COMMENTARY

Proprioception: where are we now? A commentary on clinical assessment, changes across the life course, functional implications and future interventions

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Abstract

Proprioception, the sense of where one is in space, is essential for effective interaction with the environment. A lack of or reduction in proprioceptive acuity has been directly correlated with falls and with reduced functional independence in older people [1]. Proprioceptive losses have also been shown to negatively correlate with functional recovery post stroke [2] and play a significant role in other conditions such as Parkinson’s disease [3]. However, despite its central importance to many geriatric syndromes, the clinical assessment of proprioception has remained remarkably static [4]. We look at approaches to the clinical assessment of proprioception, changes in proprioception across the life course, functional implications of proprioception in health and disease and the potential for targeted interventions in the future such as joint taping, and proprioception-specific rehabilitation and footwear.

Keywords: proprioception, ageing, falls, geriatric syndromes, life course, older people

Introduction

The loss of proprioception with increasing age is central to a number of geriatric syndromes, in particular falls [5], yet it is relatively little considered in clinical practice. This article will look at current approaches to clinical assessment, changes across the life course, and functional implications in health and disease, as well as briefly consider potential future interventions.

Proprioception is the sense of where one’s body is in space. By its very nature, it is critical for meaningful interaction with the environment. Its neurological basis arises primarily from muscle spindles with a smaller component from tendon organ afferents, cutaneous receptors and minimal input from joint receptors [6]. These muscle spindle and cutaneous afferents allow identification of limb position and movement via neural discharge encoding what is essentially a change in muscle, skin or joint stretch. This is in keeping with Sherrington’s original description of proprioception as an awareness of movement derived from muscular, tendon and articular sources. However, what is of particular current interest is that in addition to these sources, and therefore in contrast with the common perception of proprioception as a peripheral nervous system entity, it is becoming increasingly apparent that there is a significant central component to its processing [6–11].

Clinical assessment

In contrast to the research setting, there appears to have been little progression in the assessment of proprioception in the clinical setting [4]. The following description of proprioceptive assessment remains the clinical standard (see Supplementary data are available in Age and Ageing online, Figure S1; Table 1):

In testing position sense clinically, ask your patient to look at the great toe while you demonstrate the
### Table 1. Types of proprioceptive testing

<table>
<thead>
<tr>
<th>Name of test (proprioceptive sense tested)</th>
<th>How to perform</th>
<th>Specific cognitive requirements</th>
<th>Variables to control</th>
<th>Equipment needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toe position sense (JPS)</td>
<td>See Supplementary data are available in <em>Age and Ageing</em> online, Figure S1</td>
<td>None</td>
<td>Distance moved extraneous cutaneous stimulation</td>
<td>None</td>
</tr>
<tr>
<td>Ipsilateral remembered matching (JPS)</td>
<td>See Supplementary data are available in <em>Age and Ageing</em> online, Figure S2A–C</td>
<td>Intact working memory</td>
<td>Time to reference position distance moved dominance of side used type of movement: active Vs passive</td>
<td>For qualitative assessment, trained observer only. For quantitative assessment, specialised biomechanical equipment [12]</td>
</tr>
<tr>
<td>Contralateral matching (JPS)</td>
<td>See Supplementary data are available in <em>Age and Ageing</em> online, Figure S2D and E</td>
<td>Intact inter-hemispheric communication</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contralateral remembered matching (JPS)</td>
<td>See Supplementary data are available in <em>Age and Ageing</em> online, Figure S2F–H</td>
<td>Intact working memory and inter-hemispheric communication</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kinaesthetic testing (kinaesthesia)</td>
<td>The limb or joint being tested is attached to a motor platform, and the slowest movement velocity detected by the subject is measured</td>
<td>None</td>
<td>Extraneous auditory and cutaneous stimulation (addressed by playing white noise and placing a pneumatic sleeve over proximal and distal skin segments of body part being assessed)</td>
<td>Specialised motor-driven equipment audio equipment pneumatic sleeve [4]</td>
</tr>
<tr>
<td>Dynamic position test (dynamic position sense)</td>
<td>Subject is asked to open their hand when their elbow joint rotates through a predetermined target position in the absence of vision</td>
<td>Intact JPS and working memory</td>
<td>Dominance of side used Time to reference position</td>
<td>Video camera specialised torque motor-driven equipment [13]</td>
</tr>
<tr>
<td>Thumb finding test (dynamic position sense)</td>
<td>One upper limb is actively or passively positioned in space, the subject is then asked to touch the positioned thumb with their contralateral thumb and forefinger in the absence of vision</td>
<td>Intact JPS and inter-hemispheric communication</td>
<td>Time to reference position distance moved, dominance of side used type of movement: active Vs passive</td>
<td>None</td>
</tr>
<tr>
<td>Finger–nose test (dynamic position sense)</td>
<td>One or both limbs are actively or passively positioned and the subject asked to touch their nose with their forefinger in the absence of vision</td>
<td>Intact JPS and inter-hemispheric communication</td>
<td>Time to reference position distance moved dominance of side used type of movement: active Vs passive</td>
<td>None</td>
</tr>
</tbody>
</table>

