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SENSORY AND MOTOR NEURONES AND SPINAL REFLEXES: A NARRATIVE REVIEW

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Abstract: *Neurones are specialised, polarised cells that transmit electrical and chemical signals, underpinning both simple reflexes and complex motor behaviours. Sensory (afferent) neurones relay peripheral information to the central nervous system (CNS), while motor (efferent) neurones convey commands to skeletal muscles. Interneurones within the spinal cord integrate these signals, enabling coordinated motor output. The spinal cord's dorsal, ventral, and lateral horns support sensory processing, motor execution, and the integration of ascending and descending pathways. Spinal reflexes are rapid, stereotyped responses mediated by organised neural circuits. Monosynaptic reflexes, such as the myotatic (stretch) reflex, involve direct sensory–motor communication, regulated by γ-motoneurones and reciprocal inhibition to maintain muscle length and tone. Polysynaptic reflexes, including the flexor withdrawal reflex, engage interneurones to coordinate synergistic and antagonistic muscle activity, adapting to limb posture, stimulus location, and contextual factors. The inverse myotatic reflex, mediated by Golgi tendon organs, safeguards muscles and ligaments by modulating force during contraction. These reflexes employ reciprocal, non-reciprocal, presynaptic, and recurrent inhibitory mechanisms, collectively ensuring precise, adaptable, and stable motor control. A detailed understanding of sensory and motor neurone organisation and spinal reflex dynamics is essential for elucidating human movement, informing clinical assessment, and guiding neuromuscular rehabilitation.*

Keywords: *sensory neurons, motor neurons, spinal reflexes*

INTRODUCTION

Neurones are highly polarised specialised cells (Seong, Yuan, & Arikkath, 2015) that act as the primary communicators which transmit electrical and chemical signals across complex neural circuits, enabling everything from simple reflexes to advanced problem-solving (Rasband, 2016). So, according to the functions, neurones can be classified into three categories: sensory or afferent neurones, motor or efferent neurones, and interneurones (Chan et al., 2025).

The human spinal cord is a highly organised, complex part of the central nervous system (the CNS) whose function is to ensure the conduction of neural signals from the peripheral nervous system to the brain and from the brain to the peripheral nervous system, which are relayed and controlled by the spinal interneurones (De Leener, Taso, Cohen-Adad, & Callot, 2016). Therefore, the spinal cord is divided into posterior (dorsal), anterior (ventral) and lateral (middle) horns and is surrounded by ascending and descending tracts (the white matter), which is divided by the grey matter into posterior, lateral and anterior columns (Cho, 2015). So, the dorsal segment (the dorsal horns) mediates exteroceptive sensory processing, the ventral segment (the ventral horns) is crucial for motor execution and the generation of rhythmic motor behaviour, while the middle segment is thought to play a major role in the integration of ascending and descending information for fine-tuning motor output (Ossewald & Pfaff, 2019).

The reflex arc is the anatomical nervous pathway (Jaiswal & Morankar, 2017) which is responsible for the passage of nervous impulses from the receptors to the CNS by the afferent tracts and for the transport of electric impulses to target organs (muscles) by the efferent tracts (Nuzhna, Iakovenko, Gryshchenko, Cherno, Khmyzova, & Yastremskiy, 2018). So, the reflex is defined as an involuntary, qualitatively unchanging reaction of the nervous system to a specific stimulus, and it has five basic components: different receptors, the sensory or afferent neurones, receptors of the CNS, the motor or efferent neurones, and the effectors (e.g., organs and muscles) (Costa, da Veiga Argus, Pisetta, & Evangelista, 2020). Therefore, reflexes play multiple roles, such as for posture, for locomotion, and for maintaining homeostasis in the organism (Costa et al., 2020), and they have a protective role for the body from irreparable damage (Jaiswal & Morankar, 2017).

This review summarises the current knowledge about the sensory and motor neurones and the spinal reflexes based on the literature review with the aim to describe them as well as mechanisms of their action.

Method

This manuscript presents a narrative review and does not report any original data. The literature included in this review was identified through searches of PubMed, which served as the primary database, and Google Scholar, which was used as a supplementary database. The search strategy employed the following terms and Boolean operators: ("sensory neurone" OR "afferent neurone") AND ("motor neurone" OR "efferent neurone") AND ("reflexes" OR "spinal reflexes"). In addition, reference lists of the selected articles were manually screened to identify further relevant publications.

