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Kinaesthesia and Methods for its Assessment

Literature Review

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In this review measurement techniques used for kinaesthetic sense assessment are presented. Kinaesthesia is an important part of human movement control and provides us with better understanding of specific movement system adaptations to fatigue, training and injury. Additionally, decreased kinaesthesia can be an injury predisposing factor, which stresses the necessity for its assessment in sports injury prevention programs. First, terminology and functional concept of kinaesthesia is presented in relation to other related concepts like proprioception and sensory-motor function. For better understanding, basic underlying neurological backgrounds are discussed in chapter two, encompassing peripheral sensory fields as well as the basics of the central processing. Additionally, factors affecting kinaesthesia and its adaptations to training are presented. Functional aspects are discussed, supporting the role of assessment of kinaesthesia in sports and rehabilitation. In the third chapter, a proposal for measuring methods classification is given. In the final chapter, different measuring protocols and their modifications are presented. Due to their usefulness in sports and injury prevention, methods for measuring sense of joint position, movement onset and active tracking are discussed in more detail. Possibilities and examples of their application to sports and sports injury rehabilitation settings are presented. Some basic guidelines are given of how to use these methods in training or for screening kinaesthesia.

Keywords: kinaesthetic sense, proprioception, measuring methods, joint position sense, sense of movement, sense of force, active tracking.

Introduction

People rely on their senses to successfully interact with the surrounding environment. During movement, specialized senses enable perception of self or extrinsically induced movement of our bodies. Three different but basic senses have been recognized, to be of importance for regulation of human movement. These are vision, vestibular and kinaesthesia or proprioception (Guerraz & Bronstein, 2008; Mergner, 2007; Soechting & Flanders, 2008). This review is going to focus on kinaesthetic sense but it should be kept in mind that other senses are functionally and neurologically linked or interwoven with kinaesthesia.

In sports, the development of the kinaesthetic sense itself is almost never the primary focus of training interventions. Its improvement rather happens in parallel to other functional and structural changes which are the primary aim of a certain type of training. Kinaesthetic sense is thought to be developed by some degree using sensory-motor training (Vuillerme, Teasdale, & Nougier, 2001). In the last decade, kinaesthesia has been correlated to sports injury prevention and rehabilitation, and is proposed to be an important factor in re-establishing proper motor control after injury (Riemann & Lephart, 2002). But kinaesthesia is not an isolated sense or ability, rather an integral part of the movement controlling system. As its sub-modality, kinaesthesia is responsible for perceiving specific characteristics of our own movement, and for being able to correct it accordingly to the goals or demands of the movement and the task performed (Proske, 2006). From this perspective, the essence of kinaesthesia is the corporal self-awareness and is of most importance in sports and rehabilitation. For example, novice athletes rely on their kinaesthetic sense for the correct execution of the new movement they are learning. Moreover, experienced athletes rely on their kinaesthethic sense to influence otherwise automatic movement, and to correct it accordingly to the environmental and internal task demands to achieve superior skill. Kinaesthesia is an important tool used by the motor control system, enabling improvements in movement skills and building correct movement patterns that are the resulting outcomes carried out almost automatically.

Kinaesthesia is actually a functional sensory conglomerate which is based on three different sub-senses (Proske, 2006; Proske & Gandevia, 2009). One of the most often described in literature is the sense of orientation and position of individual limbs and body. Second sense enables us to perceive the movement of the limbs, and the third sense enables us to feel the force produced by our own muscles and an effort experienced while the muscle force is being produced. Based on the information enabled by the three main body senses, humans can actively interact with the environment, this way achieving desired movement. Especially in clinical practice, measures of kinaesthesia are of primary importance to evaluate the rehabilitation results. In sports, affected kinaesthesia has been shown to be an important injury predisposing factor. On the other hand, measures of kinaesthesia in functional movements enable us to understand the effects of practice and other intrinsic factors, such as fatigue. Especially in research and clinical practice, protocols devoted to measuring kinaesthesia have been used. In sports, the understanding of kinaesthesia has been facilitated by motor control research. No tools have been developed to isolate kinaesthetic sense, but rather to measure more complex sensory motor function. In this review, understanding of the concept of kinaesthesia and its neurological and functional background will be presented. Explanations relevant to the understanding of measurement protocols often used in sports prevention, rehabilitation and research practice will be presented and discussed.

Defining the Term Kinaesthesia

In research, as well as in sports and rehabilitation literature, different terms such as proprioception, sensory-motor function, balance and kinaesthesia are often interchangeably used. Usually the same subject of interest is discussed but from various perspectives. Proprioception has been often falsely used to describe function of the motor controlling mechanisms during movement, especially awareness of movement, reaction to perturbation and prevention of injury. As argued by Riemann and Lephart (2002) and Lephart, Reimann, and Fu (2000) poprioception has been well defined by sir Sheringhton in the beginning of the 20th century. Sheringhton`s description of proprioception was not as broad as the today's understanding is. He described it as the sensory information originating from proprioceptors, being sensory organs sensitive to changes that take place in the organism itself (Lephart et al., 2000). Today proprioception is often discussed in the context of joint stability. Functional joint stability is one of the prime sports injury preventive factors. Sensing unpredicted joint rotations is the basis for proper motor reactions. The concept of active joint stability is focused on sensory-motor function. It represents the importance of sensory information derived from joints and muscles involved, as well as their central processing and preparation of motor responses that are executed by relevant muscles, to stabilize individual joint during applied perturbations. From organizational perspective of the motor controlling system, sensory-motor function is superior to proprioception. Kinaesthesia on the other hand has been often interchangeably used with proprioception. Lephart et al. (2000) described kinaesthesia as a sub-modality of proprioception, which is associated with the sensation of joint movement that can be either active or passive. But based on previous perspective, it might be just the opposite. Schmidt and Wrisberg (2008) in their textbook Motor Learning and Performance, distinguish between kinaesthesia as the sensation of gross body orientation and proprioception as the sense of limb positions. Some other authors have used general term proprioception that is composed of two senses; the sense of joint position and the sense of limb movement or kinaesthesia (Hiemstra, Lo, & Fowler, 2001; Ribeiro, Mota, & Oliveira, 2007). Proske and Gandevia (2009) rested on the definition of Bastian dating back to 1888 (Bastian, 1888). They defined kinaesthesia as a sense of position and movement of the limbs and the trunk. For an overview of the discussion on the different definitions of kinaesthesia, the reader is advised to reed previously published papers (Lephart et al., 2000; Proske & Gandevia, 2009).

There is no common consensus considering nomenclature and its semantics. Different authors consider the role of sensory information from different perspectives, such as joint stability, balance or ability to be aware of the limb position. However, all definitions agree in the point that kinaesthesia is a sense of body and limb movement that can be consciously perceived. Descending form neurophysiology, kinaesthesia must encompass proprioceptive information, which is used by the higher nervous structures to produce sensations (Naito, 2004; Riemann & Lephart, 2002). In its self, kinaesthesia does not include motor responses, but does need central processing and awareness for the person to sense the position or the movement of the limbs and the torso. Sense of balance, gross body orientation and joint stability remain in domain of senses like body balance and posture, but using most probably the same sensory information from the same proprioceptive fields. The difference is that this information is used for processing and preparing motor responses that are usually unconscious. This same information can be consciously perceived and this phenomenon of the awareness of the limb position and the movement is what we call kinaesthesia.

In addition to the sensation of limb position and movement, many authors mention the third sense that enables us to perceive the force produced by the muscle's contraction (McCloskey, 1978; Proske, 2006; Proske & Gandevia, 2009; Sanes & Shadmehr, 1995). This sense enables us to perceive and control the force produced by the muscles. An important effect of longer lasting force production is fatigue that is associated with the second modality of force sensation that is called sense of effort. For instance, consider the task of holding a weight in your hand, while sustaining the shoulder at the 90° flexion position. Although the mechanical force needed to maintain the position does not change, we perceive it as if the deltoid muscle must slowly increase the force production to sustain the arm and the weight in the same position. This sense is thought to be produced in the central nervous system based on comparison of afferent sensory drive derived from proprioceptors with the copy of the descending efferent command (Proske, 2006; Proske & Gandevia, 2009; Sanes & Shadmehr, 1995). If these two are dissimilar, the sense of effort is thought to increase (Sanes & Shadmehr, 1995). Even though the central mechanisms have been shown to be of primary importance, peripheral information has been shown to play a role as well (Proske & Gandevia, 2009).

