



## Masterclass

## Proprioception in musculoskeletal rehabilitation. Part 1: Basic science and principles of assessment and clinical interventions

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## ABSTRACT

**Introduction:** Impaired proprioception has been reported as a feature in a number of musculoskeletal disorders of various body parts, from the cervical spine to the ankle. Proprioception deficits can occur as a result of traumatic damage, e.g., to ligaments and muscles, but can also occur in association with painful disorders of a gradual-onset nature. Muscle fatigue can also adversely affect proprioception and this has implications for both symptomatic and asymptomatic individuals. Due to the importance of proprioception for sensorimotor control, specific methods for assessment and training of proprioception have been developed for both the spine and the extremities.

**Purpose:** The aim of this first part of a two part series on proprioception in musculoskeletal rehabilitation is to present a theory based overview of the role of proprioception in sensorimotor control, assessment, causes and findings of altered proprioception in musculoskeletal disorders and general principles of interventions targeting proprioception.

**Implications:** An understanding of the basic science of proprioception, consequences of disturbances and theories behind assessment and interventions is vital for the clinical management of musculoskeletal disorders. Part one of this series supplies a theoretical base for part two which is more practically and clinically orientated, covering specific examples of methods for clinical assessment and interventions to improve proprioception in the spine and the extremities.

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## 1. Role of proprioception in sensorimotor control

Sensorimotor control refers to central nervous system (CNS) control of movement, balance, posture, and joint stability (Lephart et al., 2000; Franklin and Wolpert, 2011). Well-adapted motor actions require intact and well integrated information from all of the sensory systems, specifically the visual, vestibular and somatosensory systems, including proprioception (Ghez, 1991; Lephart et al., 1997). Proprioception involves conscious or unconscious awareness of joint position (joint position sense), movement (kinesthesia), and force, heaviness, and effort (force sense) (Martin and Jessell, 1991; Riemann and Lephart, 2002). Proprioception is processed at all levels of the CNS and is integrated with other somatosensory and visual and vestibular information before culminating in a final motor command that co-ordinates the

activation patterns of skeletal muscles (Ghez, 1991; Shumway-Cook and Woollacott, 2001).

## 1.1. Proprioceptors

Proprioception is the product of sensory information supplied by specialized nerve endings termed mechanoreceptors, i.e., transducers converting mechanical stimuli to action potentials for transmission to the CNS (Martin and Jessell, 1991; Yahia et al., 1992). Mechanoreceptors specifically contributing to proprioception are termed proprioceptors and are found in muscle, tendon, joint and fascia, receptors in the skin can also contribute to proprioception (Martin and Jessell, 1991; Rothwell, 1994). The type and actions of the various mechanoreceptors in the human body are presented in Table 1.

The muscle spindles, found in all skeletal muscles in parallel with the extrafusal muscle fibers (Peck et al., 1984; Kulkarni et al., 2001; Banks, 2006) are considered the most important source of proprioception (Gordon and Ghez, 1991; Proske and Gandevia,

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**Table 1**  
Mechanoreceptors of the human body.

Mechanoreceptors	Type	Stimulation
Joint	Muscle spindle	Muscle length Velocity of change of muscle length
	Golgi tendon organ	Active muscle tension
	Ruffini ending	Low and high load tension and compression loads throughout entire ROM
	Pacinian ending	
Fascia	Mazzoni ending	
	Golgi ending	
Skin	Ruffini ending	Low and high tension loads during joint movement
	Pacinian ending	
	Hair follicle receptor	Superficial tissue deformation/stretch or compression during joint movement
	Ruffini ending	
Skin	Pacinian ending	
	Merkel ending	
Skin	Meissner ending	

Martin and Jessell (1991), Rothwell (1994), Yahia et al. (1992), Sojka et al. (1989), Johansson et al. (1990), Needle et al. (2013).

2012). They are highly sensitive and their density varies widely throughout the body, reflecting different functional demands. The sub-occipital muscles of the neck have an exceptionally high density of muscle spindles, thought to reflect the cervical spine's unique role in head and eye movement control (Liu et al., 2003). Importantly the sensitivity of the muscle spindles can be adjusted via innervation of the polar ends of the intrafusal muscle fibers by gamma motoneurons (Gordon and Ghez, 1991).

Joint proprioceptors have historically been considered "limit detectors", stimulated at the extremes of joint range-of-motion (ROM) (Burgess and Clark, 1969). However it is now known that joint proprioceptors provide input throughout a joint's entire ROM under both low and high load conditions stimulating strong discharges from the muscle spindle and are thus vital for joint stability (Sojka et al., 1989; Johansson et al., 1990; Needle et al., 2013).

## 1.2. Role of proprioceptors

Proprioceptive information is processed at the spinal level, brain stem and higher cortical centers, as well as subcortical cerebral nuclei and cerebellum (Bosco and Poppele, 2001; Amaral, 2013; Lisberger and Thach, 2013; Pearson and Gordon, 2013). The information is mainly transferred, via several ascending pathways, to the medulla and thalamus and then to somatosensory cortex (conscious proprioception); or via the spinal nucleus to the cerebellum (unconscious proprioception) (Fig. 1). Cervical proprioceptive information is also transferred to the superior colliculus in the midbrain which is thought to be the reflex center for eye and head movement co-ordination (Corneil et al., 2002). Cervical proprioceptors also have important central connections to the vestibular nuclei (Figs. 1 and 2) and are involved in reflexes involving head and eye movement control and balance (the cervico-ocular, cervico-collic and the tonic neck reflex) (Bronstein et al., 1991; Gdowski and McCrea, 2000; Peterson, 2004). These work in conjunction with other reflexes acting on the neck and eye musculature associated with the vestibular and visual systems (Fig. 3).

The role of proprioception in sensorimotor control is multifold. To plan appropriate motor commands, the CNS needs an updated body schema of the biomechanical and spatial properties of the body parts, supplied largely by proprioceptors (Maravita et al., 2003). Proprioception is important also after movement for comparison of actual movement with intended movement, as well as the predicted movement supplied by the efference copy (corollary discharge). This is suggested to have importance for motor learning

by updating of the internal forward model of the motor command (Wolpert et al., 2011). During movements proprioception has importance for: feedback (reactive) control, feedforward (preparatory) control and the regulation of muscle stiffness, to achieve specific roles for movement acuity, joint stability, co-ordination and balance (Ghez, 1991; Riemann and Lephart, 2002; Milner et al., 2007). Cervical proprioceptive information also has a highly important specific role for head and eye movement control (Corneil et al., 2002). The roles of proprioception are summarized in Table 2.

