Making Sense of Proprioception

The meaning of proprioception, kinaesthesia and related terms

by Barry C Stillman

Summary While people from different backgrounds may legitimately assign different meanings to the same word, it is desirable for communication and comprehension purposes if all who use 'proprioception', 'kinaesthesia' and related terms reach a general consensus as to their most appropriate meaning. This essay represents an attempt to define these terms in a manner which has validity and relevance for a broad spectrum of readers. It is also hoped that readers will gain a better understanding of the nature, functions and assessment of the proprioceptive system.

The dominant theme of this paper is that the proprioceptive system has some functions which are sensory and others which are not. The sensory functions, collectively termed 'proprioception' (proprioceptive sensation or kinaesthesia), involve awareness of the spatial and mechanical status of the musculoskeletal framework. They include the senses of position, movement and balance. Proprioceptive sensation is also integral to developing motor control when learning new skills. Conversely, the contribution of the proprioceptive system to motor control during learned skills is largely mediated without sensation; as also are its roles in reflex protection of joints against potentially harmful forces and protection of the body against falls (balance).

Sense and Perception

Sense (sensation) literally means recognising a single specific type of stimulus as, for example, touch or warmth. Perception on the other hand is a cerebral process designed to clarify the nature of the source of a stimulus or stimuli. A typical example of perception is identifying an object such as a coin or button held in the hand. Since it is often difficult to decide whether a given conscious experience is a simple (sensory) or more complex cognitive (perceptual) one, there is a valid argument for using the words 'sense' and 'perception' interchangeably; as in this article. Note, however, that despite their common designation, the so-called proprioceptive senses are almost always examples of perception.

Classification of the Senses

The Scottish physiologist Charles Bell was first to identify the fundamental anatomical basis for sense/perception and movement: 'Between the brain and the muscles there is a circle of nerves; one nerve [ventral roots] conveys the influence from the brain to the muscle, another [dorsal roots] gives the sense of the condition of the muscle to the brain' (Bell, 1826, page 172). Bell included within this muscular sense the senses of position and movement, and other senses evoked by muscle contractions.

In a similar vein the English pathologist and anatomist Henry Bastian wrote: 'I refer to the body of sensations which result from or are directly occasioned by movements … kinaesthesis. By means of this complex of sensory impressions we are made acquainted with the position and movements of our limbs, we are enabled to discriminate between different degrees of "resistance" and "weight", and by means of it the brain also derives much unconscious guidance in the

Introduction

Semantics, the systematic study of the meaning of words, should not be considered an insignificant pastime mainly undertaken by academics and pedants. Poor semantics often causes unnecessary misunderstanding and disagreements. However, even when careful attention is given to the meaning of words, communication difficulties may still remain when the words are used to represent complex or incompletely understood concepts, as is the case with the proprioceptive system. This paper examines the current use of terms related to the proprioceptive system, suggests certain changes, and thereby aims to improve understanding of the proprioceptive system and its clinical assessment.

Table 1: Classification of the senses

Category	Subcategory	Environment	Receptor (sense)
Special senses	Teleceptors	Distant external	Eyes (vision), cochlea (hearing), nasal mucosa (smell)
	Other	Immediate external	Taste buds (taste)
Somatic senses	Exteroceptors	Immediate external	Skin (touch, pressure, vibration, warmth, cold, pain)
	Proprioceptors	Musculoskeletal	Deep tissue* (position, movement, etc), labyrinth (posture, balance)
	Other	Musculoskeletal	Deep tissue (warmth, cold, pain)
Visceral senses	Interoceptors	Visceral	Some viscera (pressure, stretch, pain)

* All subcutaneous structures other than viscera; including muscles, joints, bones, fascia and interosseous membranes

performance of movements generally' (Bastian, 1887, pages 5, 6).

In 1906, the English physiologist Charles Sherrington introduced his classification of the senses, which every physiology text since has adopted or closely paralleled (table 1). In Sherrington's classification proprioceptors are those afferent nerve endings (actually beginnings) which are activated by and transmit afferent information about mechanical stimuli generated within the musculoskeletal framework. Because this afferent information does not always reach the cerebral cortex, it does not always produce sensation. Accordingly, the generic term '(neuro)receptor' is preferable to 'sense organ'. Sherrington's other categories of sensation are 'exteroception' and 'teleception', where the sources of the stimuli are the immediate and distant external environments respectively, and 'interoception' where the viscera are the stimulus source.

