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Can proprioception really be improved by exercises?

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Introduction

Over 100 years ago Goldscheider [29] systematically measured and compared the smallest joint rotations that could be detected at nine different joints in the body. As a result of 4,000 measurements made at a constant velocity (0.3°/s) he reported that the ankle exhibited the highest threshold (1.2°) and the shoulder the lowest threshold (0.2°) of the joints studied. Goldscheider was one of the first to systematically quantify the awareness of body segment positions and orientations, later defined as "proprioception" by Sherrington [62], who coined the term from the Latin *(re)ceptus* (the act of receiving) and *propius* (one's own). The classic methods for testing proprioception involve (a) using methods similar to those of Goldscheider to determine the *lowest threshold for detecting joint rotation* and (b) determining *joint position sense* from the accuracy with which contralateral joint angles can be matched or a limb segment repositioned in three-dimensional space without the aid of vision. The threshold for detecting joint rotation is one critical factor in preventing joint injury. Modern methods for testing such thresholds (for review see [3, 55]) employ known joint rotation velocities because of the velocity-dependent nature of the threshold (lower thresholds are found at higher velocities), the desired probability of sensing a given threshold, as well as weight-bearing and non-weight-bearing test conditions. For example, correctly detecting ankle inversion with a 75% probability of success requires a mean threshold rotation of 0.09±0.09° in healthy young adults and 0.39±0.44° in healthy 70-year-old subjects under weight-bearing test conditions [28]. In current sports medicine practice, rehabilitation and training frequently utilize certain exercises to improve proprioception. The rationale for prescribing such exercises is to prevent unnecessary ligament sprains and joint injuries.

The present study examined whether targeted exercises improve proprioception. Our results show little evidence to support such a contention and suggest that the appropriate experiments remain to be conducted.

Exercises and the ankle

Approximately 4,000,000 ankle injuries occur in the United States every year, one-half of which involve severe sprains [66]. Many ankle injuries occur during sporting activities, and they are one of the most common athletic injuries in amateur and professional athletes alike [25, 47]. Although a recent educational and exercise intervention managed to halve the ankle injury rate in one sport [6], more can be done to prevent ankle injuries. Apart from prophylactic devices, trainers use exercises to prevent ankle injuries. Some exercises are aimed at building muscle strength about the joint, while others seek to improve proprioception at the joint. We examined the rationale underlying the use of exercises for "proprioceptive training" at a joint. Even though we focus here on the ankle joint, our arguments should apply to any joint, including the knee and shoulder, which is the target of proprioceptive training.

One rationale for using ankle exercises is to rehabilitate ankle muscle strength and coordination as quickly and safely as possible following an injury. Typical weight-bearing exercises involve the performance of increasingly challenging unipedal balance tasks, first on a firm floor, then on a compliant surface such as foam, and then on a reduced base of support such as an ankle disc training device [26, 63]. This rationale seems justified if the exercises are aimed at improving motor performance in terms of maximum eversion strength and rate of developing evertor muscle force in order to preemptively prevent unwanted inversion (for example [4]). However, the extent to which such exercises, which involve a particular set of muscles and predictable stimuli, can help to prevent injury caused by unpredictable stimuli in a real life situation is unknown.

In the rehabilitation setting a second rationale given for the prescription of these balance exercises is to improve what has loosely been termed "ankle proprioception" (see, for example, the papers [31, 36, 43, 63] and textbooks [2, 10, 13, 33, 34, 40, 53, 66]), which is considered impaired postinjury [8, 9, 20, 22, 69]. However, as we argue below, the use of the term "ankle proprioception" in this context has most often been allowed to include measurement of skill in motor tasks such as balancing, not really true tests of proprioception. In fact, a recent paper from an experienced research team has actually found no impairment in the threshold for detecting ankle rotation after recurrent ankle sprains [56]. In 1997 the American Orthopaedic Society for Sports Medicine and the Foundation for Sports Medicine Research sponsored an Instructional Course entitled "Proprioception, Open and Closed Kinetic Chain Exercises: Implications to Assessment and Rehabilitation with Emphasis on the Lower Extremity," which clearly infers that such balance exercises improve proprioception. However, as one of the Mayo brothers once said, "understanding must come before belief in medicine."

