

RESEARCH ARTICLE

Assessing Proprioception in Children: A Review

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ABSTRACT. Proprioception is the subconscious and conscious awareness of the spatial and mechanical status of the musculoskeletal framework. When working with children with motor delays and sensory integrative dysfunction, occupational therapists routinely assess the client's proprioceptive system. However, currently available assessments for occupational therapists are primarily observer-based and concerns have been raised about the reliability of observer-based assessments of sensation. The author's purpose was to review measures of proprioception currently available to occupational therapists and explore direct measures of proprioception from neuroscience and rehabilitation that can be adapted for pediatric clinical use. Observer-based and direct measurements of proprioception assessments complement each other in meeting clinical needs. A better understanding of both types of evaluation will improve proprioceptive evaluation.

Keywords: proprioception, children's motor development, assessments

During the formative years of early development, children experience and learn about the world through their senses. As they sense and feel things around their environment, they learn to move and navigate the world. In the Ayer's sensory integration theory, three senses are posited to have a major impact for motor development: tactile, vestibular, and proprioceptive (Ayres, 1972; Bundy, Lane, & Murray, 2002). Difficulties in any of these sensory systems may cause difficulty with developing motor skills in children. In this paper, the focus is primarily on the proprioceptive senses and the importance of assessing proprioception when evaluating children with motor delays. In the present article I also review proprioceptive assessments available for clinicians who work with children.

Proprioception and Related Senses

In the literature and in clinical practice, the term *proprioception* can have slightly different definitions depending on the background of the user. Thus, it is important to start with a clear definition. I take a broad definition: proprioception is the subconscious and conscious awareness of the spatial and mechanical status of the musculoskeletal framework (Proske & Gandevia, 2012; Stillman, 2002). This awareness includes joint position sense, movement sense, force perception, and effort (Bastian, 1887; Proske, Schaible, & Schmidt, 1988; Schmidt & Lee, 2014; Sherrington, 1906). Stillman included balance within proprioception, but I address balance separately, as it is an outcome of functioning proprioceptive and vestibular systems to be discussed in more detail later.

