established, and a slow-learning phase, in which longer-term structural modifications are made on specific motor modules. Even a small amount of training may be enough to induce neural processes that continue to evolve even after the training has stopped, which provides a potential basis for consolidation of the task. In addition, studying mice while they are learning a new complex reaching task, has found that "motor learning leads to rapid formation of dendritic spines (spinogenesis) in the motor cortex contralateral to the reaching forelimb". However, motor cortex reorganization itself does not occur at a uniform rate across training periods. It has been suggested that the synaptogenesis and motor map reorganization merely represent the consolidation, and not the acquisition itself, of a specific motor task. Furthermore, the degree of plasticity in various locations (namely motor cortex versus spinal cord) is dependent on the behavioural demands and nature of the task (i.e., skilled reaching versus strength training).

Whether strength or endurance related, it is plausible that the majority of motor movements would require a skilled moving task of some form, whether it be maintaining proper form when paddling a canoe, or bench pressing a heavier weight. Endurance training assists the formation of these new neural representations within the motor cortex by up regulating neurotropic factors that could enhance the survival of the newer neural maps formed due to the skilled movement training. Strength training results are seen in the spinal cord well before any physiological muscular adaptation is established through muscle hypertrophy or atrophy. The results of endurance and strength training, and skilled reaching, therefore, combine to help each other maximize performance output.