As the above quotation from Bastian indicates, kinaesthesis (kinaesthesia), while focusing on movement sense, does not exclude position sense or the other muscular senses redefined almost a decade later by Sherrington. Indeed, given the minimal distinctions that can be made between Bastian's 'kinaesthesia' and Sherrington's 'proprioception', it seems appropriate now to treat both words as synonyms; as in figure 1. This view is also held by several other authors from different disciplines (eg Clark and Horch, 1986; Schmidt, 1991).

Common variations in the definition of proprioception and kinaesthesia in current published literature are to define proprioception as in figure 1, while defining kinaesthesia either as the same as proprioception, except for the exclusion of balance (Fitzpatrick and McCloskey, 1994), or as movement sense alone (Jerosch and Prymka, 1996). Although not this author's preference, these alternatives are not conceptually harmful.

However, problems do arise when 'kinaesthesia' is defined as movement sense, and 'proprioception as either position sense (Barrack and Skinner, 1990) or position and movement sense (Warner et al, 1996; Gardner et al, 2000). The concern here is that all the other senses listed under proprioception/kinaesthesia in figure 1 are left unclassified and apparently (but incorrectly) unrelated to position and movement sense.

Moreover, little value can be derived from having two words with the same meaning. Hence 'kinaesthesia' should not have the same meaning as the simple relatively self-explanatory 'movement sense', nor should 'proprioception' mean just 'position sense'.

Likewise, 'pallaesthesia' and 'piesesthesia' are redundant alternatives for 'vibration sense' and 'pressure sense' respectively.
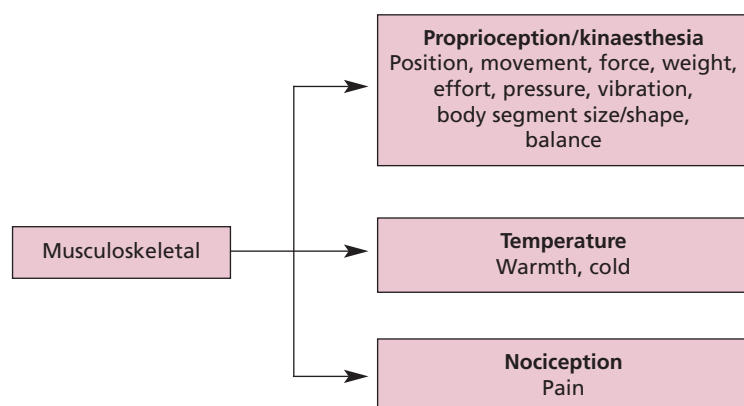
Fig1: Classification of the musculoskeletal senses

Position *versus* Movement Sense

Without looking, normal individuals can accurately sense the position of a limb segment even after it has been motionless and unattended consciously for a long time. This position sense is served by slowly adapting mechanoreceptors; mainly secondary spindle endings and tendon organs in muscle, and tendon organs and Ruffini spray endings in other deep tissues. For reviews of the various types of proprioceptor see Grigg (1994) and Hogervorst and Brand (1998).

When an unobserved limb is passively moved at sufficient speed, its owner can normally sense attributes of the movement as it occurs; for example its direction, amplitude and velocity. This movement sense stems from the more rapidly adapting proprioceptors; mainly the muscle spindle primary endings, and lamellated corpuscles in other deep tissues. However, since 'every position is arrived at through a movement and every movement causes a change in position' (McCloskey, 1978, page 806), position and movement sense are commonly linked during daily activities. Information gained during movement to a position may help localise the end position, while information gained about the start and end positions can be used to deduce features of the interposed movement.

Clinicians may assess position sense in isolation from movement sense by passively moving the joint to (and from) each test position using an indirect path with several random changes in direction (Remedios *et al*, 1998). By contrast, clinicians cannot isolate movement sense without sophisticated equipment; that is they cannot prevent patients from gaining movement cues from the postures at the start and end of the movement. Nevertheless, since spindle primary endings are partly slowly adapting, and secondary endings and Ruffini endings partly rapidly adapting, there is substantial overlap in the receptors responsible for position and movement sense, and a high probability that movement and position sense will be equally affected in most patients.