We argue here that belief has indeed come before understanding when it comes to the effect of exercise on proprioception. Indeed, it may be premature to conclude that such exercises can improve true proprioception in terms of the two classic proprioceptive modalities: accuracy of joint position sense or the threshold for detecting joint movement (see below). This is because the relevant experiments have yet to be performed to prove or disprove the hypothesis that training improves joint proprioception. We do not dispute that these rehabilitative balance exercises improve balance performance in specific tasks; our point is that the resulting outcome should be stated in exactly those terms – as improvement in balance performance (as, for example, in [21, 26]), not as improvement in "proprioception." We believe that ascribing any part of that improvement to improved kinesthesis or proprioception remains premature.

This lack of evidence for an effect of training on proprioception is due to the exercise interventions noted above. Although designed to "improve ankle proprioception," invariably the exercises incorporate a motor task into the methods used for evaluating the outcome measure(s). Consequently, while an improvement in the performance of such tasks is often ascribed to an improvement in sensory function, it can equally well be ascribed to an improvement in motor function without any proprioceptive improvement. However, an improvement in both sensory and motor function and the adoption of a different behavioral strategy remain viable alternative explanations. Because the relative contributions of each of these factors to improving task performance have yet to be documented, it is therefore premature to conclude that such exercises "improve proprioception."