Kinaesthesia as a part of a more general motor controlling mechanism. The kinaesthetic sense is from functional and neurophysiological perspective a part of a motor controlling system and represents its sub-modality. This information is important for the movement controlling system which must be supported with the information on the movement in progress. From this perspective, information of the onset of the movement, velocity, acceleration, direction of movement, and position of an individual limb or joint in time are of importance to enable detection of the movement progress and deviations from the expected trajectory. These deviations can be caused by extrinsic or intrinsic perturbations. For example, perturbations like unexpected change in load that is being carried or other unexpected environmental changes. Perturbations, like sudden increase in radial forces during skiing on divers snow or unforeseen change in ground consistence during running demand adaptive activity of the locomotor system. Based on this feedback better comparison between expected and actual movement can be better met.

Neurological and Functional Background

The peripheral sensory system. As mentioned by sir Sherringhton already in the beginning of the 20th century, our body's poses specialized sensory organs called proprioceptors located in different peripheral tissue (Lephart et al., 2000). Most commonly described are joint-, muscle-, tendon- and cutaneus tissues. Proprioceptors are specially designed to be sensitive to certain types of mechanical stress like elongation, compression and increased pressure induced by the movement deformation (Morrissey, 1989; Young, Stokes, & Iles, 1987). There are also other types of sensors sensitive to chemical irritants, called nociceptors. Inflammation or intra-articular effusion usually stimulates their activity. This abundant sensory information is then sent via different ascending neural tracts to the higher levels of the neural system for processing (Kandel, Schwartz, & Jessell, 2000).

Effects of the specific proprioceptive fields on movement have been studied mostly in rehabilitation studies. Anterior cruciate ligament has been given a lot of attention, because it affects reflexive knee stabilization (Johansson, Sjölander, & Sojka, 1991; Krogsgaard, Dyhre-Poulsen, & Fischer-Rasmussen, 2002). Similar function has been also suggested for the shoulder capsule (Myers & Oyama, 2008) in gleno-humeral movement. Other sensors located in the ligaments, menisci, tendons and skin, were shown to contribute to perception of joint angle and movement as well (Proske & Gandevia, 2009; Riemann & Lephart, 2002).

Muscle-tendon system as sensory organs. An important role to perception of human movement has been ascribed to the proprioceptors located in the muscles. Two main proprioceptors, thought to significantly contribute to kinaesthetics, are the muscle spindle and the Golgi tendon organ (Figure 1). Muscle spindle is a fusiform-shaped organ, with its polar ends attached to muscle fibres. It is a specialized organ that consists of encapsulated muscle fibres, called intrafusal muscle fibres (Windhorst, 2007). From functional perspective there are different types of muscle spindles, but this diversity surpasses the scope of this text. In the centre of the muscle spindles, lie small nerve endings, sensitive to stretch of the capsule, or intrafusal muscle fibres. When they are stimulated, afferent impulses are conveyed to the spinal cord. It differs from other sensors by its own motor innervation of intrafusal muscle fibres via the γ-motor neuron. As the nature of the muscle spindle structure suggests, it is sensitive to tension induced by muscle stretch. It is thought that it contributes to the sense of muscle length, velocity of its contraction and the rate of muscle stretch. Some researchers argue that sensory information arriving from the muscle spindle is far too complex to contribute to the sense of position (McCloskey, 1978; Proske, 2005). Their arguments are based on specific characteristics of the muscle spindle innervations and its influence on the afferent output. Intrafusal muscle fibre can contract and stimulate intrafusal nervous structures, causing the muscle spindle afferent discharge, even if the muscle is not stretched. Sensory signals derived may not be exclusively a consequence of change in the muscle length. This discrepancy between firing after muscle stretching resulting from outer forces or stretching due to γ activity is enabled by a complex coordination of α and γ motor neurons, called α γ coactivation. This debate remains open for future research. Nevertheless, the γ motor system controls the excitability of muscle spindles and consequently influences sensory information and consequently muscle contraction.

But the muscle spindle system can be influenced by other factors that have an important effect on the way sensory information is discharged. The γ-motor neuron is governed by higher nerve centres. There are also evidences that suggest that other proprioceptors from joint ligaments, capsule, menisci and skin can influence the excitability of muscle spindle with direct influence on the γ-motor neuron (Johansson et al., 1991). The exact nature of these connections remains unknown, but research has shown that peripheral sensory information can profoundly affect the muscle spindles afferent firing (Johansson, Pedersen, & Bergenheim, 2000; Johansson et al., 1991). This suggests that the position of the joint and stress put on the skin can influence kinaesthetic sense.

The second important proprioceptor is located in the tendons, called the Golgi tendon organ. It consists of nerve endings that run between collagen fibres of tendons. When tendons are stretched, nerve fibres of the Golgi tendon organ are compressed and stimulated to fire. The afferent nerve fibre is called Ib afference. It has a short indirect connection with the α-motor neuron of the homologous muscle via the inhibitory interneuron. Golgi tendon organs are sensitive to tendon stretching, accomplished by an increased musculotendinous tension, and give information on muscle or tendon tension. From motor perspective it inhibits the muscle, some think of it as a protective mechanism preventing overstress in the muscolotendinous unit. It is thought that the Golgi tendon organ balances stress on different individual muscle fibres, as its nerves spread through areas where individual muscle fibres connect to tendons (Banks, Hulliger, Saed, & Stacey, 2009).

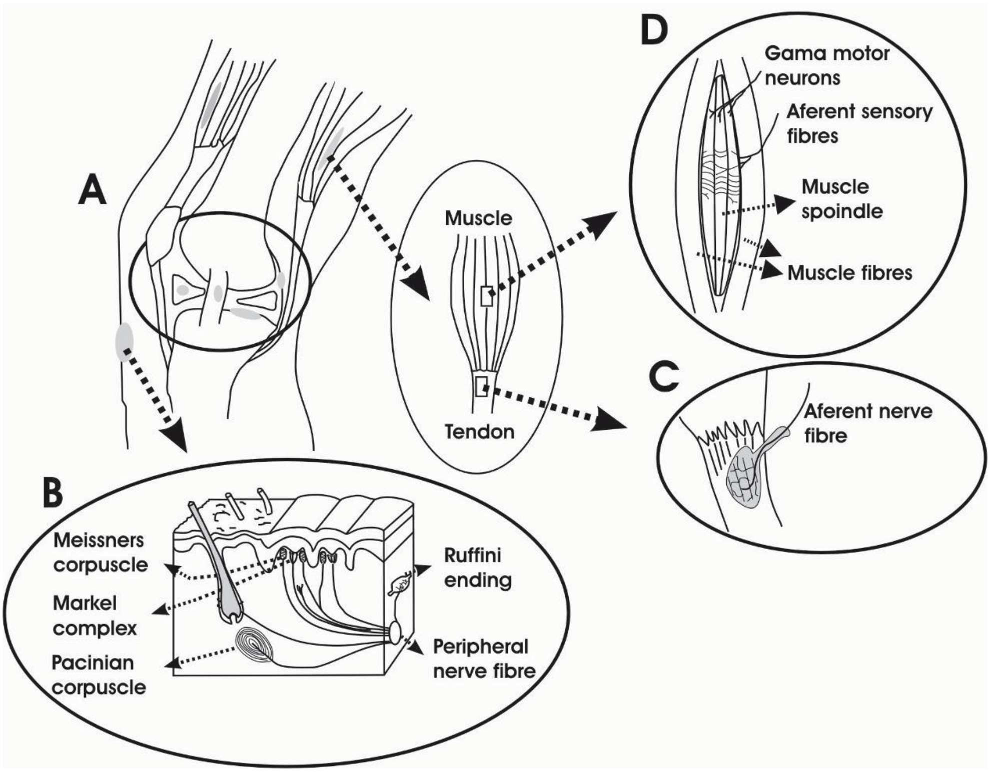

Figure 1. Depicts proprioceptive sensory organs located in various locations of the locomotor system. Joint structures poses various sensors located in joint capsule, ligaments, menisci and cartilage (A). During movement mechanical stress causes elongation, torsion and compression of various joint soft structures. Such mechanical stress represents the stimuli for

joint sensory receptors to fire. In picture B various coetaneous sensors are presented and their corresponding location in the skin. Pressure on the skin stimulates coetaneous sensors to discharge sensory information that can be used in position and load perception. Golgi tendon organ are located in the junction of muscle and tendon fibres (C). They are sensitive to muscle contraction and tendon elongation. Muscle spindle (D) represents the major sensory organ that functions as a sensor of muscle contraction. Its sensory function can be directly controlled by higher nervous centers and by other joint and coetaneous afferents.

