

Review

Assessing proprioception: A critical review of methods

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Received 23 July 2014; revised 25 September 2014; accepted 20 October 2014

Available online 3 February 2015

Abstract

To control movement, the brain has to integrate proprioceptive information from a variety of mechanoreceptors. The role of proprioception in daily activities, exercise, and sports has been extensively investigated, using different techniques, yet the proprioceptive mechanisms underlying human movement control are still unclear. In the current work we have reviewed understanding of proprioception and the three testing methods: threshold to detection of passive motion, joint position reproduction, and active movement extent discrimination, all of which have been used for assessing proprioception. The origin of the methods, the different testing apparatus, and the procedures and protocols used in each approach are compared and discussed. Recommendations are made for choosing an appropriate technique when assessing proprioceptive mechanisms in different contexts.

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Keywords: Joint motion sense; Joint position sense; Kinaesthesia; Movement discrimination; Proprioception

1. Updated understanding of proprioception

Body movement is a fundamental and essential component of human life. In daily activities, most of what a human does in their interaction with the environment is associated with the generation of movement. Further, in competitive sports, precise and coordinated body movement is critical for success. A fundamental shift in the research field of human movement control has occurred in recent decades, largely due to a growing understanding of the role that sensory information plays in neuroplasticity through use-dependent mechanisms.¹ The most important source for the promotion of task-specific neural development is argued to be proprioception.^{1–5}

The question “What is proprioception?” has often been asked in the literature.⁶ Different conceptualizations of “proprioception” by researchers have led to different

definitions, and consideration of their historical emergence is relevant here.

The fundamental anatomical basis for the connection between the brain and limbs was first identified in 1826 by a Scottish physiologist, Charles Bell. Bell wrote that “between the brain and the muscles there is a circle of nerve; one nerve (ventral roots) conveys the influence from the brain to the muscle, another (dorsal roots) gives the sense of the condition of the muscle to the brain”.⁷ In Bell’s view, “muscular sense” refers to a closed-loop system between the brain and the muscles: the afferent pathway from the muscles to the brain and the efferent pathway from the brain to the muscles.

Sixty years later, the English anatomist and pathologist Henry Bastian introduced the term “kinaesthesia”, derived from two Greek words “kinein” (move) and “aisthesis” (sensation): “I refer to the body of sensation which results from or is directly occasioned by movements . . . kinaesthesia. By means of this complex of sensory impression we are made acquainted with the position and movements of our limbs . . . by means of it the brain also derives much unconscious guidance in the performance of movement generally”.⁸

Peer review under responsibility of Shanghai University of Sport.

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Subsequently, in 1906, the English neurophysiologist Sir Charles Sherrington coined “proprioception”, from a combination of the Latin “proprius” (one’s own) and “perception”, to give a term for the sensory information derived from (neural) receptors embedded in joints, muscles and tendons that enable a person to know where parts of the body are located at any time. He referred to proprioception as “the perception of joint and body movement as well as position of the body, or body segments, in space”.⁹

Currently, both “proprioception” and “kinaesthesia (kinaesthesia)” continue to be used as terms in the published literature. However, specialists from fields such as neurology, neurophysiology, neuropsychology, sports and exercise medicine, and orthopaedic surgery have different interpretations of the two terms. Some researchers define proprioception as joint position sense only, and kinaesthesia as the conscious awareness of joint motion;^{10,11} while others consider that kinaesthesia is one of the submodalities of proprioception, and that proprioception as a construct contains both joint position sense and the sensation of joint movement (kinaesthesia).^{12–19} Proprioception defined in this way accords with Bastian’s conceptualization of kinaesthesia (kinaesthesia), each including both position and movement senses. Although joint position and movement have been considered as two separate sensory entities,^{20,21} any movement is accompanied by changes in information regarding both position and movement senses.^{22–25} That is, the senses of joint movement and joint position are always associated with each other in daily activities.²⁶ Consequently, it has been argued that it is appropriate to interpret “proprioception” and “kinaesthesia (kinaesthesia)” as being synonymous.^{26–29}