JPS, joint position sense.
The main problems with this approach are examiner variability and low sensitivity in detecting proprioceptive deficit [4]. One explanation for this could be examiners moving the digit by varying magnitudes. Normal subjects would be expected to identify movement of 1 degree or less [14] and therefore any movements that are larger than this may be missing more subtle but functionally significant deficits.

So what are the alternative methods of proprioceptive assessment and could any of them be clinically applicable? Understanding the different types of proprioception is essential. Mounting evidence suggests that different sensory pathways comprise the proprioceptive system and can, to a certain extent, be thought of as separately functioning entities [6]. The three commonly accepted subdivisions are joint position sense (JPS) also known as statesthesia; kinaesthesia or the sense of movement and dynamic position sense, the ability to monitor position during motion—an amalgamation of statesthesia and kinaesthesia [6, 10].

Table 1 summarises the different proprioceptive tests, their important variables and their requirements in terms of patient cognition and equipment. The majority of these tests focus on JPS and, in the research setting at least, joint position matching tests are often used (see Supplementary data are available in Age and Ageing online, Figure S2) [4, 12]. In contrast to JPS, studies looking at kinaesthesia alone, in the older population at least, are less numerous [10]. Likewise, kinaesthesia assessment is not incorporated into routine clinical practice. This seems unlikely to change given the specialised equipment necessary for its assessment (see Table 1) [4]. Dynamic position sense has been assessed in the research setting using tasks involving coordinated movements with predefined goals (see Table 1) [15]. In contrast to kinaesthetic sense, dynamic position sense is something that is, to some extent, assessed routinely through activities of daily living. Functionally, very important examples include gait in the visually impaired, placing a tea cup on a saucer [10] or indeed reaching for any object in the absence of visual feedback. Although not specifically described as such, we suggest that ‘the non-visual localisation of the extremities of body segments in space’ [4] such as the finger–nose test and the thumb finding test (see Table 1) provide an appropriate clinical method by which dynamic position sense could be assessed, as an awareness of body position during movement is essential for their accurate completion.