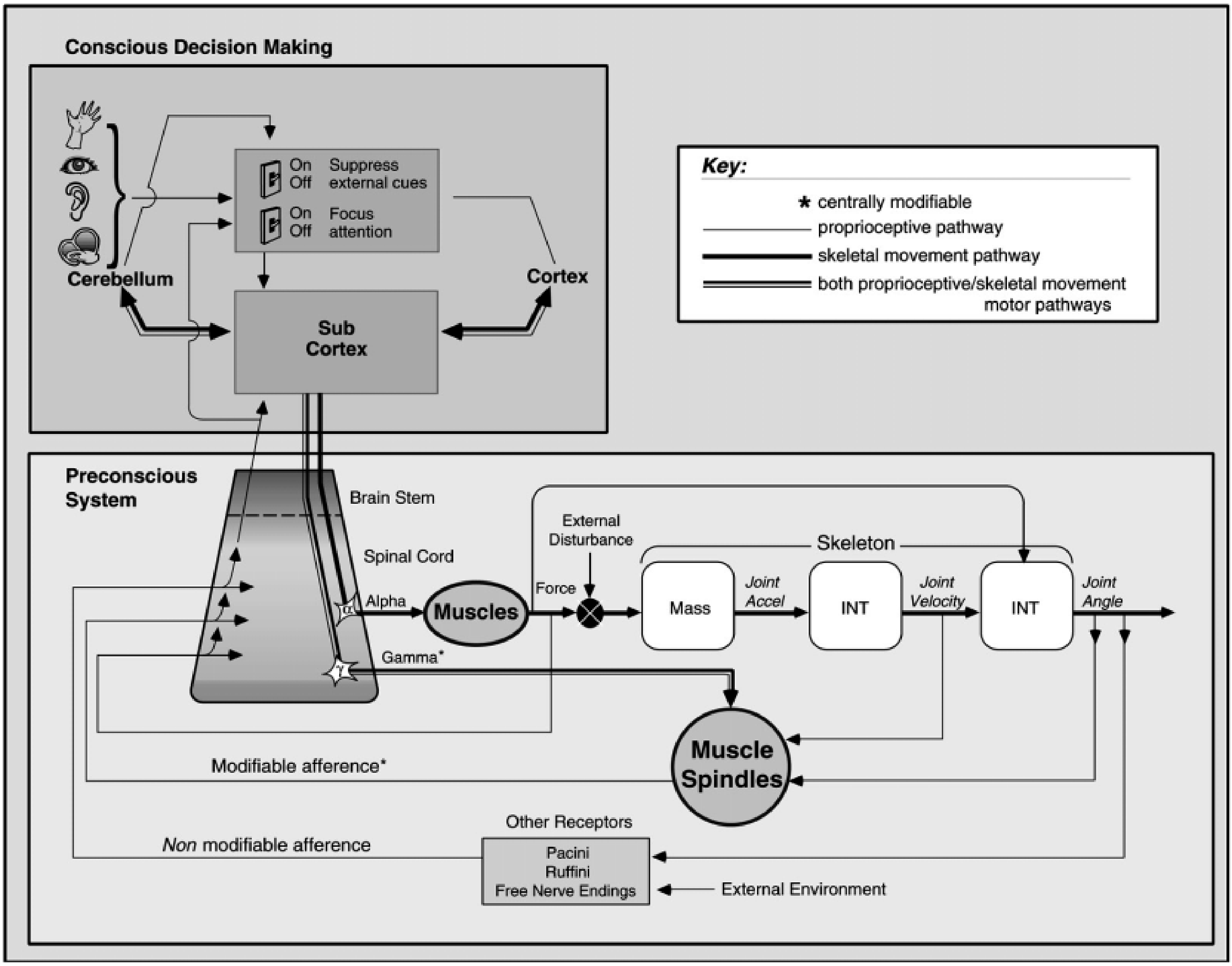

Fig. 1 Schematic drawing showing the main pathways and functions thought to be involved in proprioception. *Thin lines* afferent pathways and structures subserving proprioception; *thick lines* efferent pathways subserving motor actions leading to skeletal movement. *Above* A novel aspect of this diagram indicates schematically the higher nervous system structures controlling attention and motivation; these may have to suppress tactile, visual, auditory, and vestibular cues and focus attention in order to optimize proprioception, by modulating the state of cerebellar and reticular structures controlling arousal. Those structures then modulate the rubrospinal and rubro-bulbospinal pathways that help modulate spindle output via the gamma system recruitment. *Below* The classic autonomous systems subserving proprioception. The motor pathways (*bold lines*) subserving skeletal movements employ a "control systems" representation in which the muscle forces applied to the body segment mass are (mathematically) integrated to yield body segment velocity, and then integrated one more time to yield body segment position (posture). Sensory feedback on those forces emanate from the Golgi tendon organs. Body segment (and joint) velocity and position feedback is provided mainly by the spindles, the only sensory receptors whose output is centrally modifiable via the gamma motoneurons

Proprioceptive receptors and their central projections

The sensory receptors subserving proprioception include the I, II, III, and IV afferent receptor systems summarized in Fig. 1. These systems provide somatosensory input via the dorsal column-medial lemniscal pathways of the spinal cord to the mesencephalic reticular formation, cerebellum, thalamic relay nucleii, and sensory cortex, and thence to parietal lobe areas 5 and 7 and to the premotor area [42]. In short, these systems are thought to subserve conscious proprioception. A second set of pathways subserve subconscious proprioception, modulating movement and balance via the spinocerebellar tracts to the cerebellum. Since there is no evidence that training changes the number of peripheral receptors, we must look for possible central mechanisms to explain how training might modify proprioception.

Efferent modulation of afferent information

The input-output relationship of any receptor can be defined in terms of its *gain*, where the gain is defined as receptor output firing rate divided by the magnitude of the input stimulus. The gain of most afferent receptors is not known to be modifiable by central nervous system influences at the receptor. Thus the output of the Golgi tendon organs, Ruffini endings, or pacinian corpuscles are not known to be modulated by central neural command at the receptor. This is not to say that their gain remains fixed for every condition, because many receptors show *adaptation*. Adaptation, of course, means that for a given constant stimulus their gain decreases with time, essentially as the novelty of the stimulus wears off.