Muscle *versus* Joint Sense

The question may be asked: Is there a true muscle sense and a true joint sense, and if so what are they? Following Kellgren's (1939) seminal studies of referred pain from deep tissues, it is now clear that localisation of all sensations to their point of origin is greatest at the body surface, and increasingly limited in deeper structures. Although some senses such as ache, pain, tension and pressure may be experienced in a muscle or joint, or even a smaller component such as a tendon or ligament, rarely does such an experience allow the person to conceptualise sharply the involved structure. Experiments using normal conscious co-operating subjects have confirmed that when surgically exposed tendons are pulled so as to stretch the muscle belly (McCloskey *et al*, 1983), or afferents from muscular proprioceptors electrically stimulated (Gandevia, 1985), or muscle spindles stimulated by externally applied mechanical vibrations (Roll *et al*, 1989), the resulting sense is always of position or movement of the skeletal segments on which the muscle acts. In none of these studies was any sense experienced in the muscle bellies or their tendons. Similarly, electrical stimulation of finger joint proprioceptive afferents by Burke *et al* (1988) and Macefield *et al* (1990) mainly produced illusions of finger movement.

In summary, for the most part proprioceptive senses are derived from muscles and joints rather than experienced in muscles and joints. For this reason it is questionable whether physiotherapists can train patients to sense individual contracting muscles more than vaguely, especially deeply placed muscles such as transversus abdominis and multifidus. More detailed arguments along similar lines are provided by Bosco and Poppele (2001).

Part-time Proprioceptors

If the corpuscular musculoskeletal receptors and vestibular apparatus are considered full-time members of the proprioceptive system, then skin receptors and the retina of the eye may be characterised as part-time proprioceptors. While table 1 shows the primary role of the skin receptors and retina as reacting to stimuli derived from the external environment, sometimes they provide the central nervous system with proprioceptive information about the musculoskeletal framework, as elaborated below.

During standing, afferent information from skin receptors in the soles of the feet

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can be used by the proprioceptive centres of the brain to help clarify the posture of the more proximal limb and axial joints (Kavounoudias *et al*, 2001). The same applies in standing when there is even the lightest fingertip contact with an external surface (Clapp and Wing, 1999; Lackner *et al*, 2000). If a standing subject's eyes are open, vision can also help identify body segment positions (Fitzpatrick and McCloskey, 1994). These proprioceptive roles of the skin and retina also apply during other postures and many dynamic functional activities such as reach-to-grasp. Of course this does not stop the skin receptors and retina from undertaking their more usual duties; that is responding to the external environment.

Skin mechanoreceptors in the hand function almost as often proprioceptively as they do exteroceptively. Thus Erik Moberg, the renowned Swedish exponent of sensory hand assessment, wrote: 'In the unique combination of explorative and manipulative performances of the fingers, with their refined motor control and dense cutaneous innervation, the distinction between proprioception and exteroception seems almost to vanish' (Moberg, 1990, pages 133, 134).

If we actively move a fingertip across the surface of an unseen object, we may perceive the texture and temperature of that surface. This is a purely tactile (exteroceptive) activity, sometimes called 'active touch' (Kalaska, 1994; Craig and Rollman, 1999). However, if we touch and grasp the object, the skin and musculoskeletal receptors can provide proprioceptive afferent information about the object; that is information about the object's size, shape, hardness and weight (Jones, 1996). The proprioceptive role of hand skin receptors was proven by Edin and Johansson (1995) when they showed that when skin surrounding finger joints is experimentally strained in the manner which would naturally occur during finger movements, that is stretched over one side of the joint and relaxed over the other, normal subjects sense finger movement even if the joint is not moved. In the published literature this manipulation-precipitated concurrence of exteroception and proprioception is often referred to as 'stereognosis' (Bennett and Karnes, 1998) or 'haptic sense' (Appelle, 1991).