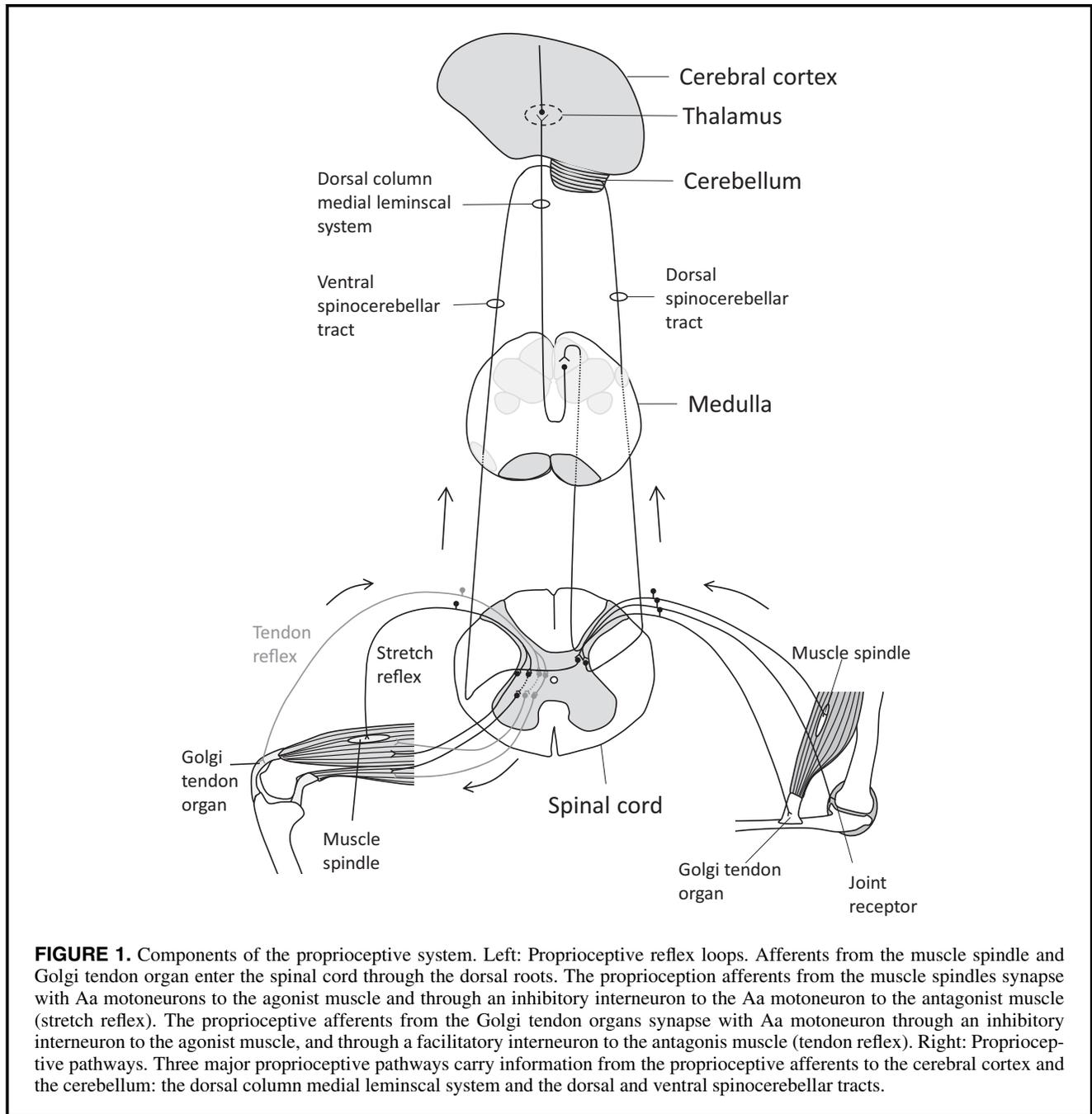
In some literature, the term *kinesthesia* refers to movement sense and proprioception refers to static position sense (Barrack & Skinner, 1990; Gardner, Martin, & Jessell, 2000; van Beers, Sittig, & Denier van der Gon, 1998; Warner, Lephart, & Fu, 1996), but I do not make this distinction. Clinically, it is often difficult to distinguish movement sense from static position sense, as information from joint positions will provide cues about direction and speed of movement. Therefore, I do not make this distinction between the two terms.

Proprioception primarily originates from proprioceptors in the joint receptors, muscle spindles, and Golgi tendon organs. Signals from the proprioceptors are then processed at various levels: the spinal cord, the cerebellum, and the cerebral cortex (Figure 1). The signal that terminates at the spinal cord forms the protective reflex loops with the $A\alpha$ and $A\gamma$ motor neurons that protect our muscles from being overstretched and protect our joints from dangerous stresses. This particular pathway does not result in any sensation of stimulus (e.g., stretch) and therefore is called an asensory function of the proprioceptive system. Although protective reflexes are not considered a proprioceptive function in the strict sense of the definition, it is important to note as we consider the assessments of the proprioceptive system later in the discussion.

The second destination of the proprioceptive signal is the cerebellum, traveling through the spinocerebellar tract. These signals are subconscious but greatly important for posture regulation, balance and fine-tuning of movement for accuracy and fluidity. Finally, there are connections that terminate at the cerebral cortex, which primarily travel through the dorsal column medial lemniscal system. These are the only proprioceptive afferents that reach the conscious mind and allow cognitive perception of the signals. Although proprioceptive signals can be brought to conscious awareness, they are usually processed subconsciously in most day-to-day activities.

Aside from proprioceptors, mechanoreceptors in the skin also provide information about movement. Pressure sensors in the soles of the feet provide information about the load distribution on the feet and are used to assist with balance and postural control. Similarly, the skin is stretched during movement and the mechanoreceptors detect the stretch and provide information

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regarding joint movement. Localization of touch on the body also contributes to the development of body awareness.

The vestibular system and the proprioceptive system work closely together in keeping a body in balance. The vestibular system is important for detecting gravity, orientation and linear movement, particularly that of the head. The semicircular canals in the ears detect rotational movement and the utricle and saccule in the ears detect linear movements. Integrating information about orientation from the vestibular system and joint status from the proprioceptive system, a body is able to

maintain functioning balance without visual information. When either of these systems is dysfunctional, balance is hard to maintain without visual input.