The one peripheral receptor whose gain can be modulated by the central nervous system is the muscle spindle (Fig. 1). Output from this receptor has been shown in a classic series of experiments to contribute to the conscious perception of limb position and movement (for example, [45, 46, 59]). This complex receptor receives efferent innervation via gamma static and gamma dynamic fusimotoneurons. Spindle feedback is important for postural control and proprioception; for example, elegant experiments have shown it is the primary sensory source of information for maintaining balance during upright stance [18, 19], especially in the absence of vision. The direction of movement has been hypothesized to be coded in terms of spindle discharge rates being greater in stretched than shortened muscles, while velocity may be coded as the difference in spindle output between agonist and antagonist muscles [58]. Spindle feedback is known to be systematically modulated by fusimotor activity in cyclic movements [1, 52]. Direct measurements of fusimotor neuron activity in humans show their activity to be modulated during activities such as the Jendrassic maneuver, as well as mental computation, the sound of hand clapping, and a subject listening for instructions on how to move [57]. Under ordinary conditions the muscle spindle is exquisitely sensitive to small stretches of its primary receptor ending. Thus, while its firing rate might increase by 500 impulses per second per millimeter stretch for very small stretches, it may increase by only 5 impulses per second for larger stretches of 1 mm or so [44]. What happens when its efferent input is modulated by the gamma system? The control of static and dynamic gamma motoneurons is known to be independent of the alpha motoneuron system [32]. We know that the gain of the muscle spindle can be approximately halved by eliminating its gamma motoneuron input (for example, [30, 45]). Similarly, electrical stimulation of the dynamic gamma motoneuron axon can triple the gain of the primary ending to stretch velocity, while stimulation of the static gamma axon reduces it [44]. Thus one can conclude that spindle output is the only source of afference that potentially is modifiable by training. Is spindle output volitionally modifiable, however?

There is evidence that humans can modulate the gain of muscle spindles volitionally, depending on the task (see review in [64]). Proprioception has been thought to improve when muscles are contracted at a joint [24], likely as a result of increased fusimotor activity [19]. Moreover, a slight increase in fusimotor drive, along with increased skeletomotor drive, has been demonstrated to occur when increased precision was required in a visually-guided manual tracking task [39]. Subjects significantly increased spindle output when asked to tense the muscles within which the muscle spindles lay. This is an example of the alpha-gamma coactivation demonstrated by Granit [30], and it is evidence that spindle output can be volitionally increased. However, this is not evidence that the increased fusimotor firing rate actually results in an increase in proprioception per se because the experiment was not designed to test such a hypothesis. The increase in precision could have simply been associated with a change in muscle tone that changed limb mechanical properties, such as muscle stiffness or damping, in a way that allowed subjects to improve the precision of their motor performance.

To test the hypothesis that subjects can alter their proprioceptive acuity one would need to design a prospective, randomized, controlled experiment involving the training of subjects over weeks, months, or possibly even years, to develop their proprioceptive acuity. Ideally, under one test scenario the measure of proprioceptive acuity would not involve a motor task. For example, a recent prospective trial used passive position sense to show that exercise training does not improve proprioception at the injured ankle [8]. It is known that ensemble responses of primary muscle afferents yield improved discrimination of muscle length changes than the response of a single afferent [7], and that discrimination improves with increases in ensemble size [54]. Thus plausible, but unfortunately invasive, measures of information serving proprioception include the degree of correlation between ensembles of afferents [35] and ensemble measures of fusimotor activity [54], spindle gains, and perhaps even central nervous system gain. Additionally, measures of subject perception can help provide mechanistic insights from tests performed with and without motor tasks. Until such controlled experiments are performed, there is little direct experimental evidence that supports the hypothesis that training can improve proprioception.

It should be noted that muscle fatigue, a common factor in athletic competition, can play a role in diminishing input to the proprioceptive systems. For example, ipsilateral medial hamstring muscle has been shown significantly to decrease ensembles of primary afferents from the gastrocnemius muscle to discriminate between muscles stretches of various amplitudes (see, for example, [54]).

Possible central mechanisms

There are other theoretical mechanisms for increasing the benefit derived from a given afferent inflow that do not require direct efferent modulation. One possibility involves attention, the neuropsychological process by which the central nervous system acts upon proprioceptive information perceived as being relevant. Put simply, it is possible that proprioceptive exercises increase the attention paid to proprioceptive cues by the brain, first at the conscious level early in training, then later, after perhaps more training, at the autonomous level. As Tononi and Edelman [68] write in their review, “The unity of conscious experience is also evidenced by our inability to perform multiple tasks, unless some tasks are highly automated and impinge less on consciousness. We cannot make more than a single conscious decision within an interval of a few hundreds of milliseconds, the psychological refactory period.” We return to the interaction between training and attention below.

