Masterclass

Proprioception in musculoskeletal rehabilitation. Part 2: Clinical assessment and intervention

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A B S T R A C T

Introduction: Proprioception can be impaired in gradual-onset musculoskeletal pain disorders and following trauma. Understanding of the role of proprioception in sensorimotor dysfunction and methods for assessment and interventions is of vital importance in musculoskeletal rehabilitation. In Part 1 of this two-part Masterclass we presented a theory-based overview of the role of proprioception in sensorimotor control, causes and findings of altered proprioception in musculoskeletal conditions, and general principles of assessment and interventions.

Purpose: The aim of this second part is to present specific methods for clinical assessment and interventions to improve proprioception in the spine and extremities.

Implications: Clinical assessment of proprioception can be performed using goniometers, inclinometers, laser-pointers, and pressure sensors. Manual therapy, taping, and bracing can immediately enhance proprioception and should be used to prepare for exercise interventions. Various types of exercise (active joint repositioning, force sense, co-ordination, muscle performance, balance/unstable surface, plyometric, and vibration training) should be employed for long-term enhancement of proprioception.

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1. Introduction

Proprioception is essential for well-adapted sensorimotor control. Proprioception fulfills roles in feedback and feedforward sensorimotor control and regulation of muscle stiffness, being specifically important for movement acuity, joint stability, co-ordination, and balance. Cervical proprioception is uniquely important for head-eye co-ordination and movement control. Proprioception can be disturbed in musculoskeletal disorders due to pain, effusion, trauma, and fatigue. A variety of assessment procedures and interventions have been developed to specifically test and enhance proprioception, respectively. We present an overview of clinical assessment and intervention methods for proprioception of the spine and extremities. Reference is made to research where interventions have been reported to demonstrate positive effects on proprioception. A special focus is made on exercise therapy.

2. Clinical assessment of proprioception

Clinical assessment of proprioception should employ tests for measuring joint position sense (JPS), kinesthesia, or force sense (Roijezon et al., 2015). In the laboratory, custom-built devices or expensive computer-interfaced equipment are frequently employed (Lephart et al., 1994; Borsa et al., 1997; Docherty et al., 1998; Waddington et al., 2000; Callaghan et al., 2002; Docherty and Arnold, 2008; Benjaminse et al., 2009; Learman et al., 2009), but are typically impracticable in the clinical setting. Researchers and clinicians have attempted to develop clinical tests for the spine and extremities, although some tests are more developed for some body parts (e.g. cervical spine) than others. Further development and refinement of clinical tests is needed.

2.1. Clinical apparatus

Goniometers, inclinometers, pressure sensors, and laser-pointers are affordable and easy-to-use in a clinical context. There is also scope for new affordable and accurate technology that includes smartphones with built-in accelerometers and gyros,
2.2. Specific tests

2.2.1. Joint position sense

For the cervical spine, active JPS testing can use a laser-pointer attached to a headband to determine patients’ ability to relocate to the neutral starting position with the eyes closed after performing an active head movement (e.g. right rotation) (Fig. 1). The difference between the starting and end position can be measured in millimetres, and the joint position error then calculated in degrees (Roren et al., 2009; Chen and Treleaven, 2013). This method is reliable and valid when compared to sophisticated laboratory equipment (Swait et al., 2007; Roren et al., 2009; Chen and Treleaven, 2013). Errors greater than 4.5° are considered to indicate abnormal cervical active JPS. Others have used the cervical range of motion (CROM) device to measure cervical active JPS and found this to also be a reliable and valid method (Wibault et al., 2013; Treleaven et al., 2015).

For the extremity joints, goniometers (universal, bubble, digital) can also be used to measure active JPS. The sequence of events is the same as that described for laboratory measurement of active JPS (see Masterclass Part 1) (Roijezon et al., 2015). Depending on the device used and the extremity joint measured, reliability and measurement error of active movement goniometry can range widely (Gabbe et al., 2004; Lephart et al., 2007; Dickson et al., 2012; Kolber and Hanney, 2012; Hamid et al., 2013), and this should be carefully considered if goniometry is used to measure active JPS of extremity joints. For the shoulder joint, laser-pointer active JPS tests have also been developed and show promise in those with and without shoulder injury (Balke et al., 2011). There is potential for using the laser-pointer to measure JPS in other joints but, to date, there is limited research.