Proprioception and Motor Skill Learning

Proprioceptive awareness of postures and movements is most required during the learning of new skills. For example, when first learning to touch-type there is a high consciousness particularly of wrist and hand movements. By being conscious of what is happening an individual can more readily (ie consciously) change how it is happening. As learning proceeds and the typing movements are refined, afferent feedback signals from the participating body segments are systematically stored in the brain as templates of properly executed typing movements. Research employing functional magnetic resonance imaging and positron emission tomography indicates that the cerebellum and pre-frontal cerebral cortex are the main sites for this learning process (Jenkins *et al*, 1994; Flament *et al*, 1996).
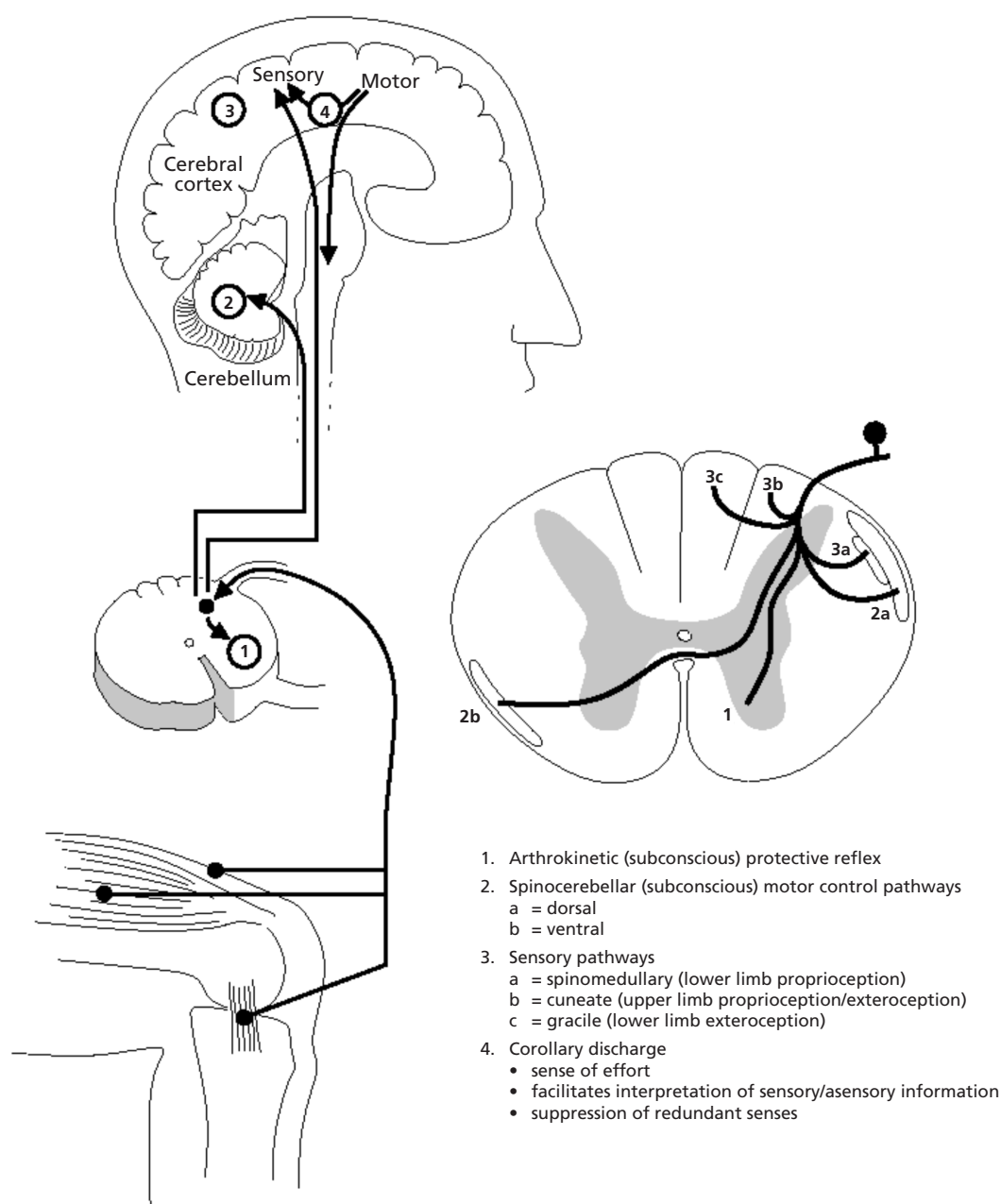
Once fully learned, typing involves minimum proprioceptive consciousness of the participating body segments, and maximum use of stored afferent templates. That is, at a subconscious level afferent signals fed back from proprioceptors in the periphery are cross-checked against the stored afferent templates to help verify correct performance. The great advantage of shifting control of learned activities from a conscious cerebral process to a largely subconscious propriocerebellar one, is that instead of focusing on the process we are freed to concentrate on its outcome.