## 2. Assessment of proprioception

A variety of tests have been developed to investigate proprioception in individuals with musculoskeletal disorders. These tests assess which individuals have significant impairment and are valuable for the guidance and evaluation of rehabilitation interventions.

### 2.1. Specific tests

Specific tests of proprioception assess an individual's status with regard to JPS, kinesthesia, or force sense (Riemann et al., 2002; Proske and Gandevia, 2012). Tests can be performed under passive (biasing joint mechanoreceptors) or active conditions (stimulating joint and muscle-tendon mechanoreceptors) (Riemann et al., 2002; Clark, 2014). JPS tests assess precision or accuracy in repositioning a joint at a predetermined target angle (Lephart et al., 1994; Benjaminse et al., 2009). Kinesthesia tests assess the ability to perceive joint movement measured using threshold to detection of passive motion (TTDPM) (Lephart et al., 1994; Benjaminse et al., 2009), movement discrimination tests (Waddington et al., 1999; Waddington et al., 2000), or the acuity of a tracking task (Kristjansson and Oddsdottir, 2010). Force sense tests assess the ability to perceive and produce a previously generated and pre-determined sub-maximal quantity of force (Dover and Powers, 2003; O'Leary et al., 2005; Benjaminse et al., 2009).

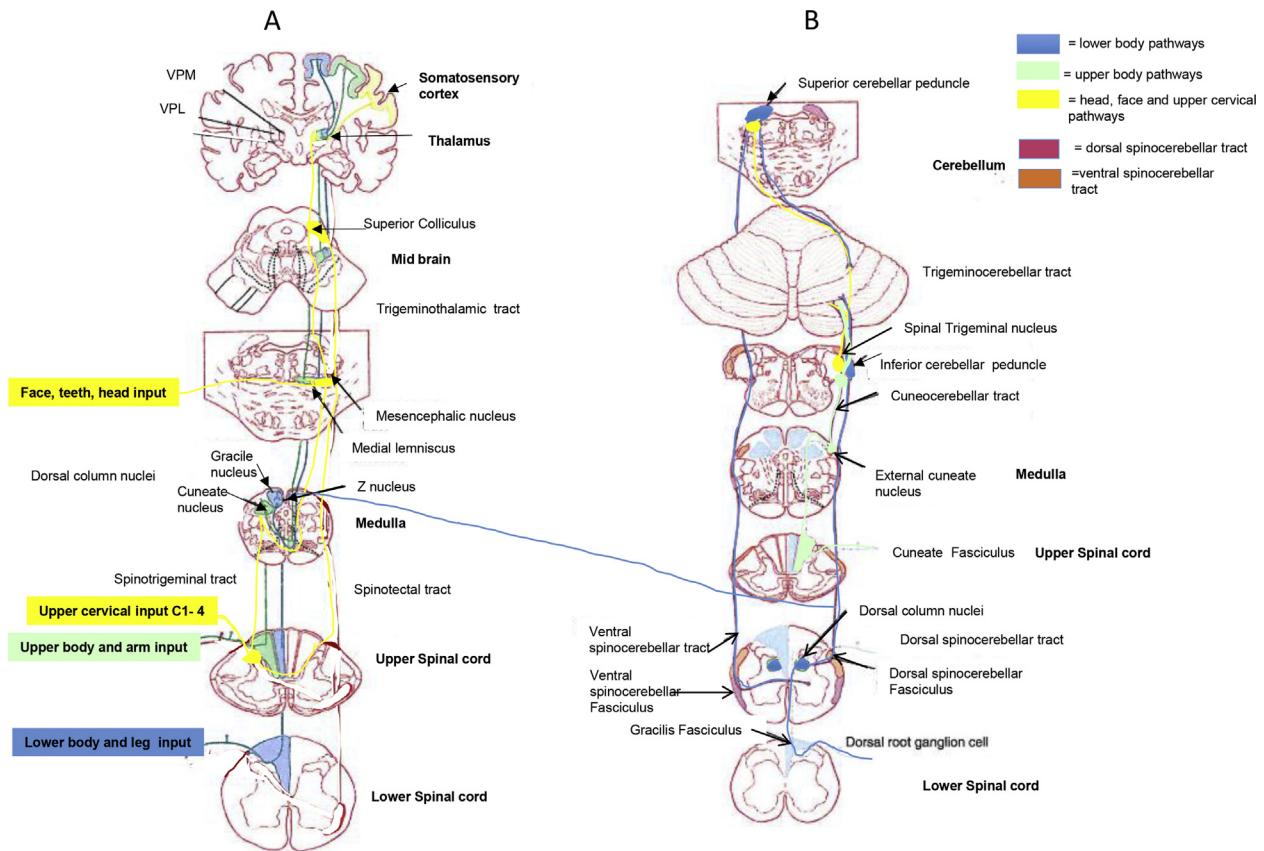
Several variables are commonly calculated in JPS, TTDPM and force sense tests. Variables include constant error (CE), variable error (VE), and absolute error (AE) (Schmidt and Lee, 2011). These variables are intended to describe different aspects of JPS and force sense (Fig. 4). Acuity at a pursuit or tracking task is commonly presented as deviation from target, or time on target (Schmidt and Lee, 2011).

Researchers have used three to five test trials to generate reliable mean values at the extremity joints (Dover and Powers, 2003; Benjaminse et al., 2009; Nagai et al., 2012). In tests of spinal proprioception 6 trials are recommended (Allison and Fukushima, 2003; Swait et al., 2007).