Joint structures and their sensory role. Joints can be thought of as hinges, where an actual movement of a body segment takes place. Different soft joint tissues function as joint movement restraints and act as stabilizers. During movement this soft tissue is mechanically stressed, causing stimulation of imbedded proprioceptors. It was not until the mid 20th century that the first proofs were presented that joint ligaments have a neurological function besides their already recognized mechanical stabilizing function (Solomonow, 2006). Some basic classifications of these sensory organs exist, but because not all afferent nerve fibres can be ascribed to one class exclusively, the classification remains relatively open (Johansson et al., 2000; Johansson et al., 1991). The distribution of these afferents differs between ligaments, joint capsules and cartilage structures (Figure 1). Ligaments have been most often the subject of research. In some, distribution of proprioceptors is homogenous throughout the length of the ligament, while in others most afferents are located near the ligament insertion to the bone (Johansson et al., 1991; Solomonow, 2006). As described by Solomonow (2006) there are two theories trying to explain the functional role of the diverse distribution of sensory afferents. As sensors in the bony insertions of ligaments are under lesser strain due to higher stiffness of surrounding tissue, their excitation threshold is elevated. As such, afferent excitation will be produced only at higher strains causing ligament elongation. Conversely, if afferents are evenly distributed in the ligament, this may indicate an ongoing service as a sensor for the detection of angle, position, load, joint velocity, etc.

These proprioceptors are not limited to ligaments exclusively. Basically four types of proprioceptors can be found in all soft tissues of joint. These are Golgi-like tendon organs, free nerve endings, Ruffini and Pacinian corpuscles (Johansson et al., 2000; Macefield, 2005; Solomonow, 2006). For a specific location of specific proprioceptors an extensive review is provided in literature (Johansson et al., 2000). An additional functionall characteristic is the fast or slow adaptability to mechanical stress. Sensors that are slow adapting contribute sensory information during static positions as well as during slow movements.

Faster adapting sensory is thought as being able to sense the nature of rapid movements (Solomonow, 2006)

Skin and its sensory function. Additionally to muscle and joint sensory function, coetaneous sensory system has been shown to effect kinaesthetic sense as well (Macefield, 2005; Rowe, Tracey, Mahns, Sahai, & Ivanusic, 2005). The extent to which these affect kinaesthesia is dependent on the body location (Macefield, 2005). Basically these receptors are located in the skin, and differ between different coetaneous regions of the body (Figure 1). Basic types are Meissner and Pacinian corpuscles, Markels complex and Ruffini endings. As discussed previously, coetaneous receptors can affect the excitability of muscle spindle and as will be presented in the following test, can be more important than the muscle and joint receptors for the perception of a joint position.

The spinal level. The first level where sensory information is processed is the spinal cord (Figure 2). After reaching spinal level, sensory information is conducted to higher levels of the nervous system and motor information back to the muscles. Most simple and most often described neural circuit is the stretch reflex. As the muscle spindle is excited by muscle stretch, it sends sensory impulses via Ia and II afferent fibres that enter the spinal cord in the posterior horns of the spinal grey matter. There it connects via the synapse to the α-motor neuron and causes it to fire. The α-motor neuron and its branches terminate on muscle fibres that it innervates and causes muscle contraction (Enoka, 2008; Kandel, Schwartz, & Jessell, 2000). More complex neuronal connections are present, besides simple monosynaptic stretch reflex. Local networks can be divided in single- bi or oligo – synaptic loops, also called reflex loops. An example of bi-synaptic connection is the pre-synaptic inhibition, moreover the control of which by the higher nerve centres represents oligo-synaptic connectivity. Other examples of oligo-synaptic reflexes are cross extensor and withdrawal reflex. The bigger the number of synapses, the more complex is the reflex, and the bigger is the chance to be controlled by higher nervous structures. This first functional connectivity between sensory and motor connections is thought as a basic blueprint of simplest motor behaviour. But their contribution to kinaesthetic sensations is important as so far as the sensory information can be modified by mechanisms such as increased muscle spindle discharge.

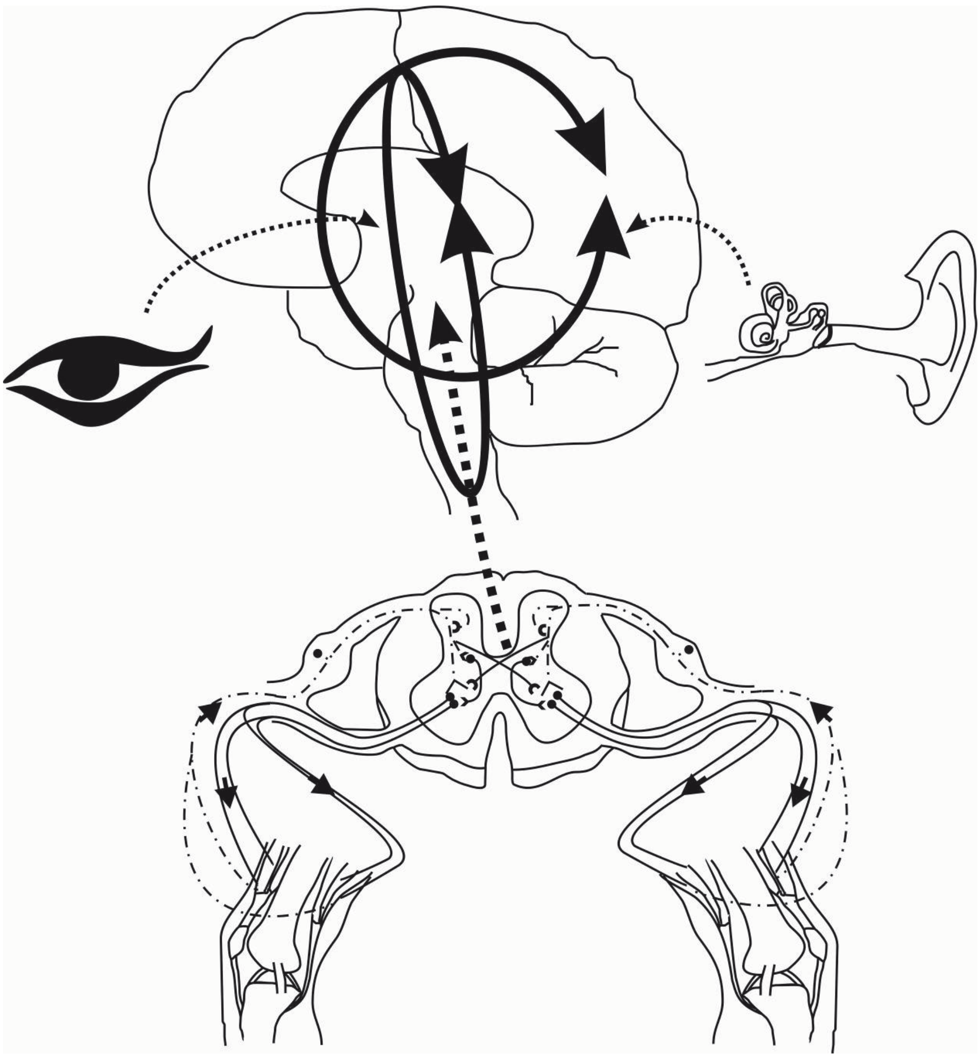

Figure 2. Sensory information from various proprioceptors, eyes and vestibular organ are conveyed to higher nervous structures. First levels of processing takes place at the spinal level. This level doesn't have a direct connection to kinaesthetic sensations, but can be influenced by it. Central processing takes place in sensory, motor and pre-motor areas of the brain. Processing of peripheral sensory information as well as copy of motor command is used to process the specific kinaesthetic sensations. Unconscious processing of sensory information takes places in cerebellum and can have an influence on motor control.

Central processing of kinaesthetic senses. The sensory information that is used for perception of kinaesthesia is transmitted via lateral dorsal tracts to the sensory cortex (Riemann & Lephart, 2002). There the information is supposed to be processed and enable perception of kinaesthetic senses (Naito, 2004). This information can be used by the motor controlling system to prepare and execute voluntary movement. The information on current body posture, movement and orientation in space plays a considerable role in adapting ongoing movement to constraints of the environment. In motor control higher processing of sensory information is thought to contribute to most elaborate adaptations of movement. The comparison of the planed and actual movement enables the motor controlling system to prepare correction of the following movement or prepare new ones. Based on the time constrain rationale kinaesthetic sensation cannot directly contribute to open loop control or to fast adaptations of movement. Although kinaesthetic sense is thought to demand time, and is not fast enough to contribute to faster movement corrections, this might not be the case. Perceived change in body posture can influence fast open loop movement adaptations. Due to such information, the motor controlling system is able to adapt to the otherwise fast and by kinaesthetic sense unaffected motor responses. An example can be the adaptation of a cyclist's leg musculature during steep uphill riding (Fonda & Sarabon, 2010). Other specific adaptations to perception of body posture or limb position on motor output have been shown (Knikou, 2005; Niessen, Veeger, & Janssen, 2009).