The inclusion criteria comprised full-text articles published in English within the last ten years that focused on key components of the CNS as the primary subject of investigation. Exclusion criteria included conference abstracts and articles without full-text availability, publications not written in English, articles published more than ten years prior to the search, and studies that did not address the specified key components of the CNS.

Sensory neurones

Sensory neurones possess only afferent fibres, and they carry the information obtained from the interior of the body and the external environment to the CNS (Varga & Mravec, 2015). Sensory neurones are primary afferents originating from the neural crest that convey information from the periphery to the central nervous system (Crawford & Caterina, 2020). Their axons enter the spinal cord via the dorsal roots, where sensory input is organised by modality and relayed to second-order neurones in the dorsal horn, and the cell bodies of these neurones are located in the dorsal root ganglia and display a pseudounipolar morphology that supports efficient signal transmission (Middleton, Perez-Sanchez, & Dawes, 2021). Somatosensory afferent fibres mediate modalities such as nociception, touch, and proprioception and together form the somatosensory system, which transmits sensory information from peripheral receptors to central targets (Crawford & Caterina, 2020).

Muscle spindle

Muscle spindles are the primary proprioceptive sensory organs that continuously inform the CNS about muscle length and movement (Kröger, 2018). Most human skeletal muscles contain numerous muscle spindle organs (Dimitrou, 2022), which play a key sensory role in the physiology of these muscles (Sun, Fede, Zhao, Del Felice, Pirri, & Steco, 2024). Accordingly, the muscle spindle is described as a mechano-sensory organ that detects and mediates both static and dynamic information about skeletal muscle fibre length and stretch, transmitting this sensory information to the CNS, where it contributes to the generation of appropriate motor responses (Barrett, Quick, Mudera, & Player, 2020). The muscle spindle is an encapsulated sensory organ located in parallel with extrafusal muscle fibres (Wilkinson, 2022) within the belly of skeletal muscles and is innervated by one primary (group Ia) and several secondary (group II) proprioceptive sensory neurones. These neurones respond to stretch of the intrafusal fibres, such that voluntary or passive changes in limb position (i.e., muscle length) lead to increased or decreased firing rates (Oliver, Florez-Paz, Badea, Mentis, Menon, & de Nooij, 2021). There are three types of intrafusal fibres within the muscle spindle: large nuclear bag 1 fibres, larger nuclear bag 2 fibres, and smaller nuclear chain fibres (Sun et al., 2024).

In humans, the sensory innervation of the muscle spindle arises from both group Ia and group II afferent fibres, sometimes referred to as type Ia or type II fibres, respectively (Kröger & Watkins, 2021). Type Ia afferent nerve terminals form annulospiral endings (primary endings), innervating all intrafusal fibres and showing peak responsiveness to variations in muscle fibre length and stretch magnitude. By contrast, type II afferent neurones (secondary endings) innervate nuclear bag 2 fibres and chain fibres and exhibit maximal activity in response to muscle-stretch magnitude (Sun et al., 2024). Under passive conditions, type Ia fibres exhibit both strong dynamic and fairly good static muscle-length sensitivity, whereas type II fibres primarily demonstrate static length sensitivity with lower dynamic sensitivity. These response patterns align with the general view that type Ia firing encodes both static muscle length and stretch velocity, while type II firing encodes static muscle length (Dimitriou, 2022). Overall, the muscle spindle functions as a stretch sensor that measures both the magnitude and speed of muscle length changes, as intrafusal fibres extend in parallel with the associated muscle fibres, generating action potentials in afferent sensory neurones according to the degree and rate of stretch (Côté, Murray, & Knikou, 2018).

Golgi tendon organ

Golgi tendon organs are mechanoreceptive structures located at the myotendinous junctions of skeletal muscles (Oliver, Florez-Paz, Badea, Mentis, Menon, & de Nooij, 2020). They are innervated by large-diameter Ib proprioceptive sensory neurones, with group Ib afferent terminals interweaving among the collagen fibres that connect extrafusal muscle fibres to tendons or aponeuroses (Imai & Yoshida, 2018; de Nooij, 2022). Golgi tendon organ afferents are highly sensitive to extrafusal muscle contraction, which tensions the collagen fibres and increases afferent firing, allowing detection of changes in muscle tension (Lyle & Nichols, 2019; Imai & Yoshida, 2018). These organs are most effectively stimulated by active contractile force and can detect forces as small as those generated by single muscle fibres (Nichols, 2018). Ib afferents exhibit similar activation thresholds and conduction velocities to group Ia afferents but respond to different stimuli: they are dynamically sensitive to rapid changes in contractile force while showing minimal activation during muscle stretch (Oliver et al., 2020). Golgi tendon organs provide force feedback that, in combination with muscle spindle-mediated length signals, regulates locomotor step cycles and contributes to postural balance and stability (Nichols, 2018; Imai & Yoshida, 2017).