The original definition of proprioception, given by Charles Sherrington when he first used the term, was that proprioception is “. . . the perception of joint and body movement as well as position of the body, or body segments, in space”, and the “perceptions of the relative flexions and extensions of our limbs”.⁹ Here Sherrington refers to proprioception as “perception” of body position and movement. Perception, from the Latin “perceptio” (perceive), is the identification, organization, and interpretation of sensory information, in order for humans to internally represent and understand the environment.³⁰ All perceptions require signals within the nervous system, which derive from physical stimulation of various sense organs.³¹ For instance, hearing involves sound waves impacting the eardrum, and vision includes light impinging the retina of the eye and the transduction of these different forms of energy into electrical energy within neurons. Likewise, proprioception requires the stimulation of mechanoreceptors to threshold via body movements (changes of body position). However, a characteristic of perception is that it is not simply the passive receipt of a sensory signal, but rather, perception is shaped by memory and learning.³²

In this understanding, proprioception can be defined as an individual’s *ability* to integrate the sensory signals from mechanoreceptors to thereby determine body segment positions and movements in space.^{1,33–37} In other words, proprioception is not merely a physiological property, but rather, it has both physi-

ological (hardware) and psychological (software) aspects.^{37,38} To be specific, proprioception is the perception of body position and movements in three-dimensional space, and overall *proprioceptive performance* is determined by the quality of both the available *proprioceptive information* and an individual’s *proprioceptive ability*. Thus, the hardware (peripheral mechanoreceptors) provides proprioceptive information to the brain for the software (central processing) to integrate and use.³⁹

More specifically, Ashton-Miller et al.⁴⁰ have argued that if proprioception is only the afferent (hardware) part of the system, proprioception cannot be trained because there is no capacity to train a signal. In contrast, a recent systematic review by Witchalls et al.⁴¹ has demonstrated that proprioception as a measure of the neuromuscular response to a stimulus must involve sensory input, central processing, and motor output in a closed loop. In light of this latter view, it is insufficient to consider proprioception just as a cumulative neural input to the central nervous system (CNS) from the mechanoreceptors located in muscles, joints and the skin,^{42–45} and it is inappropriate to interpret either passive movement detection without muscle activation or a measure of reflex muscle activation⁴⁶ as overall proprioceptive ability.

In the past century, (neuro)physiologists have had a strong interest in investigating the roles of peripheral mechanoreceptors in determining proprioception, and have used different techniques, such as vibration or anaesthesia, to differentiate the functional roles of the different mechanoreceptor types.^{47–49} However, to execute functional movements in daily activities, exercise, and sports, proprioceptive information from a variety of mechanoreceptors is available for central processing. Therefore a complex array of different sources is utilized, although muscles spindles are seen as the main transducers used to gather proprioceptive information.^{21,50} Further, an increasing number of researchers, especially those in exercise and sports, now recognize the importance of central processing in proprioception, when attempting to understand human movement.

For instance, evidence has suggested that central processing in proprioception may play a role in sport performance. Although most body movements in daily activities are automated, conscious attention is required to learn complex skills in sports and exercise, such as when using the foot to control a ball, performing a variety of arm movements in ice skating, or executing Tai Chi movements in a coordinated pattern. Learning movement skills means developing new patterns of movement by processing proprioceptive information appropriately. New neural programs are developed, refined by repetition and transferred to the more fundamental regions of the brain, from where they are executed with less effort and relayed much faster.⁵¹ It has been argued that a novice athlete spends time consciously mastering new movements using a closed-loop system of control, whereas skilled athletes only occasionally use sensory checking for successful execution of relevant movements.^{52,53} Han et al.^{53,54} found that ankle proprioception scores were significantly and positively correlated with sport performance level in soccer. They argued that elite soccer

players allocate less central capacity to processing proprioceptive information for movement control, thereby devoting more attention to tasks such as locating team mates and opponents, and determining the best opportunity to pass or shoot.^{53,55} In addition, recent evidence suggests that when attentional demands are increased, this has a detrimental impact on ankle joint proprioceptive performance in young adults.⁵⁶ A recent brain imaging study also found that in addition to peripheral reflex mechanisms, central processing of proprioceptive information from the foot was essential for balance control.⁵⁷

To date, the peripheral and central mechanisms underlying proprioceptive control are still unclear. In exercise and sport, it is unknown if proprioceptive improvement associated with exercise^{58–60} is a result of peripheral adaptation, or neural plasticity, or both;^{33,61} and if superior proprioceptive ability in athletes^{53,54,62–64} is due to intensive training or determined by selection for genetic factors.^{53,54,65} Nevertheless, the importance of proprioception has been well established in sports injury prevention and rehabilitation, sports performance selection and talent identification, and for falls prediction and intervention.^{54,59,66,67}

To examine proprioceptive mechanisms, different techniques have been reported in the literature. There are three main testing techniques for assessing proprioception – threshold to detection of passive motion (TTDPM),⁶⁸ joint position reproduction (JPR), also known as joint position matching,⁶⁹ and active movement extent discrimination assessment (AMEDA).⁷⁰ These tests have been developed from different concepts, are conducted under different testing conditions, and arguably assess different aspects of proprioceptive modalities.^{71,72} In this paper, the three techniques are reviewed systematically to compare the origin of the methods, the different apparatus used for testing, the procedures and the protocols used in each approach.