A limitation of these proprioception tests is they involve cognitive components and provide an indirect measure of proprioception. Other factors can also affect results. The size and speed of the movement should be standardized, or specific to a functional task (Preuss et al., 2003; Suprak et al., 2007). Larger errors can be expected when assessing children and the elderly compared to younger adults (Goble, 2010). Muscle thixotropy, which is history dependent passive stiffness of the muscle (Lakie et al., 1984), can also affect the results and thus isometric contraction of the muscle at the test position before assessment, especially in passive tests, i.e., prior to the passive movement, is recommended (Proske and Gandevia, 2012).

### 2.2. Non-specific tests

Functional tests such as balance tests are often used to provide an estimate of potential proprioceptive disturbances. However,



**Fig. 1.** Ascending pathways relating to proprioception. A) Dorsal column Medial lemniscus pathway to Cerebral Cortex for conscious proprioception. Proprioceptive information is transmitted via the dorsal column which is formed by axons of the dorsal root ganglia. These travel to the medulla to synapse in one of the dorsal column nuclei – the gracile nucleus (lower body) or cuneate nucleus (upper body and arm). These fibers then sweep ventrally and medially to cross the midline to form the medial lemniscus which projects to the ventral posterior lateral (VPL) nucleus of the thalamus and then projects to the relevant somatosensory area of the cerebral cortex. Lower limb axons of the dorsal spinocerebellar tract (B) also branch to the nucleus z which then joins the medial lemniscus and projects information from the lower limb to the cerebral cortex. Input from the face, teeth and head enter the brain stem at the level of the pons and synapse in several brain stem nuclei including the mesencephalic nucleus, main sensory nucleus and the spinal nuclei of the trigeminal nerve. Some fibers also ascend to join the spinotrigeminal tract with input from the upper cervical spine. From the reticular formation they join the trigeminothalamic tract to the ventral posterior medial (VPM) thalamic nucleus and this is relayed to the relevant area of the somatosensory cerebral cortex. Input from the cervical spine is also projected via the spinotectal tract to the superior colliculus which is located in the midbrain and is a reflex center for co-ordination between the visual system and the neck. B) Spinocerebellar pathway to the Cerebellum for unconscious proprioception. For the trunk and lower part of the leg, dorsal root ganglion cells synapse in the dorsal nuclei then on to the gracilis funiculus to form the dorsal spinocerebellar tract which enters the cerebellum via the inferior cerebellar peduncle. The ventral spinocerebellar tract also supplies input from the lower limb to the cerebellum via the superior cerebellar peduncle. For the upper limb, dorsal root ganglia from the cervical spine ascend in the cuneate fasciculus to the external cuneate nucleus forming the cuneocerebellar tract and enter the cerebellum via the inferior cerebellar peduncle. Proprioceptive input from the face and head projects to the spinal trigeminal nucleus plus the main sensory nucleus to form the trigeminocerebellar tract and ascends to the cerebellum via the inferior peduncles. Information is also projected from the mesencephalic nucleus to the cerebellum via the superior cerebellar peduncle (Rothwell, 1994; Bosco and Poppele, 2001; Amaral, 2013; Pearson and Gordon, 2013; Lisberger and Thach, 2013).

these are not specific tests of proprioception or a body part as they involve all areas of the body and other sensory and motor functions. Therefore, specific perturbations of sensory information during the test are sometimes used to differentiate proprioceptive function. For example, vibration to disturb muscle spindles (Goodwin et al., 1972; Brumagne et al., 2000), occluding or perturbed vision to decrease reliance on vision and changing head position or applying galvanic current to the mastoid process to disturb vestibular information (Fitzpatrick et al., 1994; Hwang et al., 2014). Soft (unstable) surfaces in standing can be used to disturb the ankle and place more emphasis on other areas of the body or other sensory systems (Kiers et al., 2012), or alternatively challenge proprioceptive reflexes and ankle joint stability since the monosynaptic stretch reflex is intact (Chiang and Wu, 1997) and neuromuscular co-contractions are increased on soft surfaces (Mohapatra et al., 2014). Positioning the body in a neck torsion position by rotating the trunk under a stationary head and comparing to a neutral head–trunk position, with vision occluded during balance tests, has recently been suggested as a possible method to bias the cervical proprioceptors (Yu et al., 2011).

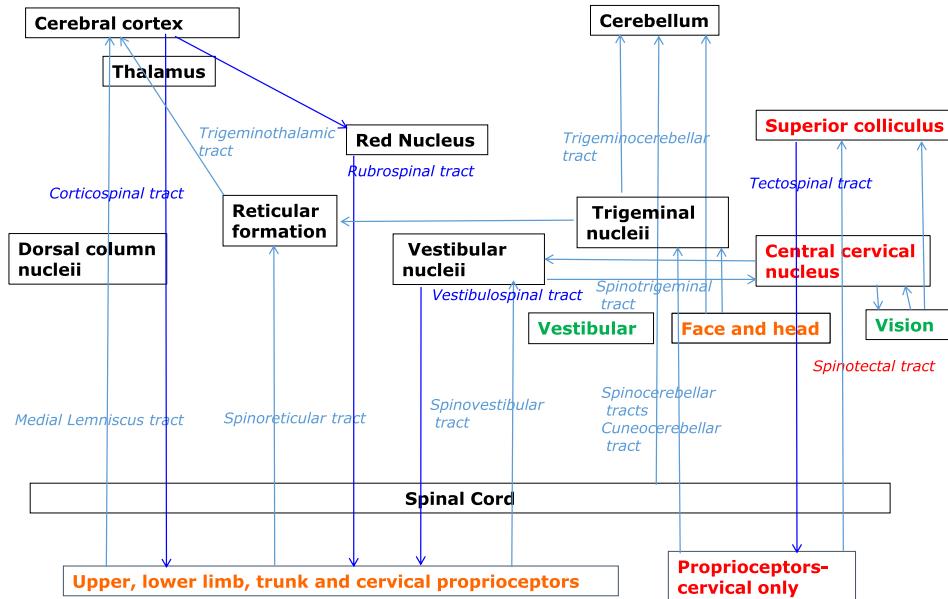
In cervical pain disorders oculomotor and eye–head co-ordination tests are often included as non-specific proprioception tests due to the neurophysiological connections between cervical proprioceptors and visual and vestibular organs (Treleaven, 2008).