From research involving joint position matching tests, some important observations on factors that affect proprioceptive acuity have been made [12]. Variables that increase proprioceptive acuity include using the non-dominant arm, performing the task in the far left of body space, holding the reference position for a longer time period and active, weight-bearing tasks [12, 13] (see Table 1). The time to reference position is also important as longer time periods result in further perceived movements. Although all of these factors could be relevant for the rehabilitation of older people, perhaps of greatest functional significance is the proprioceptive benefit of active, weight-bearing tasks [12]. This could be explained in part by muscle stretch increasing the ‘gain’ on muscle spindle discharge and thus effectively amplifying it. An alternative or perhaps supplementary explanation comes from the mounting evidence that active movements induce somatosensory learning where passive movements do not [16]. Therefore, it has been postulated that sensory input from active movements—which would primarily be proprioceptive—is important for neuroplasticity. That is to say, active movement induces somatosensory (primarily proprioceptive) as well as motor learning [16]. This might explain the importance of proprioception to functional recovery post stroke [2]. It also indicates that functional, weight-bearing tests of proprioception may be more accurate as well as more clinically relevant.

Changes across the life course

There have been multiple studies looking at changes in proprioceptive function with age [1, 5, 7–10, 12, 17]. Work done by Goble et al. indicates that JPS becomes more accurate through childhood and adolescence, peaks in young adulthood and then progressively deteriorates after this (see Supplementary data are available in Age and Ageing online, Figure S3). The improvement through childhood is attributed to neural development and sensorimotor learning. The decline in later life is multifactorial and can broadly be divided into central nervous system (CNS) and peripheral nervous system (PNS) changes.

Peripheral changes include a reduction in myelin that appears to affect sensory nerves first, a reduction in muscle spindle sensitivity, changes in muscle spindle composition including a differential reduction in fast myosin heavy chain isoforms [18] and fewer skin receptors [10, 17]. Some of these changes, for example the alteration in myosin heavy chain isoforms, are partially reversible with exercise [18]. Neurophysiological studies in older adults also show a reduction in H latencies—an electrophysiological reflection of the spinal reflex. This could contribute to postural instability [17]. In terms of clinical change, a loss of distal vibration sense is the only neurological finding that can be safely attributed to age alone.

Although proprioception is classically thought of as pertaining to the PNS, there is a growing interest in the central processing of proprioceptive input. Studies using functional MRI imaging and muscle vibration to give the proprioceptive illusion of movement have demonstrated a right hemisphere predilection for proprioceptive processing [8]. More specifically, activation of the right putamen correlates with proprioceptive acuity and there is an age-related decline in its
activation with muscle tendon vibration [8, 9]. In fact, in the older adult group, the integrity of the right putamen on MRI imaging strongly correlates with the subject's proprioceptive acuity, prompting the suggestion of its potential future use as a proprioceptive biomarker [9]. This connection of the basal ganglia to proprioceptive processing is perhaps unsurprising given neurophysiological findings that show many basal ganglia neurons have proprioceptive receptive fields [3]. The right hemisphere dominance for proprioception also supports the observation of the non-dominant arm being 'proprioceptively stronger' for both joint position matching and dynamic proprioceptive tests [12, 19].

The studies discussed above investigated proprioceptive processing as a result of tendon vibration giving the illusion of movement. However, there is a growing belief, as previously mentioned, that active movements themselves contribute to proprioceptive input [6, 10, 16, 20]. It is particularly interesting therefore, that older adults performing complex movements have been shown to have an excess of central activity compared with younger adults and that this is predominantly in regions associated with movement-related proprioceptive feedback [7]. When attention is diverted from the proprioceptive task in hand this appears to have a more significant effect on older people [21]. So older people show greater cortical activation than younger people for the same tasks and their proprioceptive acuity is more affected when attention is divided. Whether this observation reflects a compensatory mechanism for loss of peripheral proprioceptors, or for decreased putaminal activity or indeed another factor entirely remains to be seen.

Although a significant body of evidence now supports the presence of proprioceptive change with age [1, 5, 6, 8–10, 12, 17, 21, 22], previous studies have provided contradictory results. Initial studies using the clinical assessment of proprioception at the toe did not demonstrate any significant association with age or falls [5]. This may have been due to wide inter-rater variability and the low sensitivity of this method [4]. However, in many studies, discrepancies appear to relate to the older population used—fit and active older adults performed better than more sedentary ones and in these fit populations no significant difference with age was seen on simple matching tests [9, 10, 21]; however, differences did appear when attention was distracted with a two-task paradigm [7, 21]. Another variable has been the type of joint position matching tests used. All subjects, but especially older people appear to perform better when the reference position is held for longer and when, as described above, a single-task paradigm often with contralateral matching is used [21].