Motor commands from the cerebral cortex also provide information to the proprioceptive system, contributing to the accuracy of proprioception and the perception of effort. Corollary discharge is carried through the upper motor neuron from the motor cortex. Information from corollary discharge provides active motor command signals for the proprioceptive system to compare signal from the muscle and joints during voluntary movement. This contributes to

improved accuracy of proprioception during active movements (Crapse & Sommer, 2008; Guthrie, Porter, & Sparks, 1983; Proske, 2005; Wurtz & Sommer, 2004).

Proprioception and Motor Development

As the sensory system that informs the motor system of where the musculoskeletal system is in space, the proprioceptive system is an essential part of motor coordination and planning. The proprioceptive system provides online error information for correction of slow movements, allowing the limbs and the body to make corrections based on feedback of the location and status of the body in space. In ballistic (fast) movements, the movement is over before the proprioceptive feedback can be processed to alter the motor plan. In these movements, the proprioceptive system is useful in providing information before the movement begins, such as knowing where the limb is prior to the movement and its distance from the final state in order to plan for appropriate motor commands for reaching the target. The proprioceptive system provides feedback after the fast movement is completed, in order to verify movement accuracy and allows for correction for future movements.

An essential component of motor learning is making corrections for future movements. When children first learn a new motor skill, the performance of the movements requires a lot of conscious effort, relying on all the information available, including visual, proprioceptive, and tactile information. Information about the limb's position, speed and forces are perceived by the proprioceptive system, and combined with confirmation from the visual and tactile systems for correction to improve the accuracy and quality of the movement. As the skill improves, the movements are refined and the control process becomes more subconscious. At this time, proprioceptive information is used primarily as subconscious feedback signal to confirm correct execution of efferent motor commands.

Our understanding about the development of proprioceptive ability during early childhood is growing through studies comparing children to adults. Studies have shown that accuracy in actively matching joint positions that are passively presented improves from childhood to adolescence (Goble, Lewis, Hurvitz, & Brown, 2005). More fine tuning of movements is observed in adolescents, demonstrating more conscious awareness of proprioception and effort in the actively matching the limb positions. However, the exact developmental trajectory expected of typically developing children is yet unclear. Most research showed that proprioceptive ability improves from 5 to 8 years old, with slowing improvement and stabilization in late childhood and adolescence (Baird & Laszlo, 1981; Hay & Redon, 1997; Laszlo & Baird, 1980; Sigmundsson, Whiting, & Loftesnes, 2000; von Hofsten & Rösblad, 1988). However, in other studies near linear increase in proprioceptive accuracy was observed from 4 to 13 years old, and improvements continue to be observed up to 24 years old (Crowe,

Keessen, Kuus, van Vliet, & Zegeling, 1987; Elliott, Connolly, & Doyle, 1988; Hearn, Crowe, & Keessen, 1989). Children who have difficulty in proprioception may present with difficulties with motor coordination and planning. These children may also have poor postural control and balance due to inefficient ankle strategies and weight-shifting to maintain balance (Blanche, Bodison, Chang, & Reinoso, 2012; Weimer, Schatz, Lincoln, Ballantyne, & Trauner, 2001). These children are often reported to play too roughly with peers and often crash into things due to difficulty with force gradation when interacting with objects and people (Dunn, 1999; Parham & Ecker, 2007). Studies have shown that poor proprioception has been linked to difficulties with handwriting (Falk, Tam, Schweltnus, & Chau, 2010; Schneck, 1991), and poor coordination (Fatoye, Palmer, Macmillan, Rowe, & van der Linden, 2009; Johnston, Short, & Crawford, 1987; Mon-Williams, Wann, & Pascal, 1999). These difficulties often make it hard for children to learn new motor skills, leading to motor delays.