2. Origin of proprioception assessment techniques

Testing an individual's sensory acuity is the primary aim of psychophysics, and the standard measures used to do so were described as early as 1860 by Fechner.⁷³ Psychophysics refers to quantitative investigation of the relationship between an objective physical stimulus and the subjective perceptions it causes.²⁸ In 1860, Gustav Theodor Fechner published the *Elemente der Psychophysik* in which he reported the first experiments on the psychophysics of active movement.⁷⁴ In his study, Fechner assessed perception of differences in the amount of force required for the upper limb to overcome gravity for lifting weights. Following this classic work, in the 1880s, James McKean Cattell and Hugo Munsterberg were the pioneer researchers who first used comparison of the extent of pairs of movements made to physical stops, without visual cues, as an experimental psychophysical method for studying human movement.⁷⁵ In fact, this work constituted the earliest study of proprioception, because to compare the extent of pairs of active arm movements, without visual cues, one has to use proprioceptive information to determine limb position. Although this psychophysical study was conducted 2 decades before the

English physiologist Charles Sherrington proposed his “proprioception” concept, Munsterberg and Cattell's apparatus and methodology was not recognized as a method for conducting proprioceptive assessment for over 100 years.

There are three classical methods used in psychophysical experiments: *the method of adjustment*, *the method of limits* and *the method of constant stimuli*.⁷⁶ In *the method of adjustment*, also known as *the method of average error*,⁷⁶ the participant is required to control the level of the stimulus, starting with a level that is clearly less or greater than a reference stimulus, and then to adjust the level until they feel that the level of the stimulus is the same as the level of the reference stimulus. The difference between the adjustable stimulus and the reference one is recorded as the participant's error, and the average error is calculated as the measure of sensitivity. The current JPR proprioception test protocol is one form of the method of adjustment, where participants are usually asked to match or reproduce the previously experienced reference joint positions, using their ipsilateral or the contralateral limb.¹

The method of limits can be conducted in either an ascending or descending fashion. In the ascending method of limits, the experimenter begins the stimulus at such a low level that it cannot be detected by the participant. The level of stimulus is then gradually increased until the participant reports that they can just perceive it. In the descending method of limits, the procedure is reversed.⁷⁶ These two methods are usually used alternately in experiments and the thresholds are averaged. A limitation of the ascending and descending methods is that the participant may anticipate that the stimulus is about to become noticeable or unnoticeable and, consequently, make a premature judgement. Conversely, the participants may also become conditioned to report that they detect a stimulus and continue to report the same way. In this sense, the TTDPM proprioception technique is one form of the method of limits, where participants are required to detect joint movement under different velocities.⁶⁹

In contrast, in the *method of constant stimuli* (originally, right and wrong cases), the levels of stimulus intensity are not presented in a sequential order, but rather, in pairings with the standard stimulus, presented randomly. Therefore, the method of constant stimuli prevents the participant from predicting the level of the next stimulus, and thus reduces errors of expectation and habituation. To obtain an “absolute threshold”, the participant is required to report whether they are able to detect the stimulus; whereas to obtain “difference thresholds”, the participant makes a comparison between the constant stimulus and stimuli at each of the different levels presented. Thus, unlike the method of adjustment, with the method of constant stimuli participants compare two movements, both of which have clearly defined start and end positions, to determine which stimulus is greater. The method of constant stimulus has been thought to be the most accurate of Fechner's methods for studying the psychophysics of movement.⁷⁷ From Fullerton and Cattell's work⁷⁷ onwards, the method of constant stimuli has been widely used for assessing an individual's sensitivity to upper^{78–83} and lower^{70,84,85} limb movements. Some of these

studies have employed just noticeable difference (JND) as a measure for discrimination threshold in proprioception.^{70,83-85} However, The JND discrimination measure method is based on a curve-fitting procedure which means that outliers exert a distorting effect,⁸⁶ and that it is better suited to data sets based on several hundred trials. Fullerton and Cattell⁷⁷ suggested that as a measure, “the probable error that is the difference with which an observer is right 75% of the time, is the most convenient measure of discrimination”, and they also noted that the method of constant stimuli “requires a large number of trials, which is not practical for clinical, anthropometric or provisional purposes”.