Receptors

The skin contains a complex network of sensory nerve fibres located in both the epidermis and dermis, which transmit sensations such as pain, burning, and itching to specific areas of the brain (Ashrafi, Baguneid, & Bayat, 2015). Mechanoreceptors in the epidermis include Merkel discs with free nerve endings, whereas those in the dermis comprise Ruffini, Meissner, and Pacinian corpuscles with free nerve endings (Ashrafi, Baguneid, & Bayat, 2015). These receptors are classified according to their adaptation speed, with some responding rapidly and briefly (rapidly adapting) and others maintaining firing during sustained stimuli (slowly adapting) (Bear, Connors, & Paradiso, 2020).

Fast-adapting type II (FAII) Aβ afferent fibres correspond to Pacinian and Meissner corpuscles and are highly sensitive to dynamic skin interactions, such as skin slip, motion, and vibrations, including those occurring between the skin and an object. Slowly adapting type I (SAI) mechanoreceptors include Merkel discs and Ruffini endings. Merkel cell–neurite complexes are concentrated in areas requiring fine tactile resolution and are essential for detecting texture and object shape. Ruffini endings, in contrast, are particularly suited for sensing cutaneous stretch and joint movement (Kardashina, 2025).

Motor neurones

Motor function in humans arises from the neuromechanical interplay within the integrated neuromusculoskeletal system and is achieved through neural control of muscle contractions that generate interaction forces across the skeletal system (Sartori, Yavuz, & Farina, 2017). Motor neurones are efferent neurones responsible for transmitting motor commands to skeletal muscles. Those located entirely within the CNS are classified as upper motor neurones, whereas lower motor neurones have cell bodies within the CNS—either in the brainstem or spinal cord—but project axons through peripheral nerves to innervate skeletal muscle fibres (Cheng, Mah, & Seluakumaran, 2021). Motor neurones may also be classified according to their muscle targets. Alpha motor neurones innervate force-generating extrafusal muscle fibres, beta motor neurones innervate both intrafusal and extrafusal fibres, and gamma motor neurones innervate the intrafusal fibres of the muscle spindle (Wilkinson, 2021). Functionally, motor neurones regulate the magnitude of muscle force production (Sartori, Yavuz, & Farina, 2017) and generate mechanical forces essential for physical interaction with the environment (Hug, Avrillon, Ibanez, & Farina, 2023). Moreover, they are fundamental to all skeletal and smooth muscle contractions in the body, contributing to the control of physiological processes such as blood pressure regulation and sweat secretion through their role in activating muscle fibres (Blum et al., 2021).

Gamma motoneurones

Gamma motoneurones are small fusimotor neurones that constitute approximately 30% of all motoneurones in the ventral horn of the spinal cord and induce contraction of sarcomeres in the polar regions, thereby generating tension in the central region of intrafusal muscle fibres (Kröger & Watkins, 2021). Static gamma motoneurones innervate bag 2 and/or chain intrafusal fibres, whereas dynamic gamma motoneurones innervate bag 1 fibres (Wilkinson, 2021). Static gamma motoneurones are thought to encode centrally planned joint angle information and reinforce the intended joint position through regulation of muscle spindle sensitivity. In contrast, dynamic gamma motoneurones are associated with the encoding of joint acceleration within the planned movement trajectory (Li et al., 2015). Together, these neurones modulate intrafusal fibre tension, sensitivity, and length, enabling muscle spindles to maintain consistent sensitivity during dynamic muscle activity and to prevent excessive muscle stretch that may impose undue stress on muscles, tendons, and joints (Colón, Guo, Akanda, Cai, & Hickman, 2017). Consequently, gamma motoneurones play a crucial role in motor control, locomotion, and balance (Matthews, 2015).