**Functional implications**

Patients lacking proprioceptive sense due to large fiber neuropathies have profound deficits in motor coordination—specifically in limb position, force control, postural stability and executing coordinated movement sequences such as gait or drawing around a shape [20]. Aberrant proprioception has also been implicated in disorders such as phantom limb sensations. The hypothesis that normal cortically generated motor commands combined with an absence of the expected proprioceptive feedback are interpreted as pain or paralysis was suggested by Ramachandran et al. [23]. This led to the idea of using a mirror box to 'trick' the cortices so that visual feedback suggested that the phantom limb was indeed moving. Amazingly, patients reported that not only could they see the phantom limb move but they could also feel it move. This perceived return of control led to a significant decrease in their discomfort [23].

Proprioceptive deficits have also been linked with other conditions affecting the CNS, for example, stroke, where preservation of proprioceptive sense has been shown to be a positive-prognostic marker [2]. The apparent right hemisphere dominance of central proprioceptive processing and the common sense hypothesis that one must know that one's limb is, to know where it is, gives a loose suggestion that perhaps aberrant central processing of proprioceptive inputs may form a component of some neglect syndromes. As well as a potential relationship with neglect syndromes, the prognostic importance of proprioception in stroke patients could be related to its role in facilitating neuroplasticity [16]. A third potential factor is the peripheral effects of stroke. Changes in muscle composition have been observed in the hemiparetic leg of chronic stroke patients [24]. These changes include atrophy and, in contrast to aging muscle, a differential increase in fast myosin heavy chain composition [24]. It is not yet clear whether these changes are primary or secondary and whether they are ubiquitous within the muscle (i.e. affect muscle spindles similarly). However, it is interesting that the authors report that 'therapeutic exercise may modify or reverse' these morphological changes [24] a phenomenon also noted in relation to the changes seen in ageing muscle [25]. The proprioceptive implication of these observations remains to be seen.

The finding that activity in the right putamen is correlated with proprioceptive acuity suggests that patients with Parkinson's disease (PD) may also exhibit some proprioceptive deficit. In fact there is significant evidence to corroborate this supposition [3, 25]. Neuropsychological recordings in animals and humans demonstrate that a proportion of neurons in the nucleus subthalamicus—the region targeted in deep brain stimulation—respond to passive or active movements of the limbs. In normal animals, this is organised in a joint-specific, topographical manner; however, if they are made parkinsonian via the injection of MPTP, then the topographic organisation is lost [3]. Patients with PD have also been shown to have depressed somatosensory- and proprioceptive-related potentials [3] and diminished kinaesthetic sense when compared with healthy controls or patients with cerebellar disease. Whilst healthy controls and patients with spinocerebellar atrophy could consistently detect a 1-degree displacement of their forearm by passive movement, patients with Parkinson's could only do so for
movements of 6 degrees [3, 25]. These findings are of particular interest when one reflects on the fact that 1 degree is the maximum suggested movement in the assessment of proprioception and that clinical evaluation of patients with PD rarely identifies any sensory abnormalities.

Perhaps most established is the significant role proprioception plays in one of the ‘geriatric giants’: falls. Proprioceptive and vibration sense in the lower limbs have been shown to be significantly correlated with falls [1, 5, 26]. It appears that it is not simply remaining active that promotes proprioceptive acuity but also the type of activity one performs. Proprioceptive dynamic posture training has been demonstrated to have a significant effect on improving balance in osteoporotic women [27] and ‘Spinal Proprioceptive training’ has had a similarly positive effect on falls in women with kyphosis [26]. A study looking at the differences in proprioceptive acuity between older sedentary adults, older adults who swim or ran and older adults who performed Thai Chi demonstrate a proprioceptive advantage to remaining active but a further kinesthetic advantage in those who practiced Tai Chi rather than swimming or running [28]. This supports the idea that proprioception-specific activities could be used as a targeted falls intervention.