The number of trials can be reduced when only the variable stimuli are presented and the standard movement is eliminated, as in the method of single stimuli.^{87,88} If the same number of responses and stimuli are used, this becomes the method of absolute judgement.⁸⁹ Using the absolute judgement method, Waddington and Adams³⁸ developed the AMEDA to test participants’ ability to use proprioceptive information to differentiate between ankle inversion angles. In recent years, the AMEDA technique has been developed and validated for testing proprioception at the knee,⁹⁰⁻⁹² hip,^{66,93} lumbar spine,^{94,95} cervical spine,⁹⁶ shoulder,^{97,98} and hand.^{37,99,100} The same technique has been termed “interdental dimension discrimination” when used for assessing proprioception at the jaw in dentistry and oral rehabilitation.^{101,102}

3. Apparatus for proprioception tests

Ankle, knee, and shoulder proprioception have been extensively investigated by sports science and medical researchers. The three different approaches to test proprioceptive acuity at the ankle, knee and shoulder are presented in Fig. 1 for comparison. Each technique uses a different physical setup and explores different aspects of proprioceptive functioning (Table 1).

With respect to ease of applicability of the three testing methods, it is clear from Fig. 1 and Table 1 that the experimental setups differ in complexity, due to the necessity of having motors apply forces to slowly move body segments for some proprioception tests. In addition, the lack of portability of the testing apparatus and the prolonged testing sessions have been highlighted as problematic for particular testing methods, particularly when attempting to obtain large sample numbers.¹⁰³

4. Testing procedures for each of the proprioception testing method

The TTDPM method has been employed at various joints across the body (Fig. 1A–C), with the investigator-controlled machine moving an isolated body segment in a predetermined direction, using different speeds.^{104,105} Velocity-dependent differences have been detected, with individuals typically

