Muscle spindles

❖ Definition:

Muscle spindles are skeletal muscle sensory receptors (stretch receptors) within the body of a muscle that primarily detect changes in the length of the muscle contributing to fine motor control. They convey length information (axial and limb position information) to the central nervous system via afferent nerve fibers. This information can be processed by the brain as proprioception. The responses of muscle spindles to changes in length also play an important role in regulating the contraction of muscles, for example, by activating motor neurons via the stretch reflex to resist muscle stretch.

❖ Structure and Composition:

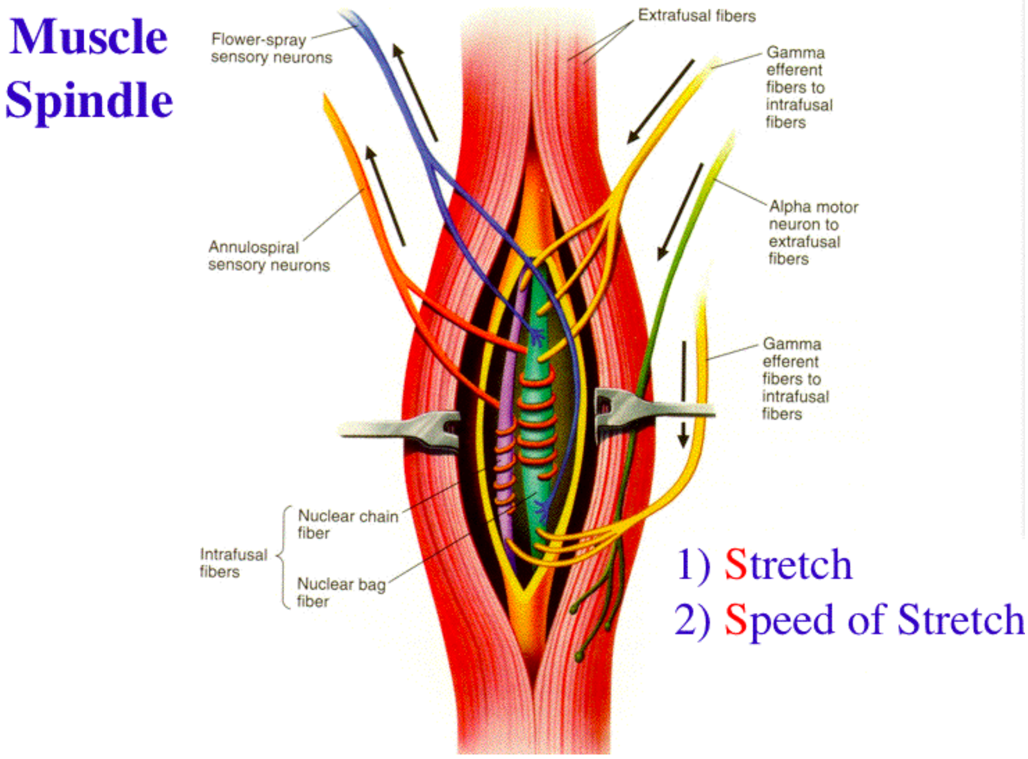


Figure: The muscle spindle is a proprioceptor, a sense organ that receives information from muscle, that senses STRETCH and the SPEED of the stretch. When you stretch and feel the message that you are at the ENDPOINT of your stretch the spindle is sending a reflex arc signal to your spinal column telling you not to stretch any further. This sense organ protects you from overstretching or stretching too fast and hurting yourself.

Muscle spindles are small sensory organs with an elongated shape. They are proprioceptors that consist of several modified muscle fibers enclosed in a sheath of connective tissue. These modified fibers are called **intrafusal fibers**. Muscle spindles are composed of 5-14 intrafusal muscle fibers, of which there are three types:

1. Dynamic nuclear bag fibers (bag$_1$ fibers),
2. Static nuclear bag fibers (bag$_2$ fibers), and
3. Nuclear chain fibers.

Intrafusal muscle fibers are oriented parallel to the regular, power-producing **extrafusal muscle fibers**. Intrafusal muscle fibers are at both ends connected to either tendinous ligaments or extrafusal fibers, namely contractile proteins. So, intrafusal fibers are stretched or shortened correspondingly, when extrafusal fibres change length. The central part of the muscle spindle is covered with a capsule of connective tissue. The sensory dendrites of the muscle spindle afferent wrap the central region. The muscle spindle is stretched when the muscle lengthens increase, this opens mechanically-gated ion channels in the sensory dendrites. This leads to a receptor potential that triggers action potentials in the muscle spindle afferent.

- The muscle spindle has both sensory and motor components.There are two types of sensory endings found in muscle spindles: the primary and secondary endings of spindles, which are located in the middle of the spindle.
    - Sensory information conveyed by primary **type Ia sensory fibers** (large diameter) which spiral around all intrafusal muscle fibres within the spindle, ending near the middle of each fibre. The primary endings respond to its speed and the size of a muscle length change. They belong

to the fastest axons as they are myelinated. They contribute both to movement and the sense of limb position.

- **Secondary type II sensory fibers** (medium diameter) end adjacent to the central regions of the static bag and chain fibres. These fibres send information by stretch-sensitive mechanically-gated ion-channels of the axons. Secondary endings are only sensitive to length and not to velocity, so they contribute only to the sense of the position. These endings have smaller axons and thus slower conduction speed.

Both endings in muscle spindles are very sensitive to low-amplitude changes in muscle length, especially if these changes occur at a high frequency. A spindle ending is located at the end of a neuron or an axon whose body is in the spinal ganglion.