Some movements are so fast that proprioceptive feedback is only possible before the movement begins (to help planning), and after the movement is completed (to help verify the outcome) (McCloskey and Gandevia 1993). With slower movements the proprioceptive system can monitor and even adjust the movement as it occurs. Especially useful is the ability of the proprioceptive system to trigger immediate, rapid and precisely-tailored compensatory muscular contractions reflexively in response to unexpected changes in external or internal forces; for example as required during standing balance. See Hasan and Stuart (1988) for other examples. Typically, these adjustments are near-complete or complete before there is any sense of the triggering stimulus. While some simple unperturbed movements are possible without propriospinal and

propriocerebellar verification, such movements always rapidly deteriorate (Nougier *et al*, 1996). For an absorbing story of life without a functioning proprioceptive system see Cole (1995).

Neuroanatomical Components of the Proprioceptive System

Three main destinations of the proprioceptive afferents and a related motor neuronal connection are outlined in figure 2. Afferent destination 1, the spinal cord, represents proprioceptive afferent connections on to Aα and especially Aγ motor neurones for producing reflexes designed to protect joints against potentially harmful stresses. Notwithstanding their undoubted importance, it

1. Arthrokinetic (subconscious) protective reflex
2. Spinocerebellar (subconscious) motor control pathways
   a = dorsal
   b = ventral
3. Sensory pathways
   a = spinomedullary (lower limb proprioception)
   b = cuneate (upper limb proprioception/exteroception)
   c = gracile (lower limb exteroception)
4. Corollary discharge
   • sense of effort
   • facilitates interpretation of sensory/asensory information
   • suppression of redundant senses

Fig 2: Components and destinations of the proprioceptive system. On the left, proprioceptive afferent pathways from skin, muscle and joint enter the spinal cord via the dorsal roots. The three derived pathways (1-3) pass to the ventral grey matter of the spinal cord, the cerebellum, and the sensory cerebral cortex respectively. A hypothetical pathway for corollary discharges from the upper motor neurones is also shown (4). The transverse section of the spinal cord on the right provides greater detail of the spinal connections

is inappropriate for Hurley *et al* (1998), Beard *et al* (1993) and others to have included these reflexes within their definition of proprioception. These reflexes do not depend on, and are invariably complete before there is any sense of either the stimulus or muscular response; that is they represent one of the subconscious (asensory) functions of the proprioceptive system. Given the established usefulness of Sherrington's classification of the senses, at least in physiology and psychology, those who would redefine proprioception as anything other than a category of sensation will need a very good reason.

Destination 2 represents the cerebellar connections, which are so important for (subconscious) regulation of postures, balance, and movement in general. Destination 3, the cerebral cortex, is the only proprioceptive afferent destination which allows perception; that is which can result in proprioception. The cerebral cortex receives proprioceptive information from the lower limbs almost exclusively by way of the spinomedullary tract in the dorsolateral white column (3a in figure 2) (York, 1985; Nathan *et al*, 1986), whereas proprioceptive (and discriminative cutaneous) information from the upper limbs is transmitted largely via the cuneate tract in the dorsal white column (3b in figure 2).