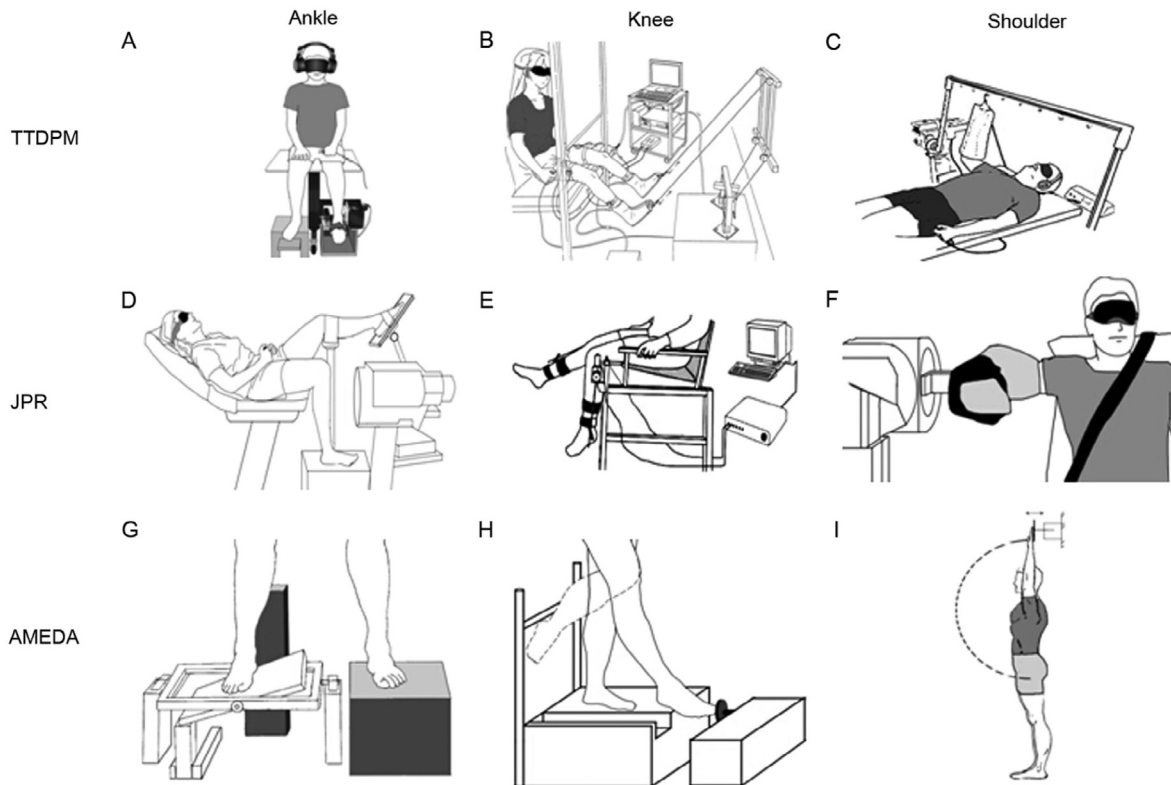


Fig. 1. Comparison of different apparatus employed in threshold to detection of passive motion (TTDPM), joint position reproduction (JPR), and active movement extent discrimination apparatus (AMEDA) proprioception tests, at the ankle, knee, and shoulder. (A) Adapted from Yasuda et al.;⁵⁶ (B) adapted from Beynnon et al.;¹³¹ (C) adapted from Lephart et al.;¹³² (D) adapted from Willems et al.;¹³³ (E) adapted from Larsen et al.;¹³⁴ (F) adapted from Janwantanakul et al.;¹³⁵ (G) adapted from Symes et al.;¹³⁶ (H) adapted from Cameron and Adams;⁹⁰ (I) adapted from Han et al.⁵⁴

Table 1
Comparison of protocols used in TTDPM, JPR, and AMEDA proprioception tests.

Variable	TTDPM	JPR	AMEDA
Movement type	Passive	Passive/active	Active
Movement velocity	Very slow	Slow/normal	Normal
Practice/familiarization trial number	Unfixed	Unfixed	Fixed, 15 trials
Testing trial number	3–5 correct answers	Usually 3–5, up to 10 trials	50
Movement difference between familiarization and testing	No	Depends on the types of movement used in target joint position establishment and reproduction	No
Proprioceptive information	Largely movement information	Depends on whether a physical stop is used during target joint position establishment	Both movement and position information
General vision	Blocked	Blocked	Available
Audio	Blocked	Available	Available
Posture	Usually lying or sitting	Usually lying or sitting	Standing
Constrain	Usually constrained	Usually constrained	No constraints
Weight-bearing	Usually none or partial weight-bearing	None, partial or normal weight-bearing	Normal weight-bearing
Attention requirement	Very high	High	Medium-high
Memory requirement	Very low	High	Low (recall)
Measurement	Difference between the start position and responded position	Error between the target position and performed position	AUC score
Unit	Degree	Degree	AUC score
Testing duration	Up to 6 h	Depends on the number of trials used	10 min

Abbreviations: TTDPM = threshold to detection of passive motion; JPR = joint position reproduction; AMEDA = active movement extent discrimination apparatus; AUC = area under the curve.

demonstrating higher thresholds for detecting the applied force at slower speeds.¹⁰⁴ A number of researchers have selected very slow speeds in their experiments, such as 0.25°/s, for example, generated by the Biodex System.¹⁰⁶ During a TTDPM test, participants are seated or lying down. The body site being tested is isolated by strapping the adjacent body segments, such as the upper body. Other peripheral information, such as tactile, visual, and aural information, is usually occluded by using air cushions, blindfolds, and headphones. With all these variables controlled, the body segment under investigation is passively moved in a predetermined direction. Participants are instructed to press a stop-button as soon as they perceive the movement and direction. They then report the perceived direction of movement of their limb. If the reported direction is wrong, the trial is discarded, and testing proceeds until three to five correct judgements are achieved.¹⁰⁶ Gibson¹⁰⁷ classifies the proprioception arising when an external device passively moves a body part, as occurs in TTDPM, as “imposed proprioception”, which he contrasts with the “obtained proprioception” that arises from active, voluntary movements.

In contrast to the TTDPM method where passive movement is used, the JPR testing method is conducted under either passive or active conditions for criterion and reproduction movements, and may involve either ipsilateral or contralateral limb movements¹ (Fig. 1D–F). There are three types of JPR tasks described in the assessment of proprioception: ipsilateral JPR (IJPR); and two contralateral JPR (CJPR) approaches. For IJPR testing, a predetermined target joint position is passively or actively presented to the participant for a few seconds. Thereafter, the joint is returned to the initial start position, either passively by the experimenter or actively by the participant. Participants are then required to reproduce the target joint position previously experienced by either indicat-

ing the target position by pressing a stop-button when the joint is passively moved into the same range, or by actively moving the joint to the target position. That is, participants need to remember the target position and reproduce the position using the *same* limb. Of the two CJPR tests, one procedure is identical to the method for IJPR testing in terms of experiencing the target joint position, but differs in that the participant is asked to reproduce the joint position by using the *contralateral* limb. That is, participants need to remember the target joint position and use the opposite limb to reproduce the position. The second CJPR test differs in that once one joint is moved to the target position, it remains in that position and the contralateral limb is required to reproduce the target joint position. That is, the test does not require a memory of the target position, but rather, participants can use this “online” information in the position task to help them to replicate the position on the contralateral side.