Children with various conditions have also been shown to have poor proprioception. Children with cerebral palsy (CP), a primarily motor-related disorder, have been shown to have poor proprioception (Goble, Hurvitz, & Brown, 2009) and sensory deficits (Cooper, Majnemer, Rosenblatt, & Birnbaum, 1995), showing that CP is not always a pure motor disorder. Children with developmental coordination disorder (DCD), another disorder generally diagnosed based on motor delays, also show poor performance on proprioceptive tests (Coleman, Piek, & Livesey, 2001; Mon-Williams et al., 1999; Piek & Skinner, 1999; Schoemaker et al., 2001; Smyth & Mason, 1998). Children with autism spectrum disorder (ASD) have been known to have motor delays and difficulty with motor coordination (Bhat, Landa, & Galloway, 2011). Studies have shown children with ASD performed poorly in tests that rely on proprioception, such as apraxia, balance and sequential finger opposition (Weimer et al., 2001). The *Diagnostic and Statistical Manual of Mental Disorders*, 5th edition (DSM-V) also cites sensory processing differences as a diagnostic criteria of ASD (American Psychiatric Association, 2013). Children who have hyper joint mobility have also been shown to have poorer proprioceptive sense possibly due to diminished activation of the muscle spindles or joint receptors. The relationship between proprioceptive delays, pediatric movement disorders and motor delays in children are tightly linked. Proprioception is important in the control of fluidity and accuracy of movements. Studies in adults with neuropathy have shown the role of proprioception in fine tuning the control of movement. Patients with neuropathy affecting lower extremity proprioception showed increased incidences of falling and decreased dynamic stability (van Deursen & Simoneau, 1999). Studies examining multijoint movements in the upper extremities showed that patients who lack proprioceptive input showed spatially inefficient hand movements (Sainburg, Ghilardi, Poizner, & Ghez, 1995; Sainburg, Poizner, & Ghez, 1993), poor spatial

reference for movements (Bard, Fleury, Teasdale, Paillard, & Nougier, 1995), and difficulty with timing of movements (LaRue et al., 1995). A BBC documentary followed a man who had isolated proprioceptive sensory loss and initially lost his ability to walk and move. Though after extensive training, he relearned the ability to walk and control movements, but his movement patterns lacked fluidity and accuracy (Rawlence, 1998). Although most children who have poor proprioception do not have complete proprioceptive sensory loss, one can infer the implications of poor proprioception on a developing motor system. Due to the importance of proprioception in motor planning and motor coordination, it is important that clinicians assess proprioception when assessing motor skills.

Assessments of Proprioception

Due to the limited availability of standardized and norm-referenced assessments of proprioception standardized for use in pediatrics (Blanche et al., 2012), many occupational therapists focus on assessing proprioception’s role in regulation and sensory seeking behavior using parent report questionnaire, overlooking proprioception’s role in motor development. Assessing how a child responds to proprioceptive signals for regulation and modulation is important for characterizing a child’s ability to participate in activities in daily life. But it is also important to assess the child’s ability to process and utilize

proprioceptive information for motor control in a comprehensive evaluation. Neglecting it would be doing a disservice to the child, and potentially missing critical opportunities to deliver interventions to improve the child’s development.

This paper will highlight proprioceptive assessments available to clinicians. Three of the clinical proprioceptive assessments (Sensory Profile, Sensory Processing Measure, and Sensory Integration and Praxis Test) described in this paper are commonly taught in current occupational therapy curriculums. These assessments are widely accepted clinically in pediatrics by occupational therapy practitioners. Subsequent literature search in other assessments of proprioception is done through MEDLINE database and the American Journal of Occupational Therapy database using combinations of words related to proprioception assessment, including *proprioception, assessment, joint position sense, kinesthesia, movement sense, and force perception*. Research results were reviewed to identify commonly used proprioceptive assessments in research and adult rehabilitation evaluations. Clinical assessment tools (refer to Table 1 for summary) are separated from research assessment protocols. Most of the relevant literature reveal research assessment protocols that require extensive laboratory equipment that may not be available to clinicians. This discussion includes adaptations to make these assessments clinically feasible (refer to Table 2 for summary).