2.2.2. Kinesthesia

For the cervical spine, kinesthesia can be assessed by following a trace or intricate pattern as accurately as possible. This can be a visual trace (e.g. figure-of-eight, zig-zag pattern) (Woodhouse et al., 2010) or by following a computer generated marker that is moving in a more unpredictable pattern (e.g. “the fly”) (Kristjansson et al., 2004). Outcome variables usually used here are the mean displacement or time on target. Advances in smart phone sensors have made “the fly” technology more readily accessible to clinicians (Kristjansson, 2014), although recent work has also been conducted to investigate the feasibility of a low cost quantitative method using video analysis of the patient tracing a pattern with a head-mounted laser (Pereira et al., 2015).

2.2.3. Force sense

Force sense can be measured by the accuracy of reproducing a specific target force. For example, the pressure biofeedback device used for assessing the cranio-cervical flexion test could be considered a method of assessing force sense in the cervical spine (Jull, 2000). The ability to hold steadily or the accuracy in achieving and maintaining a desired pressure can be used. Others have also used custom-made dynamometry placed at the mandible to measure precision and accuracy of maintaining low load upper cervical flexor force levels (O’Leary et al., 2005).

2.3. Non-specific tests

2.3.1. Balance tests

Balance tests, such as timed single-leg stance tests, have historically been used to measure lower extremity (e.g. ankle) proprioception. As discussed previously (see Masterclass Part 1) (Roijezon et al., 2015), these tests are not specific tests of proprioception since balance is a product of integrating sensory, central nervous system (CNS), and motor functions (Macpherson and Horak, 2013). Nevertheless, balance tests could potentially give an indication of improvement following proprioceptive training. Balance tests can be modified to try to bias proprioception by, for example, closing the eyes, adding neck torsion, or using unstable surfaces (Roijezon et al., 2015).

2.3.2. Oculomotor and eye-head coordination tests

Oculomotor and eye-head co-ordination assessment in people with neck pain is important as cervical spine afferents have a unique and important role in maintaining eye and head movement control (Corneil et al., 2002; Peterson, 2004). At present, clinical tests incorporate qualitative assessment of the ability to: 1) maintain gaze while moving the head; 2) co-ordinate eye and head movement; 3) eye follow while keeping the head still in neck torsion compared to neck neutral positions (Fig. 2). Recent research has found these clinical tests to be reliable and able to discriminate between chronic neck pain and asymptomatic individuals (Della Casa et al., 2014), and are described in detail elsewhere (Treleaven, 2008; Grip et al., 2009; Treleaven et al., 2011).

3. Clinical interventions to improve proprioception

In Part 1 of this Masterclass (Roijezon et al., 2015), the importance of addressing causes of altered proprioception and rehabilitation techniques intended to enhance proprioception were introduced. Pain, effusion, and fatigue can be common after musculoskeletal injury, result in impaired proprioception (Treleaven et al., 2003; Anderson and Wee, 2011; Cho et al., 2011), and, consequently, are barriers against effective interventions for enhancing proprioception and sensorimotor control. Therefore, it is important to administer techniques to reduce pain, effusion, and fatigue in order to facilitate the implementation of effective interventions to enhance proprioception. Augmentation of somatosensory information via passive techniques such as manual therapy, soft tissue techniques, and taping or bracing can be
important. Exercise therapy is a vital component in enhancing proprioception and will be considered in detail. In order to deduce that a clinical intervention yields a proprioceptive effect, one of the specific modalities of proprioception (JPS, kinesthesia, force sense) must be measured before and after the intervention. The following sections will, therefore, refer only to research where this has occurred.

3.1. Manual therapy

Joint mobilisation/manipulation can create a controlled stretch to capsuloligamentous tissue (Kaltenborn, 1999; Greenman, 2003), which is populated with multiple types of mechanoreceptors (Kennedy et al., 1982; McLain and Raiszadeh, 1995; Michelson and Hutchins, 1995; Steinbeck et al., 2003; Moraes et al., 2011), thereby affecting proprioceptive feedback to the CNS. Authors have reported that joint passive movement techniques can have an immediate and significantly beneficial effect on spinal and extremity proprioception (Jerosch et al., 1995; Jerosch and Prymka, 1996; Simoneau et al., 1997; McNair and Heine, 1999; Newcomer et al., 2001; Callaghan et al., 2002; Chu et al., 2002; Chang et al., 2010).