AMEDA tests (Fig. 1G–I) are conducted using active movements.⁷⁰ Each participant is given a familiarization session using an AMEDA apparatus before data collection commences, during which they are informed that they will experience, for example, five movement displacement distances, in order, from the smallest (moving to position 1) to the largest (moving to position 5), three times: 15 movements in total. Participants thereafter (typically) undertake 50 trials of testing, in which all five positions are presented 10 times, in a random order. On each trial in the AMEDA test protocol, only one movement out to the stop at a steady pace is allowed, followed by return to the start position. After experiencing a position and returning to the start position, participants are asked to make a judgement as to the position number (1, 2, 3, 4, or 5) of each test movement, without feedback being given as to the correctness to the judgement they make for each trial. That is, participants must use

their memory of the five movement extents from the familiarization trials to enable them to identify each stimulus and thus make a numerical judgement (1, 2, 3, 4, or 5) identifying each perceived stimulus after it is presented. This task is thus a single stimulus or absolute judgement task, wherein a single stimulus is presented and single response is made on each trial. The time required to undertake one joint proprioception test is approximately 10 min.

5. Testing protocols for each of the proprioceptive methods

Details of the protocols for each of the proprioceptive methods are listed and compared in Table 1. The different attributes of the three protocols are listed. The *ecological validity*, *testing validity*, and *data validity* of each technique varies between the different methods.

Both the TTDPDM and JPR techniques seek to minimize extraneous variables and reduce factors thought to be confounders, in order to explore proprioceptive sense in isolation. In contrast, the AMEDA approach seeks to examine how proprioception functions under natural conditions using test conditions that are more analogous to normal function. Some researchers have argued that both the TTDPDM and JPR tests of proprioception lack ecological validity^{108,109} because the testing conditions are so different from normal function that they can contribute little to understanding the role proprioception plays in daily and sporting activities. In addition, performances obtained at different TTDPDM test speeds may not be correlated.⁷¹

A number of the variables listed in Table 1 are employed to minimize other inputs and thus ensure test purity, but they may also diminish ecological validity. Examples of this are protocols that use very slow movement velocities, passive movements, non-weight bearing conditions and isolation of the joint under investigation. That is to say, few everyday movement patterns involve passively imposed movements, delivered at very slow velocities.¹¹⁰ In contrast, most daily activities require active movements at normal, functional speeds.⁴⁰ Although the isolation of inputs with a proprioceptive testing protocol may be achieved when participants are strapped in a machine (usually lying or sitting and non-weight-bearing) with vision and audition blocked out, the cost of this is that the testing does not reflect normal performance of the proprioceptive system in the real world, where individuals move freely in normal weight-bearing condition, with both visual and auditory information available. In contrast, ecological validity is enhanced by having these latter conditions available.¹¹¹

Rather than focussing on a single joint to detect whether the relevant segment has been moved, the role of proprioceptive ability in real world activities is to enable the performer to accurately judge limb movements when interacting with the environment, such as making an immediate, and likely implicit, judgement as to the degree of ankle inversion when stepping on an uneven surface in order to keep one's balance. Because most upper and lower limb functional movements are terminated with physical stops, such as the sides of a drinking glass or the slope of the ground, testing methods that encom-

pass movement extent and limb endpoint position information can be argued to be more realistic and ecologically valid.⁷⁹ Testing methods that allow not only different submodalities of the proprioceptive senses, but which do not entirely eliminate other sense information such as that of texture, vision and hearing, are more likely to characterize normal function. Therefore, if ecological validity is a research goal, the AMEDA testing method is more suitable than either the TTDPDM or the JPR protocols.