In the past a vigorous debate on the importance of central reticular discharge or efference copy and peripheral sensory information took place. Most research is dealing with search for the neurological background of effort sensation (Jones, 1995; Sanes & Shadmehr, 1995; Smirmaul, 2007). The main question in the past was whether sense of effort is produced centrally or does it need peripheral sensory information. Newer studies suggest that sense of effort is processed centrally, with less or even no contribution of peripheral sensory information (Smirmaul, 2007). Sanes and Shadmehr (1995) propose that the extent to which somatosensory information is used for effort perception is dependent on the size of movements, where smaller movements are more dependent. Further research is warranted, as knowledge on when the peripheral sensory information is important, can influence our understanding of motor control and perhaps even ways of training.

Some authors argue that sense of force production can be dissociated from sense of effort (Jones, 1995). During fatigue and increased sense of effort perception of limb position is influenced also, indicating interconnection to other kinaesthetic sensations (Proske, 2006). Understanding how training affects differentiation between sense of force and effort can have a profound effect on our understanding of superior movement skill of expert athletes. This might help coaches to develop specific training approaches to improve technique when fatigued.

Functional Aspects of Kinaesthesia

When mechanical stress is applied to the joint, proprioceptors are excited according to their responsiveness to a specific mechanical stress and the tissue being stressed. Experiments performing tension on ligaments in animal models have shown that sensory information from stressed ligaments starts firing as ligaments are stressed 4-5% of their maximal strain (Holden et al., 1994). This data lines up with the outcomes of studies that measured the strain put on ligaments during walking. The sensory subsystem is extremely sensitive and starts firing already during the support phase of walking, where knee ligaments can be stressed up to 6% of their maximal strength (Henning, Lynch, & Glick, 1985; Johansson et al., 2000), suggesting that ligaments produce sensory information during less demanding activities.

There is some evidence that the proximal joints (the shoulder) have lower thresholds for movement detection when compared to the distal joints (the elbow and most distal inter-phalangeal joints) expressed in degrees of movement until movement detection (Proske, 2006; Tripp, Uhl, Mattacola, Srinivasan, & Shapiro, 2006). This suggests a difference in the sensory function between proximal and peripheral joints. Proximal joints have a specific role from the perspective of force production as well as from perspective of movement accuracy affecting the positioning and movement of distal segments. They are the beginning of the kinetic chain producing power and represent the spatial ground base for the distal joints. As the movement continues in more distal joints, their function is to produce velocity of the movement, and compensate for the possible spatial error in positioning of proximal joints. Possible compensations can cause distal joints to be active in a wider range of motion. For example, the torso and shoulder joint must be positioned as accurately as possible when a subject is trying to hit tennis- or a volleyball ball. Elbow joint and wrist must compensate for possible but small errors of the trunk and shoulder positioning. This small errors result in adaptive movements performed through a wider range of motion in the distal joints (Tripp et al., 2006).

The discussion on the importance of cutaneous receptors in kinaesthesia is still in progress. In their review Proske and Gandevia (2009) argue that sensory information derived from multi-articular muscles on single joint position and movement is rather ambiguous. Cutaneous information aids muscle spindle to detect joint specific movements. This has been shown in the fingers, where the stretching of the skin proved to be of importance for detecting joint position.

This can be important in skills where precise manipulation of hand-held objects is important. Moreover, cutaneous receptors are an important source of information to perceive body sway (Fukuoka, Nagata, Ishida, & Minamitani, 2001). As proposed by Schweigart and Mergner (2008) and Turvey (2007) information used to perceive body movement and position can vary according to the demands and availability of different sources of sensory information. This enables adaptability of the sensory system that provides us with the relevant information.

Factors affecting kinaesthesia. Certain factors such as cold, fatigue, vibration, injury, disease and training have been shown to effect kinaesthesia. Their influence can substantially influence the ability to correctly perceive joint position and alter motor control. In sports, injury might develop as a consequence of the inability to perceive incorrect body alignment, movement and posture. This can sometimes result in an injury (Myers & Oyama, 2008).

Environmental factors such as decreased temperatures or cryotherapy can affect kinaesthesia as well as sensory-motor function. As reported by Uchio et al. (2003) the nerve conduction velocity after cryotherapy is reduced. Moreover sensory-motor control can be affected by cryotherapy (Wassinger, Myers, Gatti, Conley, & Lephart, 2007), possibly resulting in reduced joint stability. However, there is controversial evidence regarding the effect of cooling the tissue has on the joint position sense (Costello & Donnelly, 2010). The relevance of the cold on conditioning kinaesthetic sense remains a matter of debate. Based on the mentioned reports, more specific guidelines to the athletes and their coaches, for know, cannot be given.

In sports, fatigue is a constant companion of continuous and strenuous activities. The description of fatigue is basically based on the definition of a decreased ability to sustain production of the desired force (Gandevia, 2001; Gandevia, Enoka, McComas, Stuart, & Thomas, 1995). On the other hand, fatigue can cause other changes in the sensory-motor function as well, as it influences the sensory function. Fatigue can develop at the periphery or centrally in the central nervous system (Gandevia et al., 1995; Sacco, Thickbroom, Byrnes, & Mastaglia, 2000; Sacco, Thickbroom, Thompson, & Mastaglia, 1997). The causes of a compromised sensory drive are multiple. Changes can be due to muscle metabolites that can affect muscle spindle activity (Djupsjöbacka, Johansson, & Bergenheim, 1994; Fischer & Schäfer, 2005), changes in sensory relevant contribution of specific mechanoreceptors in the joint (Tripp, Yochem, & Uhl, 2007a, 2007b) or central changes (Miura et al., 2004).

Many studies considering the effect of fatigue on kinaesthetic sense were performed on the shoulder girdle and on the knee. Different fatiguing protocols induced decreased joint position acuity due to altered sensory-motor function of the exposed limbs. The joints that are active in maximal upper arm throwing were shown to recover in 7 minutes after the termination of the maximal throwing protocol involving 60 maximal throws (Tripp et al., 2007b). Interestingly, the gleno-humeral joint proved to be most strongly affected by fatigue (Tripp et al., 2007a, 2007b). These results provide support to the theory of depressed sensory function in throwing athletes, especially in the cocking and release phases of a throw. On the other hand, basic sensory-motor task like body balance is supposed to recover in 75 seconds after termination of the intense fatigue protocol, and after 15 minutes using a less intense but longer lasting fatiguing protocol (Harkins, Mattacola, Uhl, Malone, & McCrory, 2005). If fatigue plays an important role in decreasing kinaesthetic sense during sports, training protocols directed toward improving specific endurance and sensory-motor function are warranted.

Other studies have shown a decreased kinaesthetic sense of the knee (Miura et al., 2004), spine (Armstrong, McNair, & Taylor, 2008; Newcomer, Laskowski, Yu, Johnson, & An, 2000) and ankle (Forkin, Koczur, Battle, & Newton, 1996; Fu & Hui-Chan, 2005) after an injury. Deficits in kinaesthesia have been proposed to be associated with the risk of injuries of otherwise intact joints; i.e. kinaesthetic deficits related to injury prevalence (de Noronha, Refshauge, Herbert, Kilbreath, & Hertel, 2006).

As proposed by the studies using vibrations applied to the specific body parts, perception of joint movement as well as position can be influenced (Bock, Vercher, & Gauthier, 2005; Proske, 2006; Weerakkody, Taylor, & Gandevia, 2009). In sports like running, cycling, and others where vibrations are a persistent part of movement this consideration should be taken into account.

In sports practice, elastic cuffs are often used for joint bracing. It is a common believe that braces prevent injury by mechanically limiting joints range of motion (Renstrom, Konradsen, & Beynnon, 2000). As this is most probably not effective to the extent to which we would like it to be, other positive effects have been observed. Bracing or taping increases sensory input due to increased coetaneous or deeper tissue stimulation when braces compress one’s limb (Refshauge, Kilbreath, & Raymond, 2000). By these means more abundant sensory input can be provided (Ulkar, Kunduracioglu, Cetin, & Güner, 2004), that can have a prophylactic effect.

An interesting report on effect of proprioceptive neuromuscular facilitation stretching (PNF) techniques on kinaesthetic sense was presented by Brindle et al. (2010). Authors report on acute decrease in kinaesthetic acuity following PNF stretching, and discourage use of PNF stretching just prior to training or competition. However, the duration of the effect was not assessed. Moreover, additional studies are needed to evaluate the influence on movement performance, as positive effects of PNF methods have been suggested elsewhere (Chalmers, 2004; Sharman, Cresswell, & Riek, 2006).

Adaptations to training. Different training modalities have been shown to affect kinaesthetic sense. Most often effects of sensory-motor training (i.e. exercises requiring balance and functional joint stability activities) have been reported (Taube, Gruber, & Gollhofer, 2008). As shown by Tripp, Faust, and Jacobs (2009) tracking predefined movement with online feedback and vibrations applied to the hand improved kinaesthesia. Fong and Ng (2006) and Wooton (2010) showed that a long-term practice of tai-chi can influence kinaesthesia as well. Without doubt most frequently used modality is sports technique training. Posing awareness on the movement performed, kinaesthetic sensations are thought to be additionally stressed and refined.