3.2. Taping and bracing

Taping and bracing techniques are adjunct interventions used to obtain specific clinical effects including, for example, pain relief, swelling control, and protect injured anatomical structures (Macdonald, 2004). Another clinical goal of applying athletic tape (Fig. 3) and different types of brace is to enhance proprioception (Macdonald, 2004) via stimulation of mechanoreceptors responding to skin stretch and compression during joint motion (Martin and Jessell, 1991; Rothwell, 1994). Authors have reported that the application of selected athletic taping techniques, elastic bandages, and neoprene sleeves can immediately and significantly enhance spinal and extremity proprioception in uninjured and injured individuals (Lephart et al., 1992; Jerosch et al., 1995; Jerosch and Prymka, 1996; Simoneau et al., 1997; McNair and Heine, 1999; Newcomer et al., 2001; Callaghan et al., 2002; Chu et al., 2002; Chang et al., 2010).

Some researchers have reported that specific soft tissue techniques can significantly and positively affect extremity joint proprioception defined by measures of active JPS (Henriksen et al., 2004).

Fig. 2. Eye Follow in Neck Torsion. The patient keeps the head still while following with the eyes as accurately as possible a moving target (e.g. or a pen) with the eyes. The target is moved slowly side to side (20° per second through a visual angle of 40°). The test is repeated with the neck in torsion (head still but with the trunk rotated up to 45°) then repeated on the opposite side. Any difference noted in smooth eye follow (quick catch up eye movements) in these positions compared to the neutral position is noted.

Fig. 3. Proprioception Knee Taping Technique (Modified from Callaghan et al., 2002). Copyright Nicholas Clark. Reproduced with permission.
3.3. Exercise therapy

Any active exercise can be considered ‘proprioceptive training’ because it will generate a barrage ofafferent impulses to the CNS from joint and muscle-tendon mechanoreceptors (Clark and Herrington, 2010; Clark and Lephart, 2015). Thus, active exercises would seem a vital component in augmenting proprioceptive (Perez et al., 2004; Lagerquist et al., 2012; Clark and Lephart, 2015). There is, however, much overlap across the potential purposes, goals, and clinical uses for any single exercise. Terminology used in exercise therapy (e.g. ‘proprioceptive training’, ‘strength training’) can mean different things to different clinicians and researchers. A single exercise can result in multiple different physiological and physical adaptations in several body systems. In general, exercise therapy refers to the performance of repeated movements as part of a goal-directed training programme to improve a physiological or physical characteristic (Clark and Lephart, 2015). For the purpose of this paper we offer simplistic definitions according to the primary characteristics of the exercise task, introduce basic concepts, offer selected clinical examples, and present research reports on the effect of an exercise type on proprioception.

3.3.1. Active joint repositioning training

Observation of injury mechanisms suggests that there are specific points in a joint’s range-of-motion at which a joint is at risk of injury. For example, non-contact injuries occur between 9 and 22° plantarflexion in the ankle (Mok et al., 2011), 10 and 60° flexion in the knee (Koga et al., 2010), and at extremes of external rotation in the shoulder (Wassinger and Myers, 2011). This suggests there may be a ‘position of vulnerability’ in a joint’s range-of-motion that may be related to proprioceptive deficits (Myers and Lephart, 2000). Active joint repositioning training involves a similar procedure to that used in JPS testing: a starting position/angle and target position/angle are selected, and training involves moving from one position to another as closely as possible, holding each for a short duration (e.g. 5 s) (Myers and Lephart, 2000; Suprak et al., 2007). A difference between JPS testing and training is that visual feedback can be permitted for how accurately the task is performed. For the cervical spine, training can be performed by actively moving the head to a pre-determined target angle, or returning the head as closely as possible to the initial position after movement, checking accuracy by opening the eyes (Revel et al., 1994). For the extremities, both open (Fig. 4) and closed kinetic chain exercises can be employed with emphasis on repositioning training occurring within the specific range-of-motion associated with a specific injury type (Borsa et al., 1994; Lephart and Henry, 1996). Head repositioning training with eyes open and eyes closed has been demonstrated to improve cervical JPS patients with chronic neck pain (Revel et al., 1994; Jull et al., 2007). For peripheral joints, including the shoulder and knee, the addition of a ‘low’ external load to a limb segment (5–10% bodyweight) significantly improved the accuracy of joint repositioning tasks in uninjured individuals (Lamell-Sharp et al., 2002; Brindle et al., 2006; Suprak et al., 2007).