TABLE 1. Comparison of Clinically Available Assessments of Proprioception

Name	Subtests that address proprioception	Assessment type	Proprioception areas assessed
Sensory Profile (Dunn, 1999)	Movement processing	Indirect	Does not directly assess an area of proprioception
Sensory Processing Measure (Parham & Ecker, 2007)	Body position processing	(Caregiver questionnaire)	Force perception
	Body awareness	Indirect	
	Balance and motion	(Caregiver questionnaire)	
Comprehensive Observation of Proprioception (Blanche et. al, 2012)	Planning and ideas	Indirect	Force perception
	All items		
Sensory Integration and Praxis Test (Ayres, 1989)	Kinesthesia	(clinician observation) Direct	Joint position sense, movement sense
Kinaesthetic Sensitivity Test (Laszlo & Bairstow, 1980)	(proprioception-related subtests: standing and walking balance, postural praxis, finger identification, graphesthesia, localization of tactile stimuli)	Direct	Joint position sense, movement sense
	Kinesthetic acuity		
Tendon tap Perturbations of actively held positions	Kinesthetic perception and memory	Direct - reflex	Proprioceptive reflex Proprioceptive reflex
		Direct - reflex	

^aBased on the areas of proprioception identified in the definition: joint position sense, movement sense, force perception, and effort.

TABLE 2. Direct Measurements of Proprioception and Suggested Clinical Procedure

Proprioception area	Test type	Procedure	Outcome	Motor ability
Joint position sense	Verbal identification	Passive positioning the joint where the participant verbally identifies the movement without vision of limb	Accuracy of identification	Not required
	Unilateral limb matching	Passive positioning of the joint which is subsequently moved where the participant has to move the limb back to the original position	Accuracy of replacement of limb	Movement required
	Contralateral limb matching	Passive positioning the joint where the participant match with the contralateral limb without vision of limb	Accuracy of matching	Movement required
	Location identification	Passive positioning of the joint where the participant locates a distal segment (e.g. thumb) with contralateral hand without vision of limb	Accuracy of location	Movement required
	Isometric contraction	Participant actively holds a position of the limb without vision of the limb.	Stability of held limb	Ability to hold limb against gravity
Movement sense	Contralateral limb matching	Passive movement of the limb where the participant match with contralateral limb without vision of the limb	Accuracy of matching	Movement required
Force perception	Weight identification	Place weights on each hand and participant identifies which hand has the heavier weight	Accuracy of identification	Not required
Other proprioception-related function	Dynamic balance	Participant balance on uneven surface to examine ankle correction strategies	Amount of sway, time in balance	Movement required
	Tendon tap (proprioceptive reflex)	Striking tendon briskly with a reflex hammer to test the intactness of the stretch reflex loop	Brisk muscle contraction	Not required
	Perturbation of actively held joint (proprioceptive reflex)	Participant actively holds a position of the limb and the limb is suddenly perturbed	Accuracy and time to return to held position	Movement required

The assessments presented here are divided into three categories: (a) indirect assessment of proprioception, (b) direct assessment of proprioceptive function, and (c) assessment of proprioceptive reflex.

Indirect Assessments of Proprioception

Clinically, proprioception is usually assessed indirectly through parents' report or clinician observation checklist. Currently available to occupational therapists and other pediatric clinicians are three tests that examine proprioception: Sensory Profile (Dunn, 1999), Sensory Processing Measure (Parham & Ecker, 2007), and Comprehensive Observation of Proprioception (Blanche et al., 2012). The Sensory Profile is a parent report questionnaire that

examines a child's sensory processing patterns. Two of its sections focus on movement processing and body position processing related to how proprioceptive processing affects participation in daily activities. There are eight items in each section examining how much the child pursues movement, ability to navigate the environment, and postural control. The Sensory Processing Measure is a similar parents' questionnaire that focuses on sensory processing and praxis. The Sensory Processing Measure has three sections that focus on proprioception and related functions: body awareness, balance and motion, and planning and ideas. These sections focus on ability to grade and control forces and body movements, to navigate the environment, and to plan and execute movements. The Comprehensive Observation of Proprioception is a clinician observation scale,

focusing solely on behaviors and movement patterns that are relevant to proprioceptive processing. The observational items are drawn from the literature relating to proprioceptive dysfunction. These indirect assessments provide clinicians with information about the child's behavioral patterns relating to proprioceptive functioning with short testing time. They are commonly used screening tools to identify children that require further proprioceptive testing.