In practice, a superior sensory-motor function was observed in expert athletes compared to non-athletes (Vuillerme, Teasdale, & Nougier, 2001). Research, however, presents no beneficial effects of expertise on kinaesthetic sense (Freeman & Broderick, 1996; Kioumourtzoglou, Derri, Mertzanidou, & Tzetzis, 1997). Some authors even suggest that specific effects of sports training might even decrease kinaesthetic sense (Allegrucci, Whitney, Lephart, Irrgang, & Fu, 1995). Others, however, present evidence that experienced athletes poses superior awareness of movement, incorporating sports specific tools like rackets (Fourkas, Bonavolontà, Avenanti, & Aglioti, 2008). In the future, more task specific oriented studies are needed to illuminate the specific adaptations of kinaesthetic awareness to specific sports.

Central adaptations have been proven as a consequence of balance and skill training. It was shown that cerebral areas become less active in well adopted movements, suggesting an increased involvement of sub-cerebral centres (Taube et al., 2008). When novel movement strategies are demanded, the activity of cerebral centres increases, causing remodulation of the already established connections and movement strategies (Adkins, Boychuk, Remple, & Kleim, 2006; Boniface & Ziemann, 2003). This suggests that novel movement tasks should be used to cause remodulation of the already acquired but inappropriate movement strategies. Specifically, sensory information is less probable to be altered as a result of training (Ashton-Miller, Wojtys, Huston, & Fry-Welch, 2001). As argued by Ashton-Miller et al. (2001) central changes in processing of sensory information are more probable to take place, enabling more efficient awareness and perception. From the functional point of view, these changes are shown in improved balance, joint stability, intramuscular coordination, muscle strength, kinaesthetic sense and jumping ability.

Adaptations to different modalities of training are task-specific supporting the use of sport-specific exercises in rehabilitation and prevention protocols, to increase a positive transfer of the acquired adaptations (Adkins et al., 2006; Borghuis, Hof, & Lemmink, 2006).

Clasification of Measurement Methods for Kinaesthesia

Different fields of research and practice have provided the methodology used for the assessment of kinaesthetic sense (Chung, Cho, & Lee, 2006; DeMyer, 2004; Gandevia & McCloskey, 1976; Kelley, 1969; Koerth, 1922; Kurillo, Gregoric, Goljar, & Bajd, 2005; Tripp et al., 2007a). Based on the nature of various approaches, methods can be organized in two main categories (Table 1). First category includes tests that are specialized in assessing electrophysiological functions of mechanisms underlying kinaesthesia (Knikou, 2008; MacDonald & Paus, 2003; Misiaszek, 2003; Roland, 1987; Roland & Mortensen, 1987; Ruohonen & Karhu, 2010; Tibone, Fechter, & Kao, 1997; Zehr, 2002). These tests incorporate different neurophysiologic methods that are usually reserved for medical assessment and research, and therefore we paid no special attention to it in this paper. The second group includes methods that are focused on assessing kinaesthesia in the context of voluntary and consciously perceived movement (Chung et al., 2006; Gandevia & McCloskey, 1976; Koerth, 1922). This class can be further subdivided into methods for assessing sense of joint or limb position, sense of movement, force, effort and tracking tests. A nonspecific element of this group is balance testing that cannot be exclusively considered as kinaesthesia measurement technique. But these methods do provide some insight into the functional perspective of balance, where kinaesthetic sense plays an important role (Benvenuti, 2001; Winter, Patla, Prince, Ishac, & Gielo-Perczak, 1998).

It is important for kinaesthesia measuring methodology to enable progression from basic towards more functional testing (Cates & Cavanaugh, 2009). Basic measures focus on individual subsystems or simple isolated movements (Kurillo et al., 2005). Measures of specific neurophysiologic functions or kinaesthesia of isolated joints should be the methods of choice. In rehabilitation and sports, progression toward functional assessment is warranted, for providing the insight into the functional movement aspect of kinaesthesia (Chung et al., 2006). These provide qualitative data on the rehabilitation or training progression as well as on the extent of deterioration after injury or disease (Cates & Cavanaugh, 2009; Chung et al., 2006; Kurillo et al., 2005).

Similar testing movements can be used in different measurement techniques. Some methods are simpler to use, because they do not use specialized equipment. For example, clinical neurological examinations of sensory function usually include reports of appropriate perception of movement direction of a passively moved finger or a limb (DeMyer, 2004). Other methods apply sophisticated technology enabling more precise measures of different movement characteristics. For example, precise measures of individual joint angles enable quantification of kinaesthetic sense as well as expressing its importance as a part of a functional multi-joint unit (Tripp et al., 2006). Another illustrative example can be drawn from balance assessment methods. Simple time measures of ability to sustain in balance can be upgraded with specialized equipment, enabling measuring of body sway (Le Clair & Riach, 1996; Tyson & Connell, 2009). With it, an important insight into the hidden but important effects of specific kinaesthetic components on motor behavior is possible (Krishnamoorthy, Yang, & Scholz, 2005)

Table 1. Overview of methods used for assessing different modalities of kinaesthetic sense. In sports and clinical practice methods that measures kinaesthetic sense of voluntary and consciously perceived movements are most appropriate as well as most functional. Electrophysiological methods are better suited for research, enabling basic measures of underlying neurophysiologic mechanisms. Balance and equilibrium measuring methods on the other hand should not be considered strictly as measures of kinaesthetic sense, because gross sensory-motor function is assessed.

Basic classification	Method groups	Sub - methods
Electrophysiological mechanisms underlying kinaesthetic sense	H, M, F wave TMS, TES	-
Kinaesthesia of voluntary and consciously perceived movement	Joint repositioning	Active and passive
	Sense of passive movement	-
	Sense of force	Subjective grading of force, force matching, sensitivity to change in force, force tracking
	Sense of effort	
	Tracking methods	Online feedback, delayed feedback
Balance and equilibrium	Static and dynamic	

Assessment Methods Description and Proposals for Their Practical Use

Balance and equilibrium measurements. Balance testing has often been used as a specific measure of sensory-motor function and proprioception (Ashton-Miller et al., 2001; Lephart, Pincivero, Giraldo, & F. Fu, 1997). As discussed above, kinaesthetic sense represents an important building block of sensory-motor balance system on which further motor responses are building. Additionally to proprioceptive information vision and vestibular system provide very important information on body orientation and oscillation (Asseman, Caron, & Crémieux, 2005; Mahboobin, Loughlin, Redfern, & Sparto, 2005). Deprived sensory systems in elderly (Baczkowicz, Szczegielniak, & Proszkowiec, 2008; Zuckerman, Gallagher, Lehman, Kraushaar, & Choueka, 1999) and after injury (de Noronha et al., 2006) have been shown to contribute to decreased ability to sustain balance. Based on above rationales balance testing can to some extent be understood as a functional kinaesthetic assessment method.

In sports and clinical practice, simplest measures of balance are performed by measuring the time the subject is able to sustain balance (Rogers, 1980). Majority of test uses time limits till test termination or falling. More sophisticated methods use direct or indirect measures of body sway (Chiari, Rocchi, & Cappello, 2002). Different measuring tools have been applied like stabilormetry (Chiari et al., 2002; Winter, Patla, Ishac, & Gage, 2003) and accelerometry (Lamoth, van Lummel, & Beek, 2009) of individual body parts .

Common to all methods are the balancing tasks used. Most simple measures use simple upright quiet stances. By narrowing the support surface size the intensity of balancing increases (Sarabon, Rosker, Loefler, & Kern, 2010). For example Romberg testing protocol (Rogers, 1980) uses wider support surface size compared to flamingo test (Sarabon & Omejec, 2007) that is usually performed single legged. These tests take advantage of a simple biomechanical rule. By narrowing the support surface size the limits of body oscillations tighten and the possibility of a fall increases. Second approach to increasing balancing intensity is to change the consistency of support surface. This can easily be achieved by balancing on foams or unstable support surface (Salavati et al., 2009; Sarabon, Mlaker, & Markovic, 2010) The third possibility of how to increase intensity of balancing is by manipulation the sensory systems involved (Asseman et al., 2005).

More in-depth overview on different balance measurement protocols is provided in the article presented by Panjan and Sarabon in this volume of the Sport Science Review.