The validity of the testing protocol is another important consideration when determining which procedure to use for testing proprioception. It has been argued that JPR tests for proprioception have low testing validity, because the proprioceptive information available during target position generation and the proprioceptive information available during target position reproduction are not the same.^{108,109} The first difference between target position establishment and reproduction is the type of movement undertaken. It has been suggested that in passive movement, since muscles are not active, fusimotor activity and the sensory feedback from muscle spindles are diminished. Thus, input from cutaneous receptors appears to play a greater role in sensory feedback. In contrast, in active movement control, fusimotor drive and muscle spindle feedback are both involved, although input from muscle spindles is considered to play a more dominant role.^{112,113} As a result, when a target joint position is passively generated for active matching, or *vice versa*, the brain may rely on different information from different receptors in the two phases, and the results may even reflect hemispheric specialization in the use of particular proprioceptive information at that joint.³⁶ Another difference between the first or criterion movement and the second reproduction movement in JPR tests is that there is usually a physical stop at the end of the criterion movement for defining the target position, while the physical stop is removed during position reproduction. That is, during target position generation, information about movement extent and end position are both available, whereas only movement extent information is available in position reproduction. Although a movement extent/displacement matching strategy has been thought to be less effective than target position matching,³³ information about both limb movement extent and end position are needed for the most accurate judgement of limb movements.⁷⁹ Finally, because JPR tests are highly dependent on memory, particularly CJPR tests where participants need to remember a previously experienced joint position of one limb and use the contralateral limb to reproduce the target position, JPR tests are less appropriate when participants have cognitive or memory deficits.¹

The validity of data generated from the different protocols is another issue when determining which form of testing to employ. Issues may arise from both data acquisition and data analysis processes adopted. During data acquisition, proprioceptive tests usually involve a practice or familiarization session. However, the number of practice/familiarization trials varies between testing protocols. For example, some studies report using three practice trials before data collection,¹⁰⁶ while others collect the test data only when participants are satisfied

with the amount of practice.¹¹⁴ Different numbers of practice/familiarization trials may lead to learning or fatigue effects and consequently affect data accuracy. In addition, TTDPM tests record only “correct” answers and discard the trials if participants make wrong judgements.¹⁰⁶ Thus, it is possible that relatively low threshold data may be obtained from a higher proportion of wrong decisions and relatively high threshold data arise from a lower wrong judgement ratio. That is, a better result may be the outcome of chance responding. However, few studies have reported the percentage of the incorrect trials in their results; therefore it is unknown whether there is a relationship between correctness of responses and accuracy of results. Similarly, in most JPR tests, attention is seldom paid to the number of movements that participants use in position reproduction, and information is rarely given as to exactly how participants adjust the limb to reproduce the previously experienced target position.¹ Further, the number of sampling movements has been shown to have an impact on judgement accuracy,¹¹⁵ suggesting that failure to control number of movements in JPR tests could confound the results. Moreover, most TTDPM and JPR assessment protocols usually use only 3–5 trials during the test.^{106,113,116,117} This number may be insufficient to accurately determine participant ability parameters in proprioceptive tests, as noted by Ashton-Miller.¹⁰⁹ A recent study estimated that 20% of post-stroke patients with proprioceptive deficits would be unidentified if only three trials were used rather than 10 trials; however when 10 trials were used, not all patients with proprioceptive deficits were identified, suggesting that even 10 trials to obtain a proprioceptive sensitivity measure is insufficient to set as the “gold standard” for a JPR protocol.¹¹⁸ Of the three proprioceptive techniques, only AMEDA testing requires more than 10 trials.

In terms of data analysis, the usefulness of the accuracy metric derived in both TTDPM and JPR procedures has also been questioned.^{27,119} The mean value of the differences between the start and perceived positions in TTDPM tests, or between the target and reproduced positions in the JPR tests, has been interpreted as an assessment of accuracy, and the error variance an assessment of consistency. However, the mean value of the difference alone is unlikely to adequately convey proprioceptive information, because data can present as either a small mean difference with a large error variance or as a large mean difference with a small error variance. That is, participants can be very accurate, on average with a large trial variation, or have a high level of inaccuracy with excellent performance consistency. When processing proprioceptive information, the brain has to deal with noise in the CNS arising from spontaneous or background neural activity¹²⁰ that results in uncertainty in making a decision about a joint’s position in space. The AMEDA proprioception measurement was developed based on the signal detection theory^{121,122} to provide a means of analysing response data collected in the presence of uncertainty, such that sensitivity to a stimulus can be evaluated regardless of response bias.¹²³ Using the receiver operating characteristic (ROC) analysis, participants’ ability to use a continuous response scale to discriminate between the two states of a binary variable can be measured, representing how certain

participants are when they make judgements on joint movements against noise. The area under the ROC curve (AUC) represents the participant’s ability to discriminate between two joint movements, which can be calculated by geometric means.¹²⁴ If the participant is unable to discriminate between the two movements, the ROC curve would cut off half of the area and giving an AUC value of 0.5, equivalent to chance responding. In contrast, if the participant is able to perfectly discriminate two movements, the corresponding AUC would include all area below the ROC curve, and give a perfect AUC value of 1.0.^{121,122,124}