Direct Assessments of Proprioceptive Function

The Sensory Integration and Praxis Test (Ayres, 1989) is one standard clinical test available for directly testing various sensory functions in children, including subtests related to proprioception. The kinesthesia subtest assesses the child's ability to return the finger to a specific test location without vision. This subtest most directly measures proprioceptive function, namely position sense and movement sense. Five other subtests in the Sensory Integration and Praxis Test also provide some information about proprioceptive performance. The standing and walking balance subtest assesses the child's static and dynamic balance with eyes open and eyes closed, assessing vestibular and proprioceptive function. The postural praxis subtest examines a child's ability to imitate postures, assessing the child's ability to use proprioceptive information for motor planning. The finger identification, graphesthesia, and localization of tactile stimuli subtests assess the child's ability to integrate tactile and proprioceptive information related to body awareness. The Sensory Integration and Praxis Test is limited in its use for proprioceptive testing due to only having one form of pure proprioceptive assessment, and requiring special certification to administer the test. Furthermore, the test is only standardized for children between 4 years old and 8 years, 11 months old.

Although less commonly used in recent years, the Kinesthetic Sensitivity Test is another standardized test used to measure movement sense acuity and movement perception and memory (Laszlo & Bairstow, 1980). In the kinesthetic acuity subtest, the participants' hands moved up and down two ramps with different slope without vision of their hand and the ramp, and they are asked to identify which ramp is steeper. The kinesthetic perception and memory require the participants to remember the path their hand traced on a stencil using a stylus without vision of the hand and stencil. The stencil is rotated prior to being unmasked and the participant is asked to re-orient the stencil to the original position. The test has normalized data for children from 5 years old to adult (Laszlo & Bairstow, 1985). This test examines both joint position sense and movement sense, but has limited use due to the equipment needed to perform the assessment and the test is no longer commercially available.

In the following discussion I highlight other methods that assess each proprioceptive sense and related motor function: position sense, movement sense, force sense, and balance. Direct assessment of proprioceptive function

provides the most accurate information about each proprioceptive sense. Unfortunately, most direct assessments of proprioceptive are research protocols and require laboratory equipment. Clinical adaptations of these tests can be made to provide crude but direct measurements of proprioception.

Joint position sense can be assessed by moving a limb and asking the child to identify where the limb has been moved without vision of the moved limb. The position identification can be done through verbal description (Fugl-Meyer, Jaasko, Leyman, Olsson, & Steglind, 1975), contralateral limb matching (Goble, 2010), or pointing to the location (Dover & Powers, 2003; Gilman, 2002). The most accurate way of testing position sense requires elaborate laboratory equipment in order to move the limb without providing additional tactile information, such as using air splints (Hurkmans et al., 2007; Pickard, Sullivan, Allison, & Singer, 2003). Without the elaborate laboratory equipment, joint position sense can still be tested by moving the limb manually. Care must be taken to hold the limb at a location that minimizes tactile information provided, such as grip forces applied orthogonal to the direction of movement. The position sensation subtest of the Fugl-Meyer test has standardized tests of joint position sense by moving the joint segment up or down (Fugl-Meyer et al., 1975). An alternative to test joint position sense is to place the child's hand in space and ask the child to use the other hand to find the thumb without vision of the hand. Another way to test joint position sense is to test a child's ability to hold the limb in isometric contraction without vision. Large deviations from the held position can indicate poor proprioception or poor motor control. The child can also be asked to match the held limb position with the contralateral limb or replace a limb to the held position after it has been moved.

Movement sense is usually tested with similar laboratory equipment as the joint position sense. Researchers have tested movement sensitivity by establishing the joint displacement detection threshold, as the joint is gradually and subtly moved by the equipment until the person is able to identify the direction of movement (De Santis et al., 2014; Hall & McCloskey, 1983; McCloskey, 1978; Pai, Rymer, Chang, & Sharma, 1997). Without elaborate equipment in the clinic, movement sense can be tested by moving the limb manually and asking the direction of movement or assessing the contralateral limb's ability to match the movement without vision.