3.3.2. Force sense training

Perception of force and effort can be trained by activating a muscle or muscle group to a predetermined amount of force, or maintaining the same amount of force for a defined period-of-time (e.g. 10 s) (Jull et al., 2007). Cranio-cervical flexor training using the pressure biofeedback unit (Fig. 5) has demonstrated improved precision for maintaining a low level upper cervical flexion force in people with neck pain (O’Leary et al., 2007), and improved force pressure levels achieved in people with cervicogenic headache (Jull et al., 2002).

3.3.3. Co-ordination training

Co-ordination is the process of controlling the activation of many different muscles so that they act together simultaneously as a single functional unit (Gordon, 1991), and the process of integrating different body parts in specific movement patterns (Kent, 2006). Co-ordination training has a different connotation compared to movements in other types of exercise therapy. We consider co-ordination training to have primary emphasis on cueing an individual to specifically concentrate on very fine aspects of sequencing and linking multiple muscles and/or body-parts. Co-ordination training, thus, requires precise verbal cueing for the clinician and a high cognitive demand for the patient. Examples of co-ordination training are preferential activation of one muscle

Fig. 4. Shoulder Joint Active Repositioning Training. A target angle that lies at a specific point within the range-of-motion associated with shoulder injury is chosen (e.g. 80° external rotation). A low external load is added to the limb (e.g. 1 kg dumb-bell) to enhance proprioception via increased mechanoreceptor stimulation. The individual is instructed to start at 0° external rotation, and then eccentrically externally rotate as closely as possible to the target angle, isometrically hold for up to five seconds, concentrate on feeling the position, and then concentrically return to the start position. This can be performed with eyes open or eyes closed. Copyright Nicholas Clark. Reproduced with permission.
versus another muscle within a synergistic muscle group (Jull et al., 2007), specific eye-head-neck co-ordination during neck movements (Revel et al., 1994; Humphreys and Irgens, 2002), and foot-shank-thigh co-ordination on an elliptical training device (Lee et al., 2014). Different types of co-ordination training have enhanced proprioception of the spine and extremities. Cranio-cervical flexor training focusing on use of the deep upper cervical flexors versus the superficial cervical flexors can significantly enhance cervical active JPS in people with neck pain (Jull et al., 2007). Eye head neck co-ordination exercises demonstrates improved JPS in people with neck pain (Humphreys and Irgens, 2002). Fine foot orientation training during external perturbations on an elliptical training device has been shown to significantly improve passive foot kinesthesia during full weight-bearing movements in uninjured adults (Lee et al., 2014). Whole body co-ordination exercises including yoga and tai chi have also demonstrated improvements in proprioception (Tsang and Hui-Chan, 2003; Cramer et al., 2013).

3.3.4. Muscle performance training

The terms ‘muscle performance’ and ‘muscle strength’ both broadly refer to the ability of a muscle to produce force, regardless of the action (isometric vs. anisometric), load (body segment vs. free-weight), or intensity (‘low load’ vs. ‘high load’) (Mayhew and Rothstein, 1985; Sapega, 1990; Clark, 2001). Muscles must first possess inherently sufficient muscle strength before they can effectively control the mass, orientation, and alignment of body segments (Borsa et al., 1994; Hodges and Moseley, 2003; Macpherson and Horak, 2013). Muscle performance training usually involves the repeated activation of skeletal muscle around a primary axis-of-rotation and in a single plane-of-motion, typically against some ‘resistance’ (body segment or an added external load), with the primary intent of modifying muscle force generating characteristics. Examples are side-lying loaded shoulder external rotation, double-leg bodyweight squats, and side-lying loaded ankle eversion (Fig. 6). Muscle performance training has been reported to beneficially modify proprioception. In the spine, controlled head lift exercise in people with neck pain demonstrated improved force sense (O’Leary et al., 2007). Scapular and gleno-humeral anisometric bodyweight and dumb-bell strength training has been reported to significantly improve gleno-humeral active JPS in uninjured military cadets (Rogol et al., 1998). General ankle anisometric elastic resistance strength training was reported to significantly enhance ankle inversion and plantarflexion active JPS in athletes with functional ankle instability (Dockerty et al., 1998), and ankle invertor and evertor isokinetic strength training has also been reported to significantly improve ankle inversion passive JPS in recreational athletes with functional ankle instability (Sekir et al., 2007).