Joint position sense measurements. Measures of position sense have been most frequently used as a kinaesthetic sense assessment tool (Carey, Oke, & Matyas, 1996; Gandevia & McCloskey, 1976; Niessen et al., 2009; Refshauge, Chan, Taylor, & McCloskey, 1995; Sigmundsson, Whiting, & Loftesnes, 2000; Ulkar et al., 2004; Voight, Hardin, Blackburn, Tippett, & Canner, 1996). They have been proven useful in studying affects of fatigue (Carpenter, Blasier, & Pellizzon, 1998; Tripp et al., 2007a, 2007b), aging (Ribeiro et al., 2007; Sigmundsson et al., 2000; Zuckerman et al., 1999), limb dominance (Sigmundsson et al., 2000; Voight et al., 1996; Zuckerman et al., 1999), training effects (Hupperets, Verhagen, &

van Mechelen, 2009), pathology (Carey et al., 1996; Chung et al., 2006; Kurillo, Zupan, & Bajd, 2004; de Noronha et al., 2006), and other factors/conditions which modulate kinaesthetic sensation. Three basic methods of kinesthetic testing are usually employed in practice and research. Two of them deal with the ability to sense and reproduce a specific joint angle, one being a test of active and the second of passive joint position reproduction (Alvemalm, Furness, & Wellington, 1996; Laufer, Hocherman, & Dickstein, 2001; Niessen et al., 2009; Voight et al., 1996). The third method deals with the ability to perceive the onset of limb movement. (Brindle et al., 2010; Streepey et al., 2010) .

These three basic methods differ in their functional aspect of kinaesthetic sense that they measure. Active and passive joint repositioning methods enable measures of position awareness, as the third method enables movement sense assessment under various speeds, directions and ranges of motions. Additionally, different sensory fields can be stressed or excluded from measuring, by using the appropriate method and protocol setup. These possibilities will be presented through the following text.

Most common protocol used in active joint repositioning methods includes repositioning of a limb into a reference position (Alvemalm et al., 1996; Laufer et al., 2001; Niessen et al., 2009). Measurements usually start with positioning the measured limb in a specific position (Figure 3). The subject is asked to try to remember the position of the limb/joint. Then the limb is passively returned into the starting position. After familiarizing the subject with the reference position, he is asked to move the limb into the most appropriate place to match the reference position. The difference between the two represents the measure of active joint position sense. Functional upgrades have been presented by some authors. Specific spatial aspects of discrete movements, like the "cooking" position in arm throwing, have been used as a reference position (Tripp et al., 2009; Tripp et al., 2006; Tripp et al., 2007a, 2007b). The subject then has to reposition the entire upper extremity into the required reference position (Figure 3). This approach enables the assessment of the extent that individual joints have on gross limb kinaesthetic acuity (Tripp et al., 2006). By actively moving the limb, muscle spindle and Golgi tendon organs contribute to recognition of the reference position. In such basic setup the sensory inflow is practically unaffected, enabling sensory reweighing in possibly conflicting or otherwise affected movement situations (Capicíková, Rocchi, Hlavacka, Chiari, & Cappello, 2006; Kaufman, Wood, Gianna, Black, & Paloski, 2001) as well as superior joint position awareness (Laufer et al., 2001).

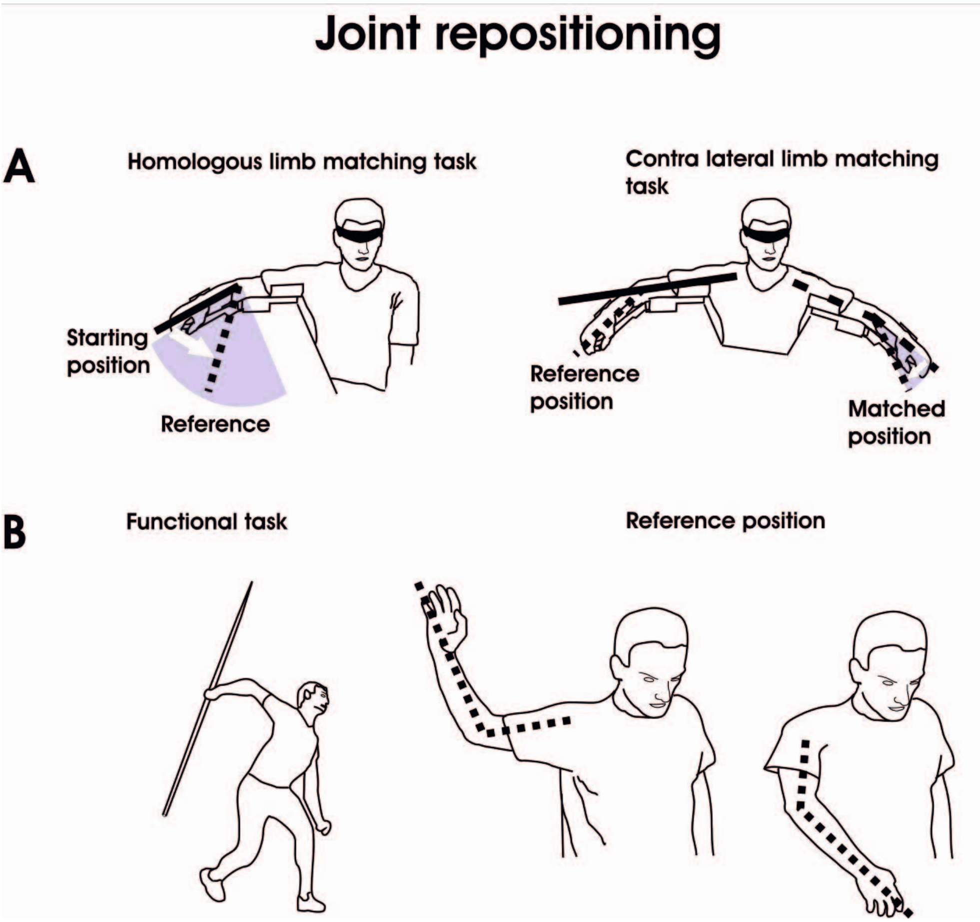

Figure 3. Picture A represents two joint repositioning approaches. First method uses a reference position which the subject has to match with the same limb on his own. The second approach uses a position of a reference limb. The task is to rematch the angle by positioning the opposite limb in to the same position. Picture B represents a functional repositioning task. A subject performs a sport specific task. He is advised to remember curtain positions, in this case late cooking and release position of javelin throw. Repositioning is performed and the difference between actual limb position and required position is measured.

Second method of joint repositioning measures uses passive movement during which the subject has to identify the reference positions (Alvemalm et al., 1996; Laufer et al., 2001; Niessen et al., 2009; Ulkar et al., 2004). In this case, a similar protocol as in active joint repositioning is used. Reference positions are set and the limb tested is returned to the starting position. The clinician or apparatus starts to move the limb through the range of motion. The subject stops the movement or marks the instance when the limb matches the reference position. The difference between the marked and reference position represents the error or acuity of passive joint position sense. While this assessment procedure is performed, muscles of the tested body segment remain relaxed all the time. Although muscles' proprioceptors are thought to be relatively inactive, they can cause possible inconsistencies in joint position sense. False sensory information due to passive stretching and thixotropy (Proske, 2006; Proske, Morgan, & Gregory, 1993) can be a source of the sensory error. One can speculate that joint receptors play an important role in passive joint position sense, but future studies are needed to support such assumptions.

A third concept deals with the sense of passive movement (Brindle et al., 2010; Refshauge et al., 1995). Usually the limb is positioned into a position that is of interest, like in end range of motion or into a position that is important from a functional perspective. Then the assessment apparatus starts the movement. The subject's goal is to sense the onset of movement and try to report it as soon as possible. Usually stop buttons or position markers are used that enable accurate recording of the position where the movement was perceived. The range of motion through which the limb moved until movement detection is a measure of passive movement sense. In these tests different speeds of passive movement are used (Brindle et al., 2010). By using faster movements the acuity is expected to increase (Ashton-Miller et al., 2001). Fast adapting joint receptors should play an important role in faster movements, as in tests using slower speeds slow adapting joint proprioceptors might contribute to movement detection as well. But still such assumptions can only be made based on functional characteristics of various proprioceptors (Johansson et al., 2000; Macefield, 2005).

The position in which the measures are performed is not supposed to be of particular importance, but as suggested by Niessen et al. (2009), the same position should be used for all consecutive measures performed. While considering the orientation of the body and limbs during testing, effect of gravity should be considered. If the limb tested must overcome gravity, muscles must be additionally engaged to produce the movement. As discussed above muscle receptors can be more effectively engaged in kinaesthetic sensation, possibly being additionally affected by the sense of effort in longer lasting measuring protocols (Proske, 2006). Same rationales should be considered if kinaesthetic sense measurements are performed under additional load. In sports, it is important to consider the use of measurement protocols performed under the gravitational constrains or load to guarantee more functional and realistic measurements.

All three methods just described are used in clinical and research practice (Carey et al., 1996; DeMyer, 2004; Gandevia & McCloskey, 1976). Measures can be performed by using relatively simple equipment. For example hand held goniometer can be used to measure joint angle in degrees or simple metric scale positioned at the end of a measured limb to express the limb position on a metrical scale (Refshauge et al., 1995).