### 3. Causes of altered proprioception

Disturbed proprioception has been found to be associated with several musculoskeletal disorders and/or experimental conditions following pain, effusion and trauma as well as fatigue.

#### 3.1. Pain

Abundant research has reported disturbed proprioception in acute and chronic musculoskeletal pain disorders at the cervical (Treleaven et al., 2003; Sjölander et al., 2008; Kristjansson and Oddsdóttir, 2010) and lumbar (Lee et al., 2010; Williamson and Marshall, 2014) spine, as well as upper (Juul-Kristensen et al., 2008; Anderson and Wee, 2011) and lower (Sharma et al., 2003; Salahzadeh et al., 2013) extremities. In the presence of pain,



**Fig. 2.** Ascending and descending pathways and connections to the vestibular and visual systems relevant for proprioception.

proprioception can be disturbed due to altered reflex activity and sensitivity of the gamma-muscle spindle system (Johansson et al., 2003) via activation of chemosensitive type III and IV afferents (nociceptors). Animal models have shown profound effects on muscle spindle afferents from intramuscular and intracapsular injections of inflammatory substances (Djupsjöbacka et al., 1995; Thunberg et al., 2001). Disturbed proprioception has also been seen in human experimental pain models (Weerakkody et al., 2008; Malmström et al., 2013). Pain can moreover influence body perception at the central level (Rossi et al., 2003; Haggard et al., 2013), including reorganization of the somatosensory cortex (Moseley and Flor, 2012). Thus pain can negatively influence proprioception at both peripheral and central levels of the nervous system.

### 3.2. Effusion

The term 'joint effusion' refers to swelling within a joint capsule, common after acute extremity joint injury, potentially persisting for extended periods of time (Frobell et al., 2009). Joint effusions

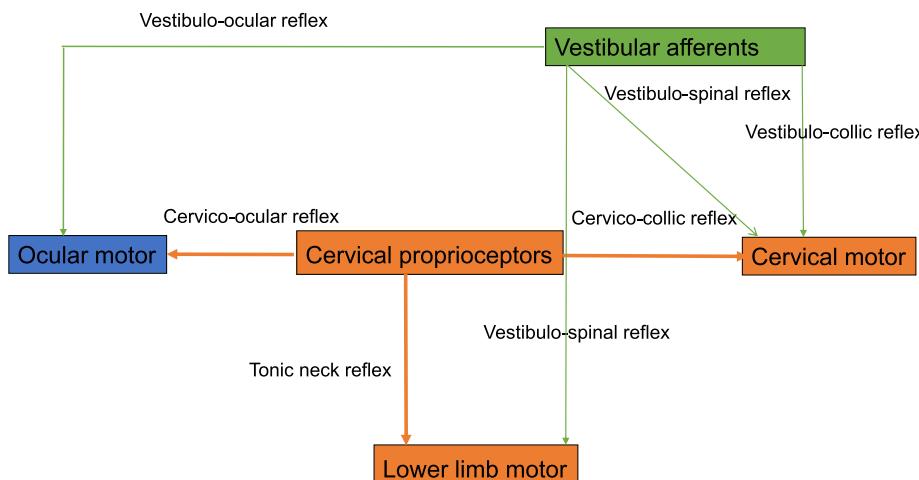
can cause significant inhibition of skeletal muscle, and can, also in the absence of pain, significantly impair extremity proprioception (Baxendale and Ferrell, 1987; Cho et al., 2011).

### 3.3. Trauma

Trauma, here referred to a single known event that causes physical injury (van Mechelen et al., 1992), frequently presents with disruption of musculoskeletal tissues and concurrent damage or destruction of mechanoreceptors innervating those tissues (Dhillon et al., 2010; Bali et al., 2012). Following trauma, and after pain and swelling have resolved, the loss of musculoskeletal tissue and its mechanoreceptors is associated with persistent impairment of proprioception (Smith and Brunolli, 1989; Borsa et al., 1997; Willems et al., 2002).

### 3.4. Fatigue

Muscle fatigue involves several peripheral and central changes, including altered metabolic state, muscle activation patterns,



**Fig. 3.** Proprioceptive reflex activity relating to balance and head and eye movement control.

**Table 2**

The role of proprioception in sensorimotor control for feedback (reactive) control, feed-forward (preparatory) control and regulation of muscle stiffness is summarized below. These control systems are used to achieve specific functional roles of movement acuity, joint stability, co-ordination and balance, and in the case of cervical proprioception, head and eye movement control.