Alpha motoneurones

Alpha motoneurones constitute the final effector component of the lower motor system (de Carvalho & Swash, 2016). They are located within the cranial and spinal motor nuclei (Lemon, 2021) and transform synaptic motor commands into precisely patterned discharges that generate muscle force (Beauchamp, Pearcey, Khurram, Negro, Dewald, & Heckman, 2025). These neurones are specialised to support the extensive repertoire of human motor behaviours (Johnson, Thompson, Tysseling, Powers, & Heckman, 2017), including the regulation of mechanical actuation, muscle tension, and relaxation via extrafusal muscle fibres, as well as the control of muscle contraction dynamics (Colón, Guo, Akanda, Cai, & Hickman, 2017).

The axons of alpha motoneurones, referred to as anterior horn cells in the spinal cord, project through peripheral nerves to innervate skeletal muscle fibres. All muscle fibres innervated by a single alpha motoneurone form a motor unit and exhibit similar mechanical, histochemical, and physiological properties, resulting in comparable contraction and relaxation velocities, fatigability, and force-generating capacity. Within the spinal cord, alpha motoneurones innervating distal limb muscles are positioned laterally in the cervical and lumbar enlargements, whereas those supplying proximal and axial muscles are located progressively more medially. Alpha motoneurones within cranial nerve nuclei innervating cranial musculature are distributed across the medulla, pons, and midbrain (de Carvalho & Swash, 2016).

Alpha-gamma co-activation

Alpha–gamma co-activation is the concurrent activation of alpha and gamma motoneurones by the central nervous system to sustain muscle spindle firing (Cheng, Mah, & Seluakumaran, 2021). This mechanism, consistently observed during movement and postural control, ensures spindle tension during extrafusal muscle contraction (Li et al., 2015; Dimitrou, 2022). Gamma motoneurones maintain the non-contractile central region of intrafusal fibres taut, preserving afferent sensitivity and enabling rapid responses to minimal changes in muscle length (Cheng, Mah, & Seluakumaran, 2021). Co-activation is particularly critical for fine motor control, such as in hand movements, and is evident during isometric or slow, constrained actions (Dimitrou, 2022; Cheng, Mah, & Seluakumaran, 2021).

Spinal reflexes

Spinal reflexes are involuntary and highly stereotyped motor responses mediated by well-defined neural pathways. The simplest reflex arc comprises a sensory receptor that detects the stimulus, an afferent neurone transmitting the signal to the spinal cord, and an efferent motor neurone conveying the response to the effector, typically a skeletal muscle fibre (Cheng, Mah, & Seluakumaran, 2021). In monosynaptic reflexes, direct synaptic communication occurs between the afferent and motor neurones, with a single synapse located within the spinal cord (Cheng et al., 2021). These reflexes generally involve a single muscle group within an agonist–antagonist pair and are commonly accompanied by inhibition of the antagonist muscle to ensure efficient movement execution (Latash, 2018).

More complex reflex actions are mediated by polysynaptic pathways, in which interneurones constitute a critical functional component. Interneurones exhibit considerable functional versatility, as they may act as first-order or last-order neurones across different spinal reflexes, participate in multiple neural networks, and contribute to a wide range of motor behaviours (Côté, Murray, & Knikou, 2018). Within antagonist muscle systems, reflex regulation is achieved through reciprocal and presynaptic inhibition, whereas synergistic muscle systems rely on non-reciprocal (Ib) inhibition and recurrent inhibition mediated by Renshaw cells (Gladchenko et al., 2022).

Reciprocal inhibition between agonist and antagonist muscles represents a fundamental mechanism of spinal motor control. This process is mediated by Ia inhibitory interneurones and ensures the precise temporal coordination of flexor and extensor muscle activity during movement (Jankowska, 2022; Chelnokov & Gorodnichev, 2021). Presynaptic inhibition further modulates spinal reflex activity by limiting excessive afferent input to central neural circuits (Gladchenko et al., 2022). Muscle afferent volleys can depress monosynaptic reflexes by reducing excitatory postsynaptic potentials or motoneuronal excitability, thereby preventing excessive reflex activation (Côté et al., 2018). This mechanism plays an essential role in regulating skeletal muscle tone, facilitating voluntary movement and postural control (Gladchenko et al., 2022).