Other more sophisticated equipment is also often present in clinics. Some newer models of isokinetic dynamometers already have active joint repositioning tests integrated into the measuring protocols (Alvemalm et al., 1996). Often more easily available equipment, like arthromot or kinateck, can be used for passive joint position sense testing. Before considering the choice of a testing apparatus, goals of measurement should be set. Single- or multi-axis movement as well as single- or multi-joint movements can be considered as the options with respect to the goal of the assessment. The above presented equipment cannot be effectively applied to multi-axial or multi-joint movements. In sports research other methods such as goniometry, kinematics and electromagnethic trackers are used to enable multidirectional recording of movements (Chung et al., 2006; Maffiuletti, Bizzini, Schatt, & Munzinger, 2005; Tripp et al., 2006; Tripp et al., 2007a). Such measurement setup provides movement screening, performed by unconstrained degrees of freedom. These functional measures are of especial interest to sports scientists, coaches and athletes.

An important characteristic of kinaesthetic sense assessment methods is their accuracy and sensitivity. The equipment used must enable sufficient angular discrimination ($< 0.5°$) (Alvemalm et al., 1996; Laufer et al., 2001; Niessen et al., 2009; Voight et al., 1996) , and sufficiently slow speeds of passive movements (Brindle et al., 2010).

Measures can be performed in different ranges of motion. According to the information coming from different fields of research, the range of movement has an effect on kinaesthetic sense (Myers & Oyama, 2008; Zuckerman et al., 1999). For instance, abundant sensory drive is present in the gleno-humeral joint if extremes of ROM are tested (Diederichsen, Krogsgaard, Voigt, & Dyhre-Poulsen, 2002; Myers & Oyama, 2008). When considering the specific adaptations of the gleno-humeral joint in some sports like handball, volleyball or swimming (Burkhart, Morgan, & Kibler, 2003), changes in joint position sense in extremes of ROM can be indicative of potentially dangerous adaptations in joint movement control (Myers & Oyama, 2008). In the knee joint position must be assessed in mid ranges of joint motion. Perturbations causing knee injuries usually occur in the mid ranges of knee range of motion (Alentorn-Geli et al., 2009). However, a specific pathological condition often requires an adapted joint position test protocol in order to achieve the needed specific sensitivity of the test (Hortobágyi, Garry, Holbert, & Devita, 2004; Tripp et al., 2006).

Sense of force measurements. Especially in sports (Cronin & Sleivert, 2005; Riganas, Vrabas, Papaevangelou, & Mandroukas, 2010; Smith, Norris, & Hogg, 2002; Wilson & Murphy, 1996), injury prevention (Hrysomallis, 2009; Kellis & Katis, 2007) and rehabilitation (Pua, Bryant, Steele, Newton, & Wrigley, 2008) measurements of maximal force production, endurance and inter-muscular force ratios have been a standard part of functional movement assessments. In sports, a special attention has been devoted to assessing explosive power (Ferreira, Schilling, Weiss, Fry, & Chiu, 2010; Glatthorn et al., 2010; James, Navas, & Herrel, 2007; McLellan, Lovell, & Gass, 2010) and lower extremity stiffness (Brughelli & Cronin, 2008). Although maximal force represents an important ability in sports as well as in daily activities, sub-maximal force accuracy and its perception are of importance as well. For example, stroke patients have affected manual dexterity (Kriz, Hermsdörfer, Marquardt, & Mai, 1995; Kurillo et al., 2005). Daily activities such as holding a spoon or a cup of tee represent a challenge. Usually their ability to accurately control force development is impaired (Kurillo et al., 2005). Another example, sport specific, can be drawn from swimming. A swimmer relies on accurate water vortex perception to be able to achieve the optimal hand propulsion (Lauder & Dabnichki, 2005; Matsuuchi et al., 2009). As fatigue and higher force developments can affect joint position sense (Jones, 1995; Proske, 2006), the ability to sustain the optimal force production is important from technical as well as from the movement-economy perspective.

Methods for the assessment of force perception have been developed especially for research and rehabilitation purposes (Jones, 1995; Smirmaul, 2007). In sports ratings of effort or force produced, like Borg's scales, are easier to use (Borg, 1970, 1974, 1978). Today, four major methods for force sense assessment are known. The first method uses the range of force that the subject is able to exert. Numbers are assigned to specific force levels. During the force production tasks the subject is asked to name the level of force he perceives of producing (Eisler, 1965a, 1965b). The second method use force matching tasks with the contra-lateral limb. The tested limb is under the load (representing the force reference), and the contra-lateral hand has to match the force level as accurately as possible (Cafarelli, 1982). Similar tests have been used using only one limb, where the subject had to develop predefined level of force with or without feedback information (Bock et al., 2005). The third type of measures assesses the ability to perceive change in force. Usually the force produced is perturbed by the force increase or decrease. The smallest difference perceived represents the sensation of force (Pang, Tan, & Durlach, 1991). And the fourth methods use active tracking methods (Figure 4) enabling functional and active force production measures (Chung et al., 2006; Kriz et al., 1995; Maffiuletti et al., 2005). Sense of force is thought to be based on sensory drive derived primarily from Golgi tendon organs and from the central representations of movement (Jones, 1995). By combining the joint position and force sense measurements more functional assessment of kinaesthetic sense can be achieved. By simply disburdening the measured limb, the sense of force can be effectively diminished, enabling simple but effective way of assessing contribution of individual senses to a specific movement.

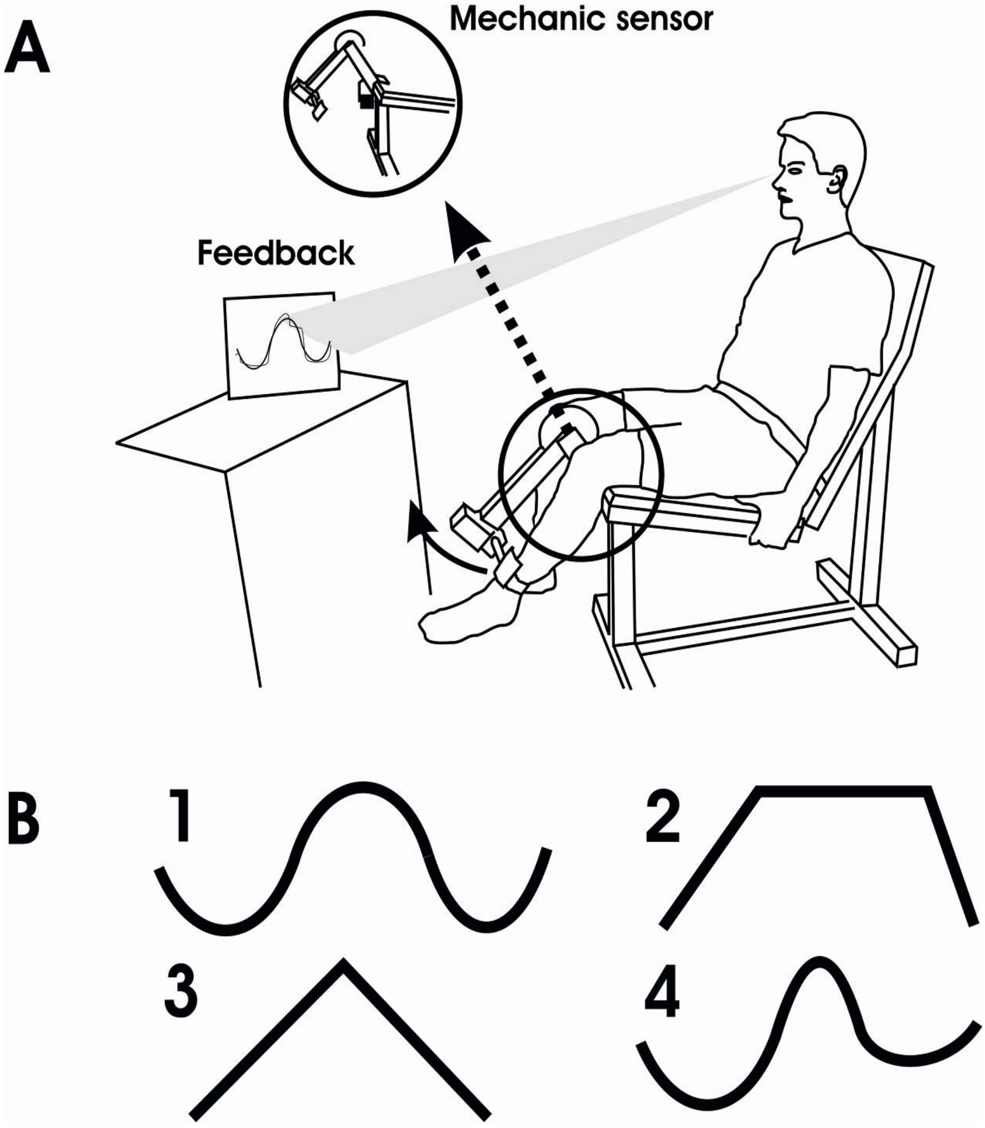

Figure 4. Picture A shows an example of force tracking method applied to the knee extension movement. Different feedback options are possible (B). Continuous sinusoidal (1), trapezoid (2) or triangular (3) movement can be used. Same movement forms can be used in random configuration (4), being more difficult to track.