The corollary discharge is upper motor neurone information which is transmitted to the proprioceptive regions of the cerebral cortex. In figure 2 it is represented as a corticocortical connection, however its exact neuroanatomy is presently unknown. It could just as easily be a brainstem branch from the upper motor neurones that reaches the cerebral cortex via the cerebellum and thalamus. Whatever its exact pathway, the corollary discharge has an important role in active as compared to passive position and movement sense. During voluntary muscle actions the corollary discharge is made available to the proprioceptive cerebral cortex for analytical purposes. In simple terms the proprioceptive cerebral cortex is better able to discern/sense position and movement if it has access to both the corollary discharge (which represents the intended movement) and peripheral proprioceptive afferent feedback (which is generated by the actual movement). Since upper motor

neurone and hence corollary discharge signals are not produced during passive movement, and since passive movement does not generate the same volume of peripheral afferent information (especially from muscles), passive position sense is generally worse than active position sense.

For the above reasons, and because active movements are more functional than passive movements, there is a good argument for clinicians using active position sense tests wherever possible (Stillman, 2000).

Assessment of Proprioceptive System Functions

Clinicians cannot expect to examine the proprioceptive system with the precision and detail possible in the research laboratory. Nevertheless, there are several different clinical tests, summarised in table 2, which can be used to investigate the different parts of this system.

First note that every test in table 2 depends on, and therefore investigates the integrity of the proprioceptors and their afferents. Even the senses of effort, fatigue and weight, which are largely derived from the corollary discharge (Gandevia, 1996), depend in part on feedback from the proprioceptors via their afferents. Thus, for example, Fleury *et al* (1995) demonstrated a markedly diminished capacity for weight discrimination in a person with no functioning peripheral proprioceptive system. Each individual test in table 2 will now be considered in more detail.

The first tests in table 2, passive position and movement sense, involve the proprioceptive pathways from the periphery to the cerebral cortex, but do not necessarily characterise the proprioceptive system's asensory joint reflex and motor control functions. Although active position sense tests are arguably more relevant to everyday functions, like passive tests they provide only limited evidence of the proprioceptive system's motor control functions. In large part the reason is that active position sense tests involve only simple motor tasks that do not challenge a person's capacity to control skilled activities.

Before administering active position sense tests it is important to check that a patient has enough voluntary motor control to be able to move the part to,

Table 2: Clinical assessment of proprioceptive system functions

Test type	Procedure*	Outcome measure	Comments
Position/movement sense (passive)	Passive positioning/movement of joint with patient describing or replicating the test position/movement using same or contralateral joint	Accuracy of description or replication	Involves proprioceptive sense derived from skin, joint and muscle
Position sense (active)	Patient isometrically holds examiner-selected position, then replicates the position using the same or opposite limb	Accuracy of replication	Involves proprioceptive sense derived from skin, joint and (especially) muscle
Deep vibration, pressure or weight discrimination	Vibrating tuning fork, pressure sensor or weights applied to deep tissues via the skin	Deep vibration, pressure and weight sense	Results not correlated to other proprioceptive functions
Tracking and point location tests (eg heel-shin, finger-to-nose, thumb finding tests)	Active limb movement to touch specified body segment (eg, nose, thumb)	Accuracy of trajectory and target location	Involves proprioceptive and cerebellar motor control functions; target location requires position sense
Isometric holding of upper limb	Upper limb held outstretched in front of body	Deviation of limb from initial position, writhing hand movements	Involves proprioceptive and cerebellar motor control functions
Proprioceptive joint reflexes	Sudden perturbation of actively held joint position	Latency and EMG activity of surrounding muscles	Results not correlated to other proprioceptive functions
Standing balance	Uni-/bilateral stance with eyes open/closed, different supporting surfaces, and with/without perturbations	Duration of maintained balance, characteristics of sway, Romberg sign (sway significantly worse with eyes closed)	Romberg sign concerns proprioceptive (including vestibular) balance-related motor control, but not proprioceptive senses; test also involves cerebellar and visual motor control functions
Stereognosis	Identification of unseen object manipulated by hand	Accuracy of identification	Involves proprioceptive sense derived from skin, joint and muscle
Skilled motor function tests of, for example, walking, dressing, manipulating tools	Examiner observation and measurement of activity	Duration, coordination, ease and success in completing task	Involves non-specific examination of the interaction of the visual, cutaneous, cerebellar and proprioceptive systems in motor control

*Unless otherwise stated, the patient's eyes are closed throughout the tests and responses.

and briefly hold it at, perceived test positions. In a study of 33 patients within 2 to 12 weeks of their stroke (or most recent stroke), the author successfully administered active tests to 25 patients (Stillman, 2000). In three patients it was possible to administer passive tests but not active tests, and in the remaining patients no test was possible. In other words, while pain, paresis and hypertonia may prohibit active position sense tests, they often also make passive tests impractical.