3.3.5. Balance/unstable surface training

Balance is the process of maintaining the body’s center of mass within its base of support via appropriate internal moments resisting destabilizing external moments acting on the body (Macpherson and Horak, 2013). Balance is the result of feedback and feed-forwards corrective movements at multiple joints to maintain the position and orientation of one body segment relative to another over the base-of-support (Macpherson and Horak, 2013). Balance training typically involves performing exercises on an unstable surface (e.g. rocker-board, inflatable devices) (Clark and Herrington, 2010). Examples of balance training exercises are standing balance tasks on soft surfaces or wobble-boards (Beinert and Taube, 2013), performing cervical movements whilst challenging balance (Gatti et al., 2011), press-ups on a Swiss-ball (Myers and Lephart, 2000), and single-leg squats on a rocker-board (Fig. 7) (Clark and Herrington, 2010). Single-leg stance, tandem stance, and double-leg stance on a wobble-board has enhanced cervical spine active JPS in a group of people with sub-clinical neck pain (Beinert and Taube, 2013). Lower extremity wobble-board training has enhanced ankle active kinesthesia (active movement during the incremental stages of CCFT (22–30 mmHg) from the PBU. Patients close their eyes during the task and then open them to check they have reached the appropriate level.
discrimination) in uninjured, elite rugby league players (Waddington et al., 1999), Australian Rules Football players (Waddington et al., 2000), and independent older people (Waddington and Adams, 2004). Swiss-ball training was shown to significantly improve knee passive JPS in uninjured students (Cug et al., 2012). Upper extremity wobble-board training has been reported to significantly improve shoulder active kinesthesia following shoulder dislocation (Naughton et al., 2005). A lower extremity exercise programme including a rocker-board, wobble-board, mini trampoline, tilted platform, and uneven walkway has also been reported to significantly improve ankle passive JPS in adults with functional ankle instability (Eils and Rosenbaum, 2001).

3.3.6. Plyometric training

Many functional tasks demonstrate an eccentric-isometric-concentric sequence of muscle actions termed the stretch-shortening cycle (SSC) (Chu, 1998). For example, from foot-strike to mid-stance of gait, lower extremity extensors use eccentric muscle actions to decelerate the body, followed by very brief isometric muscle actions, before transitioning to concentric muscle actions to accelerate the body from mid-stance to push-off (Komi, 1992; Chu, 1998). Plyometric training uses the SSC as a key feature during the execution of exercise drills. Plyometric training must be executed rapidly with meticulous technique with emphasis on the transition between eccentric and concentric muscle actions being as fast and short duration as possible (Chu, 1998). Examples of plyometric training exercises are kneeling 90-90 shoulder internal-external rotations against elastic resistance (Swanik et al., 2002) (Fig. 8), double-leg barrier jumps (Chu, 1998) (Fig. 9), and single-leg in-place (vertical) hops (Clark and Herrington, 2010). Plyometric training can beneficially modify proprioception of the extremities. Kneeling 90-90 shoulder internal-external rotations against elastic resistance and ball throwing drills against a mini-trampoline have been reported to significantly improve glenohumeral active JPS and passive kinesthesia in uninjured elite swimmers (Swanik et al., 2002). Jump-landing and jump-landing with change-of-direction training has been reported to significantly improve knee active kinesthesia in uninjured Australian Rules Football players (Waddington et al., 2000).
3.3.7. Vibration training