Proprioception is thought to be most important in the closed-loop control of slow movements of a limb, as in tracking something with a finger [60], sensing the absolute or change in position of something in space, coordinating limb movements, and in balancing tasks. During these latter tasks proprioception acts at a subconscious level to maintain body posture via spinal or longer loop reflexes acting in less than 100 ms. There is evidence that humans can, and do, use proprioception to make reflexive postural adjustments in response to small changes in the position of a limb without even being aware of the changes. For example, Cordo and Nashner [15] found that muscle activation in postural responses occurs with such short latencies that there is time for neural conduction only to the spinal cord, brainstem, and cerebellum but not to higher cortical centers for conscious control of the postural responses. The autonomous mechanisms required to perform these subconscious adjustments are indicated in the lower portion of Fig. 1. The learning of a new balancing skill initially, however, requires attention to be focused (or “switched on”) on to the relevant afferent inflow by the attention control systems, which include the reticular structures and cerebellum, limbic system, and the frontal and parietal lobes, shown schematically in the upper portion of Fig. 1.

It has been argued that afferent information is used not only for closed-loop (feed-back) control of movements but also has an important role in open-loop (feed-forward) control of movements [27, 64]. Thus, central structures can use afferent information to preset muscle stiffness as well as for updating internal models used for feed-forward controlled movements [38] and may thereby help protect joints in time-critical situations by increasing their resistance to perturbations.

Central adaptations that follow an injury suggest the possibility of considerable central neuronal plasticity. These adaptations include dynamic reorganization of brain areas, “unmasking” of previously recognized pathways, and increased numbers of synaptic connections between neurons [5]. For example, Merzenich et al. [48] have shown that within 2–9 months after loss of the median nerve, the cortical regions that normally received its sensory input are completely occupied by representations from the adjacent cutaneous regions. Moreover, increased sensory stimulation to selected fingers increases their cortical sensory representation by 25–300% [37]. Merzenich et al. [49] propose that such neural changes parallel the time course and magnitude of changes in psychophysical tests of sensory acuity. These experimental studies suggest that changes in peripheral sensory input can have quantifiable changes in neuronal representations within the brain. Whether such changes can alter proprioceptive acuity remains to be demonstrated.

On the diminishing utility of proprioception in time-critical tasks

Daily activities impose varying levels of challenge to the neuromuscular system in protecting the skeletal system and its joints and their ligaments from injury. The great majority of such activities involve external and internal forces that provide little challenge to the neuromuscular system. This is because those forces are either relatively small *or*, even if they are large, they peak relatively slowly over hundreds of milliseconds or even a few seconds. This leaves plenty of time for the afferent systems to warn of possible impending injury and for a motor response to ensure that ligamentous stresses and strains are kept within normal working ranges. Thus proprioception is useful for preventing injury in slow, moderately rapid, and even rapid tasks. However, every now and then the neuromuscular system is confronted with a challenge at the highest level, particularly during sport-related landings on hard surfaces. In essence these situations are challenging to the neuromuscular system because they usually involve large external forces, which peak very rapidly, being applied to a limb. Because there is little time before the impact force peaks in the distal region of the limb, the situation then becomes time critical and, thereby, challenging for the neuromuscular system. It is time critical because the protective motor response requires a certain fixed time interval to execute, but fixed sensory transmission latencies limit the time remaining for the neuromuscular system to complete that motor response within what we have called the “available response time” [11]. This is particularly true if long-loop, higher order brainstem, proprioceptive or even attentional mechanisms are involved, and calls into question their utility under extremely time-critical situations. Rapidly rising and large external forces are also challenging for the musculoskeletal system not only because they can cause large peak values of ligamentous stresses and strains, but they can cause passive structures such as ligaments to experience high *rates* of strain. Biomechanically this can be challenging for a ligament or tendon because the higher the rate at which the ligament strain increases, the stiffer the ligament acts, and the lower the absolute strain required to cause injury of that ligament. Thus, in essence, the neuromuscular system no longer has sufficient time to develop muscle contraction forces to limit joint displacements and ligamentous strains from becoming injurious. Indeed, the fact that sprains do occur is evidence that the external challenge exceeded the capability of the neuromuscular system to protect its joint.