Role	Source of proprioceptor input to CNS	CNS processing level	CNS processing characteristics	Characteristics of Motor output from CNS and functional consequences
Feedback Sensorimotor Control	Muscle spindle	Spinal cord	Monosynaptic reflex	<ul style="list-style-type: none"> <li>• Stimulation of alpha motor neurons innervating extrafusal muscle fibers of the same muscle</li> <li>• Inhibition of alpha motor neurons innervating extrafusal muscle fibers of the opposing muscle</li> <li>• Stretch reflex</li> <li>• Reactive muscle activation</li> <li>• Inhibition of alpha motor units innervating extrafusal muscle fibers of the same muscle</li> <li>• Reactive muscle inhibition</li> <li>• Co-ordinated stimulation of descending tracts innervating ipsilateral and/or contralateral muscle groups</li> <li>• Reactive muscle activation and inhibition</li> <li>• Co-ordinated stimulation of descending tracts innervating ipsilateral and/or contralateral muscle groups</li> <li>• Reactive muscle activation and inhibition</li> </ul>
	Golgi tendon organ	Spinal cord	Polysynaptic reflexes	<ul style="list-style-type: none"> <li>• Activation of alpha and gamma motor neurons</li> <li>• Preparatory muscle activation and inhibition before main movement</li> <li>• Allows for rapid prediction of the result of the motor command</li> <li>• Preprocess planning and activation of upcoming motor command</li> <li>• Predictions are compared with sensory information formulated from the motor command.</li> </ul>
	Muscle, tendon, joint, fascia	Cerebral cortex and subcortical	Polysynaptic reflexes	<ul style="list-style-type: none"> <li>• Reactive muscle activation and inhibition</li> <li>• Activation of alpha and gamma motor neurons</li> <li>• Preparatory muscle activation and inhibition before main movement</li> <li>• Allows for rapid prediction of the result of the motor command</li> <li>• Preprocess planning and activation of upcoming motor command</li> <li>• Predictions are compared with sensory information formulated from the motor command.</li> </ul>
	Muscle, tendon, joint, fascia	Cerebral cortex and subcortical	Voluntary reaction	<ul style="list-style-type: none"> <li>• Reactive muscle activation and inhibition</li> <li>• Activation of alpha and gamma motor neurons</li> <li>• Preparatory muscle activation and inhibition before main movement</li> <li>• Allows for rapid prediction of the result of the motor command</li> <li>• Preprocess planning and activation of upcoming motor command</li> <li>• Predictions are compared with sensory information formulated from the motor command.</li> </ul>
Feed-forward Sensorimotor Control	Muscle, tendon, joint, fascia	Cerebral cortex and subcortical	Preparatory motor commands	<ul style="list-style-type: none"> <li>• Stimulation of alpha motor neurons innervating extrafusal muscle fibers of the same muscle</li> <li>• Increase in stiffness of the same muscle</li> <li>• Inhibition of alpha motor neurons innervating extrafusal muscle fibers of the opposing muscle</li> <li>• Decrease in stiffness of the opposing muscle</li> <li>• Inhibition of alpha motor units innervating extrafusal muscle fibers of the same muscle</li> <li>• Decrease in stiffness of the same muscle</li> <li>• Stimulation of gamma motor neurons innervating the muscle spindle</li> <li>• Modification of muscle spindle sensitivity, intensity of the stretch reflex, and resulting muscle stiffness</li> <li>• Joint-muscle reflex (joint mechanoreceptors modulate muscle stiffness via their actions on gamma motor neurons)</li> <li>• Stimulation of gamma motor neurons innervating the muscle spindle</li> <li>• Modification of muscle spindle sensitivity and thereby muscle stiffness</li> </ul>
	Muscle, tendon, joint, fascia	Cerebellum	Copy of motor command (efference copy, or corollary discharge) based on past events.	<ul style="list-style-type: none"> <li>• Stimulation of alpha motor neurons innervating extrafusal muscle fibers of the same muscle</li> <li>• Increase in stiffness of the same muscle</li> <li>• Inhibition of alpha motor neurons innervating extrafusal muscle fibers of the opposing muscle</li> <li>• Decrease in stiffness of the opposing muscle</li> <li>• Inhibition of alpha motor units innervating extrafusal muscle fibers of the same muscle</li> <li>• Decrease in stiffness of the same muscle</li> <li>• Stimulation of gamma motor neurons innervating the muscle spindle</li> <li>• Modification of muscle spindle sensitivity, intensity of the stretch reflex, and resulting muscle stiffness</li> <li>• Joint-muscle reflex (joint mechanoreceptors modulate muscle stiffness via their actions on gamma motor neurons)</li> <li>• Stimulation of gamma motor neurons innervating the muscle spindle</li> <li>• Modification of muscle spindle sensitivity and thereby muscle stiffness</li> </ul>
	Muscle spindle	Spinal cord	Monosynaptic	<ul style="list-style-type: none"> <li>• Stimulation of alpha motor neurons innervating extrafusal muscle fibers of the same muscle</li> <li>• Increase in stiffness of the same muscle</li> <li>• Inhibition of alpha motor neurons innervating extrafusal muscle fibers of the opposing muscle</li> <li>• Decrease in stiffness of the opposing muscle</li> <li>• Inhibition of alpha motor units innervating extrafusal muscle fibers of the same muscle</li> <li>• Decrease in stiffness of the same muscle</li> <li>• Stimulation of gamma motor neurons innervating the muscle spindle</li> <li>• Modification of muscle spindle sensitivity, intensity of the stretch reflex, and resulting muscle stiffness</li> <li>• Joint-muscle reflex (joint mechanoreceptors modulate muscle stiffness via their actions on gamma motor neurons)</li> <li>• Stimulation of gamma motor neurons innervating the muscle spindle</li> <li>• Modification of muscle spindle sensitivity and thereby muscle stiffness</li> </ul>
	Golgi tendon organ	Spinal cord	Polysynaptic	<ul style="list-style-type: none"> <li>• Stimulation of alpha motor neurons innervating extrafusal muscle fibers of the same muscle</li> <li>• Increase in stiffness of the same muscle</li> <li>• Inhibition of alpha motor neurons innervating extrafusal muscle fibers of the opposing muscle</li> <li>• Decrease in stiffness of the opposing muscle</li> <li>• Inhibition of alpha motor units innervating extrafusal muscle fibers of the same muscle</li> <li>• Decrease in stiffness of the same muscle</li> <li>• Stimulation of gamma motor neurons innervating the muscle spindle</li> <li>• Modification of muscle spindle sensitivity, intensity of the stretch reflex, and resulting muscle stiffness</li> <li>• Joint-muscle reflex (joint mechanoreceptors modulate muscle stiffness via their actions on gamma motor neurons)</li> <li>• Stimulation of gamma motor neurons innervating the muscle spindle</li> <li>• Modification of muscle spindle sensitivity and thereby muscle stiffness</li> </ul>
Regulation of Muscle Stiffness	Joint	Spinal cord	Polysynaptic	<ul style="list-style-type: none"> <li>• Stimulation of alpha motor neurons innervating extrafusal muscle fibers of the same muscle</li> <li>• Increase in stiffness of the same muscle</li> <li>• Inhibition of alpha motor neurons innervating extrafusal muscle fibers of the opposing muscle</li> <li>• Decrease in stiffness of the same muscle</li> <li>• Stimulation of gamma motor neurons innervating the muscle spindle</li> <li>• Modification of muscle spindle sensitivity, intensity of the stretch reflex, and resulting muscle stiffness</li> <li>• Joint-muscle reflex (joint mechanoreceptors modulate muscle stiffness via their actions on gamma motor neurons)</li> <li>• Stimulation of gamma motor neurons innervating the muscle spindle</li> <li>• Modification of muscle spindle sensitivity and thereby muscle stiffness</li> </ul>
	Muscle, tendon, joint	Brainstem (and cerebrum and cerebellum)	Polysynaptic	<ul style="list-style-type: none"> <li>• Stimulation of alpha motor neurons innervating extrafusal muscle fibers of the same muscle</li> <li>• Increase in stiffness of the same muscle</li> <li>• Inhibition of alpha motor neurons innervating extrafusal muscle fibers of the opposing muscle</li> <li>• Decrease in stiffness of the same muscle</li> <li>• Stimulation of gamma motor neurons innervating the muscle spindle</li> <li>• Modification of muscle spindle sensitivity, intensity of the stretch reflex, and resulting muscle stiffness</li> <li>• Joint-muscle reflex (joint mechanoreceptors modulate muscle stiffness via their actions on gamma motor neurons)</li> <li>• Stimulation of gamma motor neurons innervating the muscle spindle</li> <li>• Modification of muscle spindle sensitivity and thereby muscle stiffness</li> </ul>
				<ul style="list-style-type: none"> <li>• Stimulation of alpha motor neurons innervating extrafusal muscle fibers of the same muscle</li> <li>• Increase in stiffness of the same muscle</li> <li>• Inhibition of alpha motor neurons innervating extrafusal muscle fibers of the opposing muscle</li> <li>• Decrease in stiffness of the same muscle</li> <li>• Stimulation of gamma motor neurons innervating the muscle spindle</li> <li>• Modification of muscle spindle sensitivity, intensity of the stretch reflex, and resulting muscle stiffness</li> <li>• Joint-muscle reflex (joint mechanoreceptors modulate muscle stiffness via their actions on gamma motor neurons)</li> <li>• Stimulation of gamma motor neurons innervating the muscle spindle</li> <li>• Modification of muscle spindle sensitivity and thereby muscle stiffness</li> </ul>