Vibration is a mechanical event that demonstrates rapid oscillatory movements and is a powerful stimulus for the muscle spindle (Goodwin et al., 1972; Roll and Vedel, 1982). Vibration training involves exercising with a device that produces a vibration stimulus (e.g. vibration platform), where the combination of muscle activation with the rapid small amplitude change in direction of joint motion becomes a powerful stimulus for the muscle spindle (Cardinale and Bosco, 2003). The intensity of the vibration is determined by the amplitude and frequency of the oscillations (Cardinale and Bosco, 2003), and devices vibrating from 5 to 50 Hz are typically used in training (Fontana et al., 2005; Moezy et al., 2008; Tripp et al., 2009). Examples of vibration training include modified push-ups (Hand et al., 2009) (Fig. 10), bodyweight double-leg squats and bodyweight lunges onto a vibration platform (Moezy et al., 2008). Vibration training can alter proprioception of the spine and extremities. Isometric neck extension using a sling system with superimposed vibration stimuli significantly enhanced force sense (steadiness) of the cervical spine in chronic neck pain (Muceli et al., 2011). Postural exercise involving lumbar hyperlordosis isometric holds while standing on a vibration platform significantly improved single-session lumbar spine active JPS (Fontana et al., 2005), and isometric elbow flexion holding a vibrating dumb-bell has been reported to significantly enhance elbow active JPS within in a single training session (Tripp et al., 2009). Isometric and anisometric double-leg and single-leg balance, squat, and lunge exercises on a vibrating platform has also shown improvement in knee active JPS after anterior cruciate ligament reconstruction (Moezy et al., 2008).

4. Summary

Clinical assessment of proprioception can be performed using goniometers, inclinometers, laser-pointers, and pressure sensors. These devices can be employed in a clinical context within tests of active JPS and kinesthesia, and force sense. Balance tests can also be employed in a clinical context for measuring integrated sensorimotor control of balance, but it should be remembered that these are not able to isolate proprioception alone. In the cervical spine, head and eye movement control should also be assessed as one of the important roles of proprioception. Following musculoskeletal injury, pain, effusion, and fatigue can result in impaired proprioception, and so these causes of impaired proprioception should be treated alongside the implementation of other interventions.

Manual therapy interventions (joint mobilisations, manipulations, soft tissue techniques) taping, and bracing show the ability to immediately and beneficially affect proprioception. Several types of exercise therapy have also demonstrated long-term improvements in proprioception in the spine and the extremities. Although manual therapy, taping, and bracing can immediately and beneficially affect proprioception, concern has been stated with regards to the size and duration of therapeutic effects of passive interventions (Cook, 2011). Nevertheless, these passive interventions can be employed immediately prior to same-session active rehabilitation.
Table 1
Proposed specific example exercises to beneficially affect proprioception of different body parts.