- The motor part of the spindle is provided by motor neurons: up to a **dozen gamma motor neurons** and one or two **beta motor neurons**, collectively called **fusimotor neurons**. These activate the muscle fibres within the spindle. Gamma motor neurons supply only muscle fibres within the spindle, whereas beta motor neurons supply muscle fibres both within and outside of the spindle. Activation of the neurons causes a contraction and stiffening of the end parts of the muscle spindle muscle fibers.

Fusimotor neurons are classified as static or dynamic according to the type of muscle fibers they innervate and their effects on the responses of the Ia and II sensory neurons innervating the central, non-contractile part of the muscle spindle.

- The static axons innervate the chain or static bag$_2$ fibers. They increase the firing rate of Ia and II afferents at a given muscle length.

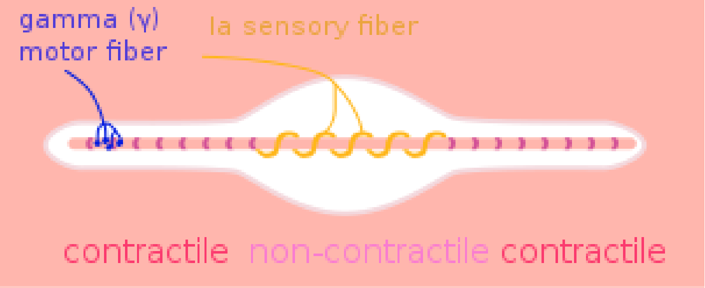
- The dynamic axons innervate the bag$_1$ intrafusal muscle fibers. They increase the stretch-sensitivity of the Ia afferents by stiffening the bag$_1$ intrafusal fibers.

Efferent nerve fibers of gamma motoneurons also terminate in muscle spindles; they make synapses at either or both of the ends of the intrafusal muscle fibers and regulate the sensitivity of the sensory afferents, which are located in the non-contractile central (equatorial) region.

❖ Function of muscle spindle:

1. Stretch reflex:

When a muscle is stretched, primary type Ia sensory fibers of the muscle spindle respond to both changes in muscle length and velocity and transmit this activity to the spinal cord in the form of changes in the rate of action potentials. Likewise, secondary type II sensory fibers respond to muscle length changes (but with a smaller velocity-sensitive component) and transmit this signal to the spinal cord. The Ia afferent signals are transmitted monosynaptically to many alpha motor neurons of the receptor-bearing muscle. The reflexly evoked activity in the alpha motoneurons is then transmitted via their efferent axons to the extrafusal fibers of the muscle, which generate force and thereby resist the stretch. The Ia afferent signal is also transmitted polysynaptically through interneurons (Ia inhibitory interneurons), which inhibit alpha motorneurons of antagonist muscles, causing them to relax.



2. Sensitivity modification:

The function of the gamma motor neurons is not to supplement the force of muscle contraction provided by the extrafusal fibers, but to modify the sensitivity of the muscle spindle sensory afferents to stretch. Upon release of acetylcholine by the active gamma motor neuron, the end portions of the intrafusal muscle fibers contract, thus elongating the non-contractile central portions. This opens stretch-sensitive ion channels of the sensory endings, leading to an influx of sodium ions. This raises the resting potential of the endings, thereby increasing the probability of action potential firing, thus increasing the stretch-sensitivity of the muscle spindle afferents.

How does the central nervous system control gamma fusimotor neurons? It has been difficult to record from gamma motoneurons during normal movement because they have very small axons. Several theories have been proposed, based on recordings from spindle afferents.

1) ***Alpha-gamma coactivation***: Here it is posited that gamma motoneurons are activated in parallel with alpha motoneurons to maintain the firing of spindle afferents when the extrafusal muscles shorten.
2) ***Fusimotor set:*** Gamma motoneurons are activated according to the novelty or difficulty of a task. Whereas static gamma motoneurons are continuously active during routine movements such as locomotion, dynamic gamma motoneurons tend to be activated more during difficult tasks, increasing Ia stretch-sensitivity.
3) ***Fusimotor template of intended movement:*** Static gamma activity is a "temporal template" of the expected shortening and lengthening of the receptor-bearing muscle. Dynamic gamma activity turns on and off abruptly, sensitizing spindle afferents to the onset of muscle lengthening and departures from the intended movement trajectory.

3. Development:

It is also believed that muscle spindles play a critical role in sensorimotor development.

❖ Example of muscle spindle activity:

A simple example of muscle spindle activity is the knee jerk reflex (Patellar reflex), sudden kicking movement of the lower leg in response to a sharp tap on the patellar tendon, which lies just below the kneecap. Tapping on the tendon of the knee extensor muscle group below the patella stretches the muscle spindle fibers. This causes activation of extrafusal muscle fibers in the same muscle. A knee jerk occurs as these fibers actively shorten. This, in turn, shortens the intrafusal fibers and causes their discharge to cease.

One of the most common positions that a health care professional will ask a patient to take for the test is to sit with knees bent and with one leg crossed over the other so that the upper foot hangs clear of the floor. The sharp tap on the tendon causes a stretch to the quadriceps. In reaction, these muscles contract, and the contraction elicits knee extension or straighten the leg in a kicking motion. Exaggeration or absence of the reaction suggests that there may be damage to the central nervous system. The knee jerk can also be helpful in recognising thyroid disease.

❖ Clinical significance:

After stroke or spinal cord injury in humans, spastic hypertonia (spastic paralysis) often develops, whereby the stretch reflex in flexor muscles of the arms and extensor muscles of the legs is overly sensitive. This results in abnormal postures, stiffness and contractures. Hypertonia may be the result of over-sensitivity of alpha motoneurons and interneurons to the Ia and II afferent signals