Thus, under some of the most challenging situations for the ankle neuromuscular system, namely the time-critical task of landing on a hard irregular surface, perhaps involving an attempt to also change whole-body momentum and thereby direction of travel without spraining an ankle, there is a time interval within which neither proprioception nor any proprioceptive training can ever be helpful. Under such conditions the foot-ground impact force, known technically as the "ground reaction force," takes less than 50 ms to reach its peak magnitude [16] and ankle inversion can reach 17° in as little as 40 ms [50]. There is simply not sufficient time for even the shortest spinal reflexes to execute an adequate motor response to prevent injury [4]. Therefore, ankle disc exercises, which involve relatively slow postural movements on the order of several hundreds of milliseconds are unlikely to be optimal sensory exercises in training for a *reactive* ankle protective strategy to guard against injury of the ankle ligaments in as little as 40 ms. For less time-critical situations, however, there seems reason to believe that proprioception plays an important role in subserving the ankle neuromuscular protective system, at least in terms of the threshold for detecting unwanted excessive ankle rotation. However, ankle disc exercises have yet to be shown to increase proprioceptive acuity in the strict sense discussed here. Further, the possibility of training proprioception for use under the more rapid joint loading conditions has never been tested.

Can skill training improve proprioception?

Suppose we hypothesize that skill or athletic training can allow an individual to improve the probability of detecting limb segment rotation in the context of a certain non-time-critical task. One mechanism might involve the individual learning to pay attention to a cue if it is important to their performance. For example, Ashton-Miller and colleagues [28, 67] have shown that when the foot is rotated slightly by an external agent the probability of consciously detecting a movement increases significantly with the magnitude and speed of the movement. Thus, when a 0.01° rotation of the foot is detectable with a 10% probability of success at a given speed, there is a 90% probability that it will not be consciously be detected [28]. With training, however, one might be able to show that this probability may change, not so much as a result of increased spindle output, but more as a result of improved selective attention to that cue and/or changes in the primary sensory cortex, as the individuals become more skilled at attending to important sensory cues. Thus it is the improvement in the probability with which they detect the rotational movement which allows them to make adjustments in their performance. With training the individual passes from the *cognitive* to the *associative* phase of learning and thence after months or perhaps years to the *autonomous* learning phase wherein the adjustments become automatic. One benefit is that the individual then may require reduced attention to perform the skill [60].

Notice that we are not arguing that training helps subjects to detect rotations that are smaller than the threshold rotation that they detect when untrained. Rather, training helps them to detect that 0.01° rotation with greater reliability than before, say with 30% success rather than 10% success. What evidence is there for such a process? Not much. Fry-Welch [23] found that healthy young subjects could be trained to reduce the threshold of the proprioceptive error in a forced-choice elbow angle comparison task, and they also could be trained to reduce absolute and variable error in an elbow-matching task. The reduction in error on the elbow-matching task resulted from a reduction in absolute error on the best and the worst trials indicating that subjects not only reduced the error in their worst trials, but they also increased proprioceptive acuity in their best trials. These experiments involved slow, non-weight-bearing movements in the upper extremity. There is a need for additional experiments to confirm these results and to determine whether training can affect proprioceptive acuity in the weight-bearing lower extremity, especially under time-critical conditions similar to those operating during an impending joint sprain.

The role of attention

Why might an individual not respond to potentially excessive joint rotations at one or more joints? Quite apart from the issue of developing sensorimotor coordination, we have argued above that in time-critical tasks nerve conduction and decision-making latencies may simply preclude a motor response. However, in slower movements more typical of those involved in postural balance tasks, rotations might go undetected by higher neural centers because of attentional factors such as divided attention (for example [70]) or lack of focus [51]). Attention can be defined as "a limited capacity to process information, thus if two tasks are performed together and they interfere, then both require attention [60]. Attention may be categorized as either "selective," "divided," "focused," or "sustained" [61]. If subjects' attention in an experiment is divided between the task of detecting the rotation and some other task activity, it can be described as being "divided." Since divided attention is known to decrease the success of performing a given task (for example [12]), and we know that as balance tasks increase in complexity then so do the attentional demands on the subject [41], we can then infer that learning to attend to what matters and to disregard irrelevant stimuli can improve "proprioception." One could speculate that with training, good gymnasts trying to remain motionless on a balance beam may learn to pay full attention to ensure that they detect every larger segmental acceleration, thereby improving their overall performance. This is called "attention switching" [71], and it may be part of the task itself. The neurobiology of attention and memory is admittedly at an early stage. It seems reasonable to speculate, however, that at least in slow movements proprioceptive thresholds could theoretically be influenced by months and years of training. This is because such training could plausibly affect many attentional factors such as sensory selectivity, arousal, motivation, memory, processing speed, vigilance, fatiguability, and appropriate attention shifting [14]. It remains to be seen however, which if any of these factors are influenced by so-called "proprioceptive" training exercises of the type commonly prescribed in the clinic.