<table>
<thead>
<tr>
<th>Exercise type</th>
<th>Cervical spine</th>
<th>Lumbar spine</th>
<th>Upper limb</th>
<th>Lower limb</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Active joint repositioning (JPS)</strong></td>
<td>Repositioning head to neutral and other points in ROM using laser-pointer (sitting, standing)</td>
<td>Repositioning spine to neutral, points in range (sitting, standing, four-point kneeling)</td>
<td>OKC and CKC shoulder, elbow, wrist, finger repositioning to different points in ROM</td>
<td>OKC and CKC hip, knee, ankle repositioning to different points in ROM</td>
</tr>
<tr>
<td><strong>Path-of-motion (kinesthesia)</strong> training</td>
<td>CCFT with PBU Force and effort perception training using a dynamometer at pre-determined percentage of isometric MVMA (flexors, extensors, lateral flexors, rotators)</td>
<td>Abdominal muscle training with PBU Force and effort perception training using a dynamometer at pre-determined percentage of isometric MVMA (flexors, extensors, lateral flexors)</td>
<td>Force and effort perception training of hand and fingers with grip/pinch dynamometer</td>
<td>Force and effort perception training using a dynamometer at pre-determined percentage of isometric MVMA (hip external rotators, knee flexors, ankle evertors)</td>
</tr>
<tr>
<td><strong>Force sense training</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Co-ordination training</strong></td>
<td>Head-eye co-ordination Trunk-head co-ordination Cervical extensor training Neck extension with neutral upper cervical spine Gaze stability (eyes still, head moves into flexion, extension and rotation) Eye follow side to side head still in head neutral and in torsion</td>
<td>TrA-multifidus co-activation UL and LL movement while maintaining trunk stability (neutral lumbar spine) Pilates</td>
<td>Scapular inter-muscular co-ordination (scapular upward rotation force couple) Rotator cuff co-ordination with gross UL movements Wrist, hand, finger fine co-ordination tasks</td>
<td>Gluteus maximus-hamstrings co-ordination during prone SLR Gluteus medius-TFL coordination during hip abduction variations Pelvis-hip-knee-ankle-foot alignment training during CKC tasks Knee valgus-varus movement control during CKC tasks Foot-shank-thigh co-ordination on elliptical trainer Tai Chi</td>
</tr>
<tr>
<td><strong>Muscle performance training</strong></td>
<td>CCFT low-load endurance Cervical extensor training in four-point kneeling external load Head-lifts into flexion, extension, lateral flexion ± external load</td>
<td>TrA, multifidus endurance Curl-ups Trunk extensor, front-plank, side-plank isometric holds</td>
<td>Bodyweight strength training Resistance training machines Free-weights Elastic resistance training</td>
<td>Bodyweight strength training Resistance training machines Free-weights Elastic resistance training</td>
</tr>
<tr>
<td><strong>Balance/unstable surface training</strong></td>
<td>Standing (eyes open or closed; narrow, tandem, SLS on firm then soft surface (foam) then unstable surface (rocker board)) Perform other exercises while in unstable positions (JPS, eye co-ordination) Tandem walk, walking with head movement Neck resistance training in slings Control motion of a moving object with the head and neck (ball on head)</td>
<td>Standing (eyes open or closed; narrow, tandem, SLS on firm then soft surface (foam) then unstable surface (rocker board)) Sitting on a Swiss-ball ± UL movements Stabilising the trunk while performing active UL movements while controlling an oscillating pole Performing active movements of trunk while controlling oscillating pole or Swiss-ball</td>
<td>Press-ups on a Swiss-ball or wobble-board Press-ups with legs elevated on a Swiss-ball Wrist gyroscopic exercise ball training Active UL movements while controlling an oscillating pole Control of ball on wall with shoulder and UL</td>
<td>Standing (eyes open or closed; narrow, tandem, SLS on firm then soft surface (foam) then unstable surface (rocker board)) Standing as above ± distraction/ perturbation from clinician (ball throwing/catching, pelvic girdle rhythmic stabilisations) Single-leg squats on rocker-board Wobble-board, Swiss-ball, mini-trampoline training</td>
</tr>
<tr>
<td><strong>Plyometric training</strong></td>
<td>Pyloball sit-ups Pyloball back extension Pyloball long-sitting side throws</td>
<td></td>
<td></td>
<td>Double-leg and single-leg hops, leaps, jumps, bounding ± barriers, boxes, platforms Depth jumps Skipping drills</td>
</tr>
<tr>
<td><strong>Vibration training</strong></td>
<td>Neck extension resistance training with vibration added</td>
<td>Lumbo-pelvic postural exercises while standing of vibration platform</td>
<td>Elbow, wrist movement with vibrating dumb-bells Arm movement with oscillating pole</td>
<td>Double-leg and single-leg squats on vibration platform Lunges on vibration platform</td>
</tr>
</tbody>
</table>

ROM = range-of-motion.
SLS = single-leg stance.
OKC = open kinetic chain.
CKC = closed kinetic chain.
CCFT = cranio-cervical flexion training.
PBU = pressure biofeedback unit.
JPS = joint position sense.
MVMA = maximum voluntary muscle action.
TrA = transversus abdominis.
UL = upper limb.
LL = lower limb.
SLR = straight leg raise.

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with a view to assisting patients to prepare for specific exercise therapy interventions and functional movements (Clark and Lephart, 2015). Thus, it is likely that a mixed mode intervention approach is optimal for enhancing proprioception in clinical practice.

As discussed in Part 1 of this Masterclass (Roijezon et al., 2015), different exercise types will affect the CNS in different ways. Some exercises will preferentially affect supraspinal levels of the CNS (e.g. cerebrum), while others preferentially affect spinal cord levels and, therefore, influence different aspects of proprioception in different functional contexts. The types of exercise commonly used to improve proprioception can vary according to different functional demands of the body areas and joints. Exercises (active joint repositioning, force sense, co-ordination, muscle performance, balance/unstable surface, plometric, and vibration training) should be used to facilitate long-term beneficial adaptations in proprioception and enhance overall sensorimotor control (Clark and Lephart, 2015).

In Table 1 Future directions should consider advances in clinical assessment of proprioception, which is lacking in a number of areas. This might also direct future research towards identifying other interventions, or the most appropriate combinations of interventions, to improve proprioception in musculoskeletal rehabilitation.

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