Force sense, also called load perception, can be assessed by measuring a person's ability to replicate forces (Chu, Hornby, & Schmit, 2015; Dover & Powers, 2003; Lafargue, Paillard, Lamarre, & Sirigu, 2003; Murtaugh & Costigan, 2003). In these tests, participants are asked to replicate forces in the contralateral limb or a previously produced force that was matched to a target force. Although load perception has been reported to have no correlation with position sense (Stillman, 2002), it is important to be considered in motor control as accurate movements to interact in the world relies on the ability to accurately sense and produce forces.

Without the use of elaborate equipment, one can assess force sense with children by putting a weight in each of the child's hand and asking the child which one weighed more.

Balance is assessed in several clinical tests: Romberg's test, Fugl-Meyer test, and neurological exams (Fugl-Meyer et al., 1975; Khasnis & Gokula, 2003). In standing balance with and without vision, the primary system involved in keeping balance is the vestibular system. The proprioceptive system takes more of a role in dynamic balance, such as balance on uneven surface that requires ankle movements to make subtle corrections. The amount of sway and the amount of time maintaining balance in various conditions (stable surface, uneven surface, one-legged stance) will provide insight about the child's proprioceptive and vestibular capabilities.

Assessments of Proprioceptive Reflex

Assessing proprioceptive reflexes is one way to confirm intact proprioceptive afferents. As discussed previously, proprioceptive reflexes do not contribute to the sensory function of the proprioceptive system. However, they allow for a unique opportunity to isolate and test the functioning of the proprioceptors prior to the signals reaching the motor cortex for proprioceptive processing. Proprioceptive reflexes can be assessed in two ways: passive tendon tap (Beard, Kyberd, Fergusson, & Dodd, 1993; Eklund, 1972; Priebe, Sherwood, Thornby, Kharas, & Markowski, 1996) and perturbations of actively held joint positions (Colebatch & McCloskey, 1987; Evarts & Granit, 1976; Fitzpatrick, Taylor, & McCloskey, 1992; Uwe Proske, 2005). It should be noted that abnormal results from reflex tests cannot be used to confirm dysfunction at the proprioceptor level, as the abnormal motor response can be a consequence of proprioceptive, neurological, or motoric mechanisms. A normal proprioceptive reflex result can on the other hand be used to rule out dysfunction of the proprioceptors.

Tendon taps (stretch reflex) are routinely used in neurological exams to assess functions of the CNS. The procedure involves identifying the tendon of the muscle to be tested, and striking the tendon briskly with a reflex hammer while the limb is at rest. The subsequent muscle contraction and limb movement is observed. This test is commonly performed at the biceps tendon, brachioradialis tendon, triceps tendon, patellar tendon and Achilles tendon. A brisk response from the muscle contraction in response to the muscle stretch resulting from the tendon tap is considered a normal response. No response could indicate a problem with the proprioceptors or neurological dysfunction in the reflex loop. Hyperactive stretch reflexes often occur as a result to injury to the nervous system.

Proprioceptive reflexes can also be tested with perturbations of actively held joint position. These protocols typically require sophisticated instruments to elicit the perturbations and to measure the small correctional movements from the sudden perturbation (Brunt et al., 1992; Pincivero,

Bachmeier, & Coelho, 2001; Riemann & Lephart, 2002). These tests can be adapted for simpler clinical use, where participants hold the tested limb in a predetermined position, and clinicians can observe reactions to manual perturbations. Normal proprioceptive response would be to correct for the perturbation and return the limb to the pre-perturbed position quickly. If a child is unable to return the limb to the pre-perturbed position and no motor disorder is noted, it is likely due to problems with the proprioceptive system.

Conclusion

In the present article I give an overview of the proprioceptive system and highlights the importance of proprioception in motor development in children. As clinicians assess motor performance in children, it is important to also include a comprehensive assessment of proprioception. Assessments of proprioception currently used by clinicians are mostly indirect assessments that provide a method for screening, where clinicians follow-up by clinical observation. Direct proprioceptive assessments that allow for more accurate evaluation remained primarily research based. Methods to adapt some of these proprioceptive assessments to make them appropriate for clinical use have been suggested. Development and standardization of more clinical tools to directly assess proprioceptive function is needed.

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