(Johansson et al., 1990; Rothwell, 1994; Bosco and Poppele, 2001; Amaral, 2013; Pearson and Gordon, 2013) Lisberger and Thach (2013).

muscle spindle discharge and spinal reflexes, and increased sense of effort (Enoka and Stuart, 1992; Gandevia, 2001). A common phenomenon after performing hard physical work or exercise (especially eccentric training) is the experience of clumsiness and difficulty performing fine motor tasks, verified in several studies demonstrating impaired proprioception (Weerakkody et al., 2003; Iwasa et al., 2005; Johanson et al., 2011; Tsay et al., 2012). Thus the potential for increased injury risk during and after exhausting physical work, such as among athletes and other physically demanding professions.

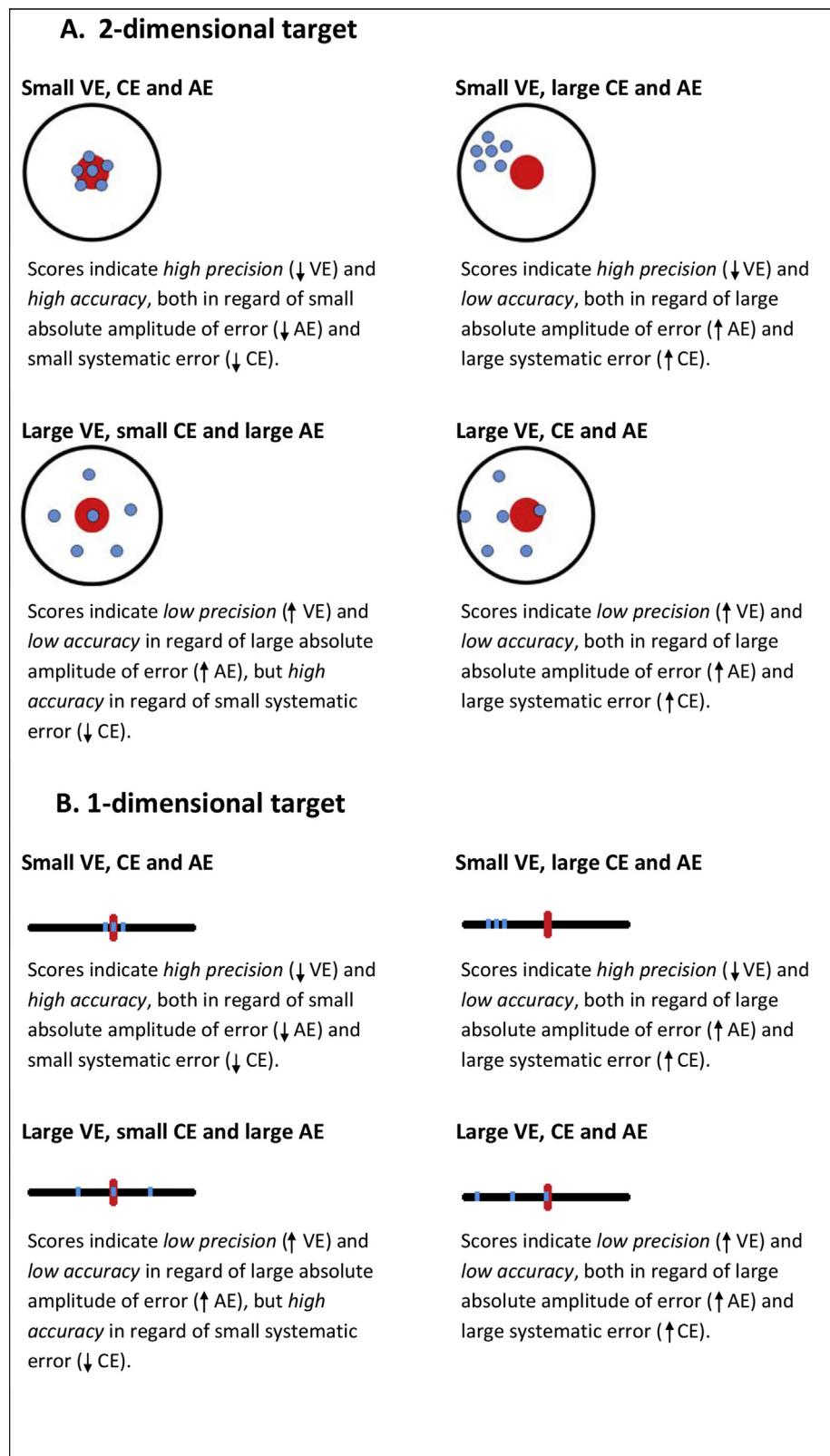
In addition to the causes mentioned above, deleterious effects on proprioception have also been reported in association with conditions such as local (Lephart et al., 1994) and general (Hall et al., 1995) joint hypermobility, stenosis (Leinonen et al., 2002) as well as due to immobilization (Moisello et al., 2008).