Among the least relevant tests with respect to the motor control functions of the proprioceptive system are the specific tests of vibration sense, pressure sense and weight discrimination. For example, Cox (1991) found no correlation in normal subjects between forearm position sense and the ability to distinguish weights held in the hand. Nevertheless, since vibration sense in particular can be precisely instrumented, its assessment is relatively objective and the results may be highly diagnostic.

Tests which focus on tracking ability have more to do with the contributions of both the cerebellar and proprioceptive systems to static and dynamic motor control. Tests which focus on target location (eg the thumb finding test) depend more on proprioceptive sense of the target positions.

Assessment of motor responses following sudden perturbation of individual joints requires sophisticated measuring instruments not generally available to clinicians. It is also difficult to interpret the results; that is to resolve whether the motor responses are a consequence of proprioceptive or of other (eg biomechanical) mechanisms.

Consequently, at present these tests have little clinical relevance.

The different types of clinical balance assessment are well-reviewed by Huxham *et al* (2001). Only a few points need stressing here. Standing balance assessments generally tax the total body motor control functions of the proprioceptive system in conjunction with other control systems. For reasons which are not easily justified, clinical balance tests rarely include the sense of balance; that is examiners rarely ask their patients whether or not they feel/felt stable or unstable during the tests. Also, this author does not agree with the commonly held view that standing on dense foam minimises proprioceptive feedback from the feet and ankles. Increased instability from standing on foam causes greater foot and ankle joint motion, and thus greater proprioceptive feedback from the foot and ankle proprioceptors. However, since there is also greater total body sway when standing on foam, there is greater stimulation of other proprioceptors such as the vestibular apparatus. Thus, standing on foam makes balance more difficult without biasing the test to any particular group of proprioceptors. Finally, since most balance tests are relatively static, they provide only limited evidence about the dynamic motor control capabilities of the proprioceptive system.

The remaining tests shown in table 2, stereognosis and skilled motor function tests, while non-specific, are of great importance as they show what the proprioceptive system is capable of in real life. Their omission from proprioceptive assessment is rarely excusable.

In light of the aims of this paper, it was not appropriate to consider clinical assessment in detail. The aim was to highlight the extent to which different tests focus on different parts/functions of the system. More detailed discussions of proprioceptive assessment can be obtained from Dickinson (1974, pages 35-62), Marks (1998), Stillman (2000, chap 1, pages 5-17) and Pincivero and Coelho (2001).

Conclusion

The English language is neither dead or exact, and the challenge of maximising trouble-free communication is often difficult. In this essay an attempt has been made to clarify the meaning of terms related to the proprioceptive system, and to offer arguments in support of their more general use. Some less satisfactory terms and concepts have been included so as to highlight how they misrepresent the functions of the system as currently understood. While future research may lead to a greater knowledge of the proprioceptive system, it may never be possible to obtain complete agreement between the various interested parties. Nevertheless, the more care and clarity with which we define our terms, the less problematic will be the differences.

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Key Messages

■ The proprioceptive system is that ascending part of the nervous system which provides for sense of the spatial and mechanical status of the musculoskeletal framework, serves motor control, and facilitates reflex defence of individual joints against injury and the whole body against falls.

■ A proprioceptor is any receptor which transmits information about the spatial and mechanical status of the musculoskeletal framework to the central nervous system. This information may reach consciousness, but often does not.

■ Proprioception (proprioceptive sensation or kinaesthesia) is that category of sensations representing the spatial and mechanical status of the musculoskeletal framework. Proprioception serves body image, and the development of motor control when learning new skills.

■ The contribution of the proprioceptive system to the motor control of learned skills, and reflex protection of joints against injury, do not depend on and are often mediated without significant accompanying sensation.

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