Future interventions

In the first instance, more accurate clinical assessment of proprioception is vital. The simplest mechanism would be to reduce the amplitude of movement that is used when testing proprioception with the current clinical method. One degree is the accepted threshold for healthy volunteers and therefore anything above that could be pathological [4, 25]. However, broadening the clinical approach to proprioceptive assessment to include dynamic position sense is also likely to be of benefit. We suggest the thumb finding test and finger–nose test as useful ways in which to do so.

To support clinical examination a biomarker of proprioception would also be of use. This would be especially helpful in the diagnostic work up of complex patients with multifactorial falls and no clinically detectable proprioceptive deficit. In the future, perhaps the integrity of the right putamen on MRI will be used as a measure of proprioceptive acuity in the investigation of older adults. More accurate detection of proprioceptive abnormalities is necessary for the monitoring of response to therapy as well as the accurate assessment of patients such as those with PD, recurrent falls or stroke.

There is considerable interest in developing interventions, particularly in view of the evidence for sensorimotor plasticity and proprioceptive learning [16]. Established interventions including posture training and Tai Chi have been shown to be associated with increased proprioceptive acuity in active older adults [22, 26, 27, 29]. However, we feel there is also a future for more proprioception-specific exercise or training that combines knowledge of the factors shown to affect proprioceptive acuity (see Table 1), with an awareness of the increased cognitive demand of proprioceptive tasks in older adults and the potential for proprioceptive learning. Such an intervention might, for example, help target the increased incidence of falls when an older person moves out of a familiar environment by facilitating the development of new proprioceptive memories and cognitive strategies that enable safe navigation of the new environment.

The importance of footwear in preventing falls in older people is well documented. Could specific footwear be designed to increase proprioceptive feedback and hence reduce falls? There are certainly some shoes that are currently marketed as increasing proprioceptive feedback; however, this is with a focus on running rather than fall prevention. Whether there is scientific credence to the design is less clear; however, it could form an avenue for further investigation in terms of the assessment and treatment of older people who fall. The benefits of therapeutic joint taping are less established in fall prevention but this approach is increasingly being used for a range of conditions in sports medicine to increase proprioceptive feedback by stimulating skin stretch receptors around the joint. Furthermore, one interesting recent study reported that ankle taping could improve proprioception in healthy young volunteers [30]. Much less is known about the value of this approach in older people but it is also an area worth investigating, particularly in the context of recurrent falls, where it could become a simple, safe and cost-effective intervention to supplement existing training strategies to improve proprioception in older people both with specific conditions and with age-related decline.

Conclusion

The loss of proprioception with age is central to a number of geriatric syndromes, in particular falls, yet it is relatively seldom considered in clinical practice. A sedentary lifestyle appears to accelerate loss of proprioceptive acuity and thus would contribute to loss of functional independence and increased falls. Although, generally staying active has proprioceptive benefit, effective detection and monitoring of the changes in proprioception that form part of the physiological process of ageing as well as some pathological processes, will enable more targeted interventions such as the use of posture training, Tai Chi and, perhaps in the future more proprioception-specific training. Assessment of proprioception should therefore include finer degrees of movement when testing JPS as well as a routine assessment of dynamic position sense. New areas for research are the integrity of the right putamen as a proprioceptive biomarker, the potential for proprioception-specific rehabilitation and the role of therapeutic joint taping or specialised footwear to improve proprioception in older people both with specific conditions and with age-related decline.
Changes in proprioception during the life course.

Role of proprioception in older adults.

Update on the clinical assessment of proprioception.

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