In summary, signal detection theory offers a means to take a participant’s uncertainty into account and produce an unbiased estimate of a participant’s proprioceptive performance. This method requires many more trials to more closely reflect the actual distribution of proprioceptive signal presentation in the brain than are currently used in TTDPM and JPS methodologies. While it is intuitively easier to understand more direct measures than the theoretical underpinnings of signal detection analysis, it does not necessarily mean that the former are more accurate. On the contrary, it is likely that signal detection theory methods capture and reflect more accurately the neural mechanisms underlying proprioceptive performance, which include proprioceptive signal collecting and processing against noise in the CNS, and decision making as to a joint’s position in space, than do the other methods.

6. Scope of review

The current review has considered kinematic aspects of proprioception. The senses of effort, force, and heaviness are also considered by some researchers to be components of proprioception.^{50,125} However, the relationships between movement-related and force-related aspects of proprioception are still unclear. Early studies suggested that the extent to which somatosensory information is used for effort perception is associated with the amplitude of movements.¹²⁶ Contrary to this notion, Han et al.¹⁰⁰ recently found finger pinch movement discrimination accuracy was not affected by the presence of elastic resistance, indicating that movement-related and force-related aspects of proprioception are separate entities and may have different neural mechanisms. In line with this argument, a recent study found that sense of effort was processed centrally, with little or even no contribution from peripheral sensory information,¹²⁷ contrary to the current understanding of movement-related proprioception, which requires both peripheral and central processing mechanisms.

7. Conclusion

Proprioception plays a crucial role in human movement control, which is fundamental for daily activities, exercise, and sports. The importance of central processing in understanding proprioception has been recognized in recent years. However, the peripheral and central mechanisms underlying proprioceptive control are still unclear. To explore proprioceptive mechanisms, three techniques have been widely used in the literature, but their applicability, ecological validity, test validity, and data

validity differ. The TTDPM method has less relative ecological validity, but has high conceptual purity,⁷² given the prior relaxation of the stimulated musculature, and the control of other information sources. This method has been widely used in neurophysiology studies,^{105,128,129} when differentiating between the contribution of different mechanoreceptors to proprioception.¹¹² Although JPR tests may have less relative test validity, the method is efficient and enables exploration of hemispheric asymmetries in sensorimotor abilities.¹ The AMEDA method appears to have better ecological validity and relatively better test validity and data validity. However, as a proprioceptive sensitivity measure, the AUC score is not as intuitively accessible as the average error measure given by JPR methods, or the threshold in degrees given by TTDPM methods. Nevertheless, it can be argued that the AMEDA test method is an effective method for assessing the performance of proprioceptive system during active, functional body movements that occur in most daily activities, exercise, and sports.

In addition to the current theoretical comparisons between the three methods, any data obtained from a proprioception testing method should have relevance and predictive validity in sport performance or clinical contexts. To date, only a few studies have investigated associations between proprioception and sport performance,⁵⁴ and proprioception and injury,^{41,66,130} and no empirical comparison between the three methods with regards to their predictive validity has been undertaken.

Acknowledgments

The authors would like to thank the University of Canberra, Key Laboratory of Exercise and Health Sciences of Ministry of Education, Shanghai University of Sport and Shanghai Municipal Science and Technology Commission (No. 13490503800) for funding the research. This paper was also supported by Shanghai Pujiang Program (No. 15PJ1407600). The funding source had no involvement in study design; in the collection, analysis and interpretation of data; in the writing of the report; and in the decision to submit the article for publication. None of the authors have any relevant conflicts of interest.

Authors' contributions

All authors conceived of the study. JH reviewed the literature and drafted the manuscript. GW participated in the study design and helped to draft the manuscript. RA participated in the study design and helped to draft the manuscript. JA participated in the study design and helped to draft the manuscript. YL made edits and comments to the manuscript. All authors have read and approved the final version of the manuscript, and agree with the order and presentation of the authors.

Competing interests

None of the authors declare competing financial or other sorts of interests.

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