On the other hand, we know intuitively that the importance attached to afferent information can be modulated *centrally* under certain conditions. Consider, for example, the clinical examination of a joint such as the ankle. Normally in the uninjured ankle joint one can sense a joint rotation of less than one degree (for example [28]). However, any clinician or patient knows that effusion and pain in a joint can make it exquisitely sensitive to movement when the joint is moved in a way that is perceived as possibly aggravating that injury. This is circumstantial evidence that central reprogramming and/or the state of arousal can alter proprioception (Fig. 1).

As indicated above, the muscle spindle is the only receptor system whose peripheral gain can be modulated by central command. Evidence is still lacking that one can volitionally learn to increase fusimotor input to spindles. However, it would be logical to assume that the Olympic gymnast who trains for 10 years to balance motionless on a narrow beam has learned something in those years of training. No amount of training can increase her sensory receptor density, but she may learn (a) systematically to increase her fusimotor drive to the spindles in such challenging tasks, (b) systematically to increase the gain of the spinocerebellar and dorsal column-medial lemniscal networks receiving spindle afference, and (c) to pay undivided attention to detect relevant afferent cues with greater probability and/or increase the somatosensory field for proprioception in the sensory cortex. If she uses any or all of these mechanisms she may be able more reliably to focus attention and detect smaller postural changes than 10 years previously. In other words, she undergoes successful proprioceptive training. If none of these effects occur, however, it is likely that her improvement is due to refined motor responses to the standard cues provided by the proprioceptive systems, and her improvement should not be ascribed to improvement in proprioception.

The challenge

The challenge then is to design and conduct rigorous experiments to test two hypotheses: (a) in healthy uninjured individuals it is possible to significantly improve proprioception by training, as demonstrated by methods for evaluating proprioception that do not involve motor tasks, and (b) proprioception in the injured ankle can be significantly improved by training, as demonstrated by methods that do not involve motor tasks. Should these hypotheses be supported by data, these experiments would logically be followed by tests of the following hypotheses: (c) improved ankle proprioception results in faster joint protection strategies or balance reactions to predictable postural perturbations, and (d) improved ankle proprioception results in faster joint protection strategies or balance reactions to unpredictable postural perturbations. Insights derived from proper tests of these and related hypotheses could lead to improved prophylactic and rehabilitation exercises, not only for the ankle but also for other joints such as the knee and shoulder.

Summary

There is little question that ankle disc training can improve ankle muscle *motor* performance in a unipedal balance task, most likely through improved strength and coordination [62] and possibly endurance. How much of the observed improvement in motor performance is due to improved ankle proprioception remains unknown.

We have reviewed a number of theoretical ways in which training might improve proprioception for moderately challenging weight-bearing situations such as balancing on one leg. Although the relevant experiments have yet to be performed to test this hypothesis, any improvement would theoretically help to reduce injuries at these moderate levels of challenge. We question, however, whether these exercises can ever improve the *reactive* response required to prevent injury under the most challenging time-critical situations. If confirmed, this limitation needs to be acknowledged by authors and practitioners alike. Alternative protective strategies for the most challenging time-critical situations should be sought.

We conclude that, despite their widespread acceptance, current exercises aimed at "improving proprioception" have not been demonstrated to achieve that goal. We have outlined theoretical scenarios by which proprioception might be improved, but these are speculative. The relevant experiments remain to be conducted. We argue that even if they were proven to improve proprioception, under the best circumstances such exercises could only prevent injury under slow to intermediate rate provocations to the joint musculoligamentous complex in question.

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