#### 4. Consequences of altered proprioception

In the short term, disturbed proprioception is likely to have adverse influence on feedback and feedforward motor control and the regulation of muscle stiffness. This may explain clinical symptoms such as balance disturbance and clumsiness in musculoskeletal disorders (Treleaven, 2011). It may also explain various

sensorimotor dysfunctions (besides increased errors in specific proprioception tests), which have been reported in the research literature. These dysfunctions include reduced drive to alpha motor neurons (Konishi et al., 2002), disturbed reflex joint stabilization (Beard et al., 1994), increased postural sway in balance tasks (Radebold et al., 2001; Treleaven et al., 2005; Röijezon et al., 2011) and increased error in visual movement acuity tasks (Sandlund et al., 2008; Williamson and Marshall, 2014). Altered proprioception is also likely to be involved, together with multiple other mechanisms, in neuromuscular adaptations commonly found in pain disorders (Falla and Farina, 2008; Hedges, 2011). Dizziness, visual disturbances and altered head and eye movement control and co-ordination can also occur specifically as a result of disturbed cervical proprioception (Treleaven, 2008; Treleaven and Takasaki, 2014).

In the long term, altered proprioception and subsequent impaired motor output from the CNS and deficient muscular protection of joint tissues (Stokes and Young, 1984; Hurley, 1997, 1999) may be patho-physiologically associated with increased risk of injury and recurrence and persistence of pain disorders, including the onset and progression of secondary (post-injury) osteoarthritis (OA). Reduced muscle performance (Elmqvist et al., 1988; Konishi et al., 2002), as a consequence of altered mechanoreceptor input



**Fig. 4.** Calculation of constant error (CE), variable error (VE) and absolute error (AE) in 2-dimensional (A) and 1-dimensional (B) assessments of joint position sense. CE, VE and AE display different aspects of the ability to reproduce a predetermined target. CE is the deviation from the target where each value is described by a positive (overshoot) or negative (undershoot) number. CE gives an indication of accuracy as an average magnitude of the movements, and an indication of any systematic error, i.e., whether the person is generally overshooting or undershooting the target. VE is the variance, or consistency, of the values regardless of how accurate (close to the target) the measures are and provides an estimate of precision. AE is the absolute difference from the target regardless of direction and gives an indication of the accuracy as overall amplitude of the error without consideration of error direction (Schmidt and Lee, 2011).

from injured structures to the CNS has been associated with the onset and progression of peripheral joint OA (Segal et al., 2010) in humans. This has also been demonstrated in animals where selective ligament and mechanoreceptor resection resulted in a rapid onset and progression of OA (O'Connor et al., 1985; O'Connor et al., 1992).

Poor proprioception may also contribute to increased injury risk (Zazulak et al., 2007) and training directed towards improving proprioception has been associated with reduced injury risk (Hupperets et al., 2010). Thus interventions targeting proprioception is relevant both in prevention and rehabilitation of musculoskeletal disorders.

## 5. Interventions to improve proprioception

Based on neurophysiology and the causes behind disturbed proprioception, several interventions may be considered for enhancing proprioception. In this paper, the theoretical basis behind general methods that aim to either reduce inhibition of proprioception or to improve proprioception are presented. Part 2 of this Masterclass offers specific clinical examples and research regarding interventions effects to improve proprioception, with specific clinical examples for the extremities and the spine (Clark et al., 2014).

### 5.1. Reduce causes of 'inhibition' of proprioception

Therapies aimed at reducing pain and effusion (e.g., analgesics, cryotherapy and compression) would theoretically have potential to improve proprioception via the reduction in causes of disturbed proprioception, although this still needs to be evaluated in clinical studies. Further, due to the deteriorating effect of fatigue on proprioception, an adequate "protection" may be to train muscle performance (strength and endurance) to increase the threshold before fatigue occurs and to reduce the negative effects of fatigue (Hassanlouei et al., 2014). Importantly, from a clinical perspective, pain, effusion and fatigue should be addressed and in addition, specific proprioception training should be performed without provoking pain, effusion or significant fatigue since they all can have a negative effect on proprioception and motor learning (Boudreau et al., 2010; Schmidt and Lee, 2011).

### 5.2. Augmentation of somatosensory information

Augmentation of somatosensory information via passive techniques such as manual therapy, soft tissue techniques and taping or braces can be valuable as they stimulate the mechanoreceptors in joints, soft tissues and skin to send a barrage of sensory information to the CNS, and in the case of manual therapy it has been suggested to involve plastic changes in sensory integration within the CNS (Haavik & Murphy, 2012). Specifically, exercise is an important element in augmenting proprioception. The muscle spindles are considered the most potent proprioceptors and are always stimulated during active movements as a consequence of alpha-gamma activation (Gordon and Ghez, 1991). The GTOs are also potent and sensitive mechanoreceptor to forces generated by active movements (Gordon and Ghez, 1991; Rothwell, 1994). Thus any active exercise can be considered 'proprioceptive training' (Clark and Herrington, 2010). Consequently there is abundance of research looking at various exercise methods to improve proprioception. The neurophysiological effects of exercise, including exercises specifically designed to stimulate proprioception will be explored in the following sections.