These methods require specialized equipment. Force based strain gauge sensors embedded into casing of daily or sports specific training apparatus can be used (Kriz et al., 1995; Kurillo et al., 2005). In sports, strain gauge sensors can be embedded into sports equipment enabling sports specific measurements (Heinrich, Mössner, Kaps, & Nachbauer, 2010; Soper and Hume, 2004). By these means, more specific measures of how the force during sports activities is perceived and controlled, can be better studied.

Active tracking measurements. Active tracking methods enable basic as well as functional testing. In the Second World War these methods have been used in the army to improve shooting (Kelley, 1969). Perhaps most classic examples of using active tracking methods come from the motor control research used as early as in 20th century (Koerth, 1922). They contributed to the better apprehension of learning and control of a single joint movement. Therapists have applied these methods to studying and rehabilitation of head and other neural injuries and diseases (Chung et al., 2006; Kurillo et al., 2005; Kurillo et al., 2004). These methods have been often used to improve the control of hand dexterity (Bock et al., 2005; Kurillo et al., 2005; Kurillo et al., 2004). Specific tasks were developed such as cup or pencil grip to mimic daily activities. Some authors expanded the use of active tracking to closed kinetic chain activities (Maffiuletti et al., 2005). In stroke rehabilitation, transfer of closed kinetic chain tracking training on gait was studied (Chung et al., 2006). By these means active tracking provided an efficient training as well as kinaesthetic sense assessment tool. Today, these computerized assessment methods are commonly used in rehabilitation after neurological dieses and injury, as well as in sports.

Common to all tracking methods is screening of specific characteristic of dynamic movement (Figure 4). For example, in majority of tasks, joint position (Carey et al., 1996; Chung et al., 2006; Maffiuletti et al., 2005) or the force produced (Bock et al., 2005; Carey et al., 1996; Kriz et al., 1995; Kurillo et al., 2004) is measured, but other applications are possible as well (Soper & Hume, 2004; Tripp et al., 2006). Commonly, subjects are asked to move according to the pre-prepared movement (reference movement). The online feedback provides them with the opportunity to compare their own and reference movement and correct it accordingly (Bock et al., 2005; Maffiuletti et al., 2005; Rosker, Kalc, & Sarabon, 2010). The difference between the two movements can be used as a measure of the movement acuity (Carey et al., 1996).

The basic measurement setup represents a movement sensor of choice and a computer to provide feedback (Figure 4). Based on this simple setup different protocols have been designed. Basic differentiation between these protocols can be done by the movement task used. Majority of measurement protocols use constant cyclic movements (Carey et al., 1996; Chung et al., 2006; Kriz et al., 1995; Rosker et al., 2010). The movement can be performed with fluent changes in the direction of movement or with a more sudden change (Figure 4). Sinusoidal movements have been most frequently used (Carey et al., 1996; Chung et al., 2006; Kurillo et al., 2005; Kurillo et al., 2004; Maffiuletti et al., 2005), but others like trapeze shapes have been used as well (Kriz et al., 1995; Kurillo et al., 2005). Secondly, in protocols involving measures of force production, ramp protocols have been used (Kurillo et al., 2005; Kurillo et al., 2004). In these protocols the reference force slowly increases and reaches a plateau that must be sustained for a given amount of time.

Constant cyclic active tracking methods differ in their frequency. Most often medium frequencies, ranging from 0.2 Hz to 0.4 Hz, have been reported in the literature (Carey et al., 1996; Chung et al., 2006; Kriz et al., 1995; Kurillo et al., 2004). Sarabon and his research group studied the effect of frequency on the active tracking ability (in press). They performed knee angle tracking on thirty subjects. A specialized brace was used to constrain the knee extension/flexion movement to horizontal plain, diminishing effect of force production by knee flexors or extensors. Subjects performed five sixty second trials in a random order. Five frequencies used were 1, 0.5, 0.25, 0.125 and 0.0625 Hz. This specter of velocities enabled comparison between fast, medium and slow movements. The most accurate tracking was observed at slowest speeds and was progressively decreasing with increase in movement velocity.

Third possibility is to use a randomly changing frequency and range of motion defined by the reference curve which a subject tries to actively mirror. Sarabon and Rosker (in press) performed a pilot study on ten subjects. They used elbow tracking of constant and randomly changing sinusoidal reference movement. Avery subject performed ten consecutive repetitions. The comparison showed decreased tracking accuracy in a random sinus tracking. Although the random tracking test was more difficult, the trend of improvement or learning effect did not differ between the two tasks. An important advantage in using the random movement is the wider dispersion between subjects, meaning higher sensitivity of the method. Still, when using the active tracking tasks effects of learning or spontaneous improvements must be considered when interpreting the results.

Tracking methods enable complex functional testing of various kinaesthetic senses. With modifications described in sections where other methods have been discussed, sense of joint position, movement, force or effort can be separately or interchangeably used.

Actual limb movement can be tracked by various sensors. Today problem is not so much which sensors to use, but rather to apply the most appropriate sensory setup that enables us to gather the data on most relevant aspects of the human movement. Electronic goniometers, electromagnetic sensors and fluorescent video trackers have been used to track kinematic characteristics of movement (Soper & Hume, 2004; Tripp et al., 2006). Other sensors like force sensors, force plates, and even EMG electrodes can be used as well, having a potential in developing explosive power in sports like volleyball, specific balance and others.

Feedback information provided during active tracking defers form method to method. With introduction of virtual reality exiting new possibilities in visual interface have been introduced (Cameirão, Bermúdez I Badia, Duarte Oller, & Verschure, 2009). Such modifications can have a beneficial affect on motivation, especially during rehabilitation training (Deutsch & Mirelman, 2007; Lucca, 2009). More importantly, type of feedback information used is known, to significantly alter motor learning (Schmidt & Wrisberg, 2008). Feedback can provide information about the movement outcome (knowledge of result) or the quality of the movement (knowledge of performance) (Wulf, Shea, & Lewthwaite, 2010). For assessing kinaesthetic sense continuous online feedback must be provided. In training and rehabilitation on the other hand type of feedback used depends on the stage of skill learning. In progression from earliest to more advances stages of motor learning continuous feedback is substituted with delayed or even missing feedback (Schmidt & Wrisberg, 2008). Tracking methods can provide different feedback options, aiding athletes and coaches through various stages of learning and skill refinement.

Conclusion

Kinaesthetic sense is an important component of motor control system. Perception of limb and body position and movement enable planning oncoming and correcting ongoing movement. Perception is based on sensory information derived from specialized peripheral sensory organs called proprioceptors. These are located in various joint, muscle, tendon and coetaneous tissue. Their role is to convert mechanical stress in messages that can be understood by the central nervous system, which uses this information in process of movement planning, initiating and repairing. Main processing that is thought to be responsible for conscious perception of position and movement sense is thought to take place in the motor and sensory cortex. But same information is used by the cerebellum in unconscious motor programming as well.

Kinaesthetic sense has been correlated with sensory-motor deficiencies following injury and disease. Other effectors such as cold, stretching, fatigue, age and training experience have been shown to alter kinaesthetic acuity. Based on its relevance in movement control it became of interest to sports and medicine.

Different kinaesthetic sense assessment methods have been developed. Specialized group of methods focuses on measuring the function of kinaesthetics underlying neuro-physiological mechanisms. These methods are useful for research and in-depth screening purposes, but are not appropriate for practical use in rehabilitation and sports. Second group of methods assesses kinaesthetic sense of voluntary and conscious perceived movements. Methods from this group are relatively simple to use, and are therefore appropriate for use in sports and rehabilitation settings. Methods such as active and passive joint repositioning, sense of passive movement and sense of force represent this group. Tracking methods represent the third group. These methods can be used to upgrade previously described methods and combine individual tests. More functional sports testing can be performed using these methods. Partially, balance and equilibrium assessment methods can be used for kinaesthetic sense screening as well. Because these tests demand active motor reactions, outcomes of these tests are not solely a consequence of kinaesthetic acuity.

In sports an interesting new insights into movement adaptation to fatigue and training is being studied using these methods. Effects of specific training modalities have been studied, but still data on its specific relevance for movement skill and sports performance are missing.

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