Non-reciprocal inhibition, also referred to as autogenic inhibition, involves the suppression of motoneuronal activity without a reciprocal inhibitory effect on the initiating neurones (Ramia et al., 2020). This process is primarily mediated by Ib afferent fibres originating from Golgi tendon organs, which respond to excessive muscle tension by inhibiting α-motoneurones, thereby reducing efferent output and promoting muscle elongation (Mostafa & Elshafey, 2018; Takahashi et al., 2023). Recurrent postsynaptic inhibition, mediated by Renshaw cells, provides a negative feedback mechanism that limits α-motoneurone firing frequency and constrains excessive muscular force production (Chelnokov et al., 2022). Collectively, these inhibitory spinal mechanisms ensure the stability, precision, and adaptability of human motor control.

Myotatic (stretch) reflex

The myotatic (stretch) reflex is an automatic response in which a muscle contracts following passive stretching, thereby regulating muscle length within physiological limits. Muscle elongation activates intrafusal fibres within the muscle spindle, increasing the firing rate of spindle afferents and enhancing α-motoneurone activity, which induces contraction of the extrafusal muscle fibres and resists further stretch. The sensitivity of this reflex is modulated by γ-motoneurones through adjustment of spindle fibre tension. Concurrently, reciprocal inhibition suppresses activity in the antagonistic muscles, allowing coordinated regulation of muscle length and the maintenance of stable muscle tone (Bhattacharyya, 2017).

In the myotatic reflex, the muscle spindle functions as an intramuscular receptor that detects changes in muscle length. Mechanical stimulation, such as tendon tapping, stretches the spindle and generates afferent action potentials that enter the spinal cord via the dorsal horn, thereby eliciting the reflex response. Accurate induction and assessment of the myotatic reflex require appropriate instruments, correct technique, and reliable evaluation procedures. The National Institute of Neurological Disorders and Stroke (NINDS) has adopted the NINDS myotatic reflex scale as the standard clinical tool for assessing muscle stretch reflexes, with its reliability validated by Litvan et al. (1996). The scale grades reflex responses from 0 (absent) to 4 (exaggerated, including clonus), with intermediate values reflecting increasing reflex amplitude within the normal range (Lin-Wei et al., 2021). Alternatively, reflexes may be described qualitatively using symbolic notation, ranging from absent (–) to very brisk (+++) (Lees & Hurwitz, 2019).

Myotatic reflex assessment is routinely performed in both the upper and lower limbs. In the upper limbs, the biceps, brachioradialis (supinator), and triceps reflexes are most commonly examined, while in the lower limbs the patellar and Achilles reflexes are standardly tested. Detailed and standardised protocols for the evaluation of these reflexes have been described by Lees and Hurwitz (2019) and Lin-Wei et al. (2021).

Goldi tendon (inverse myotatic) reflex

The inverse myotatic reflex originates from Golgi tendon organs, which detect increased muscle tension via Ib afferent fibres and activate spinal interneurones that inhibit Ia afferents. Concurrently, γ-motoneurones innervate intrafusal fibres, maintaining muscle spindle sensitivity during contraction (Naumović, 2018). By regulating motor unit activity in response to stimulus frequency, this reflex helps control muscle force (Adidharma et al., 2022; Köse, Akşit, Açıkgöz, & Ceyhan, 2023). Functioning as an adaptive protective mechanism, the inverse myotatic reflex prevents muscle or ligament injury from joint hyperextension, while increased reflex amplitude reflects synchronized depolarisation of muscle fibres (Pechlivanidou et al., 2024).

Flexor (withdrawal) reflex

The flexor withdrawal reflex is an involuntary limb response that moves the body away from a painful stimulus (Thorell et al., 2023). It is widely used to assess the functional integrity of nociceptive spinal pathways (Dafkin, Green, Oliver, McKinon, & Kerr, 2018), enabling rapid retraction of the affected area from actual or potential harm (Jure et al., 2019). Mediated by polysynaptic spinal circuits, this reflex is influenced by factors such as limb posture, site of stimulation, gait phase, psychological state, and pain threshold (Jure et al., 2019). Functionally, it involves coordinated activation of synergistic muscles to flex the stimulated limb, inhibition of antagonists, and compensatory movements in the contralateral limb to maintain balance, recruiting multiple muscle groups and joint actions depending on the stimulus location (Henrich, Frahm, & Andersen, 2021).

SUMMARY

Spinal reflexes are rapid motor responses initiated when a stimulus reaches the spinal cord via sensory (afferent) neurones. The information is processed within the spinal centres, and a response is transmitted through motor (efferent) neurones to effectors, resulting in muscle contraction and/or modulation of muscle tension.

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