### 5.3. Exercise therapy effects on proprioception

Although any exercise will stimulate proprioceptors it is well established that various exercise tasks will challenge the nervous system in different ways (Jensen et al., 2005; Adkins et al., 2006; Taube et al., 2008; Doyon et al., 2009) and that neural changes differ in various learning phases (Doyon et al., 2003). For example, muscle performance training has been found to induce angiogenesis with increased blood flow in the motor cortex and to enhance spinal reflexes, whilst motor skill tasks may preferentially have plastic effects at higher levels of the CNS (Adkins et al., 2006). Some studies suggest that muscle performance training per se, i.e., when performed without any challenge regarding motor skills, does not significantly improve proprioception (Jensen et al., 2005; Lin et al., 2009), however, several other studies have demonstrated proprioceptive improvements with this type of exercise (Docherty et al., 1998; Rogol et al., 1998). Moreover, there are studies on muscle performance training reporting enhanced proprioception in weight-bearing (closed kinetic chain) compared to non weight-bearing (open kinetic chain) exercises (Jan et al., 2009), whilst others report equal effects (Rogol et al., 1998). In practice it is likely that a combined approach of various exercises is required to achieve optimal results and due to specificity effects, exercises should preferably resemble functional activities of the specific body parts.

### 5.4. Motor skill training-implicit and explicit

Training methods with the specific aim to improve proprioception commonly involve specific acuity tasks targeting JPS, kinesthesia or sense of force, or some kind of unstable dynamic system to train balance, co-ordination and dynamic stability and simultaneously train multiple components of the sensorimotor control system (Lephart et al., 1997). Common to these exercise tasks is that they involve learning motor skills, explicit or implicit. In relation to Doyons and colleague's model on sequential learning vs motor adaptations (Doyon and Benali, 2005; Doyon et al., 2009), explicit tasks targeting precise movements may have similarities with motor *sequential learning* which primarily involves the cortico-striatal (basal ganglia) system (conscious and unconscious proprioception); while implicit tasks, involving an unstable system, primarily involves the cortico-cerebellar system (unconscious proprioception) through *motor adaptation* due to the inherently changing (unstable) environment.

Training explicit motor skills, such as precise repositioning tasks, have shown to have a preferential effect on the reorganization within the motor cortex of the CNS, when compared to muscle performance training (performed without involvement of motor skill) of the same body part (Jensen et al., 2005; Adkins et al., 2006). These plastic changes include increases in protein synthesis, synaptogenesis and map reorganization and are closely related to improved task performance (Jensen et al., 2005; Adkins et al., 2006).

Implicit motor skills training, such as with an unstable surface or object, involves some degree of uncertainty and, therefore, continuous sensory input, CNS processing, and motor actions and reactions to adjust motor commands (Taube et al., 2008; Franklin and Wolpert, 2011). Neurophysiological studies have demonstrated central adaptations at multiple levels due to exercises using unstable surfaces, including increased cerebellar and subcortical activity in combination with reduced spinal reflex excitability and cortical activity, and that these adaptations are task specific (Taube et al., 2008).

A common finding during initial unstable task training is increased co-activation of agonists and antagonists (Burdet et al., 2001; Franklin et al., 2003; Cimadomo et al., 2013), related to the

level of instability (Franklin et al., 2004; Selen et al., 2009). This increases joint stability but also effort and energy. As training progresses, muscle activity declines due to adaptation of feedback and feedforward control (Franklin et al., 2007). It has been suggested that this learning effect occurs partly by the CNS building an internal forward model used in feedforward control to minimize motion error and effort while maintaining stability (Kadiallah et al., 2012), and that muscle spindle afferents contribute in predicting future kinematic states by acting as forward internal sensory models in learned skills (Dimitriou and Edin, 2010). Feedback control, including long latency feedback responses, also adapt due to context and task demands as learning occurs (Pruszynski and Scott, 2012; Cluff and Scott, 2013).

#### 5.4.1. Sensory reweighting

There are indications that the CNS is reweighting proprioceptive input from different body parts depending on the task conditions. For example, during a standing balance task, on a soft compared to hard surface, the muscle spindles in the lower leg (triceps surae) have less importance, while proprioception from lumbar muscles gain importance (Kiers et al., 2012). This immediate reweighting may be explained by less reliable muscle spindle information from the ankle muscles, or a change from an ankle to a hip strategy (Kiers et al., 2012). However, it is still not clear if this reweighting remains over a period of training. Similar sensory reweighting has been reported for new visuomotor tasks, where reduced muscle spindle input (Jones et al., 2001) and primary somatosensory cortex activity (Bernier et al., 2009) was seen initially, probably in order to reduce sensory conflict. As performance improved with training, the somatosensory suppression was alleviated; indicating increased reliance on somatosensory information is a learning effect (Bernier et al., 2009). Nevertheless more research on sensory reweighting and its effects of training is required, especially on individuals with musculoskeletal disorders.

#### 5.4.2. Clinical considerations of exercise therapy

Any active exercise will activate proprioceptors, but various exercises will activate proprioceptors and the specific levels of CNS differently and this has implications for the individual person. Clinically a combined approach is required but emphasis should be based on the functional requirements of the specific joint or area of the body, the individual functional level and abilities, as well as the specific requirement of the person's daily life, including work, household and leisure time activities and contexts. Various clinical examples of such training methods and their effect on proprioception are presented in Part 2 of this Masterclass series (Clark et al., 2014), where they are categorized into: active joint repositioning, force sense, co-ordination, muscle performance, balance/unstable surface, plyometric and vibration training.

## 6. Summary

Proprioception is essential for effectual sensorimotor control, with important roles for feedback and feedforward control and the regulation of muscle stiffness, which are important for movement acuity, joint stability, co-ordination and balance. Cervical proprioception is distinctive due to neural connections to visual and vestibular systems, and its specific role for eye–head movement control. Proprioception can be disturbed in musculoskeletal disorders due to multiple causes including pain, effusion, trauma and fatigue; involving both peripheral and central pathophysiological changes of the nervous system. Disturbed proprioception can lead to immediate sensorimotor control disturbances, which in turn may lead to long term consequences for musculoskeletal disorders. Specific methods for assessment and intervention targeting

proprioception have been developed. Reducing the causes of the inhibition of proprioception and augmenting proprioceptive input are important strategies in clinical management, with specific emphasis placed on exercise therapy. Specific proprioception training should be performed without provoking fatigue, effusion or pain since they may have a negative effect on proprioception and motor learning. While any active movement stimulates proprioceptors, various exercises do affect proprioception and the CNS differently. Due to the task specific effects, proprioception training should be integrated into functional exercises in situations and activities that are relevant to the body part and individual.

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