Overcoming the Myth of Proprioceptive Training

Article *in* Clinical Kinesiology · March 2011

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Abstract
Emergence of proprioceptive training in industrial training facilities seems to reflect current efforts of emphasizing neuromuscular function and postural control in general training programs. While it is encouraged to continue such efforts, correction of mythical beliefs is necessary for more suitable application. Clinicians for the recovery of the sensorimotor function originally suggested the idea of proprioceptive training. Adopting this clinically originated concept to general training created two main misconceptions. One is the premature assumption that proprioception can be improved with physical training. The other is the belief that proprioception is a key factor for the improvement of balance in every occasions. However, there is not sufficient neurophysiological evidence supporting the feasibility of the improvement of the proprioception through physical training. Moreover, proprioception can be effectively used only during the slow or moderately fast closed-loop control of movement. Therefore, overemphasis on proprioception may ignore the role of the central nervous system (CNS) in carrying out motor abilities and skills. A training program should be able to facilitate the CNS adaptation that is a key factor for the development of motor abilities and improvement of skill performance. In order to create an ideal learning environment for the CNS, an exercise program should distinctively train different motor skills with adequately changing task goals and sensory environment. Also, training should help the CNS to overcome its limited attentional capacity by adequately imposing multiple task demands.

Key words: Balance, motor control, proprioception, central nervous system, exercise program, application of therapeutic exercise

INTRODUCTION

As strength and conditioning coaches started to respect the importance of neuromuscular function and postural control in physical training during the past decade, 'proprioceptive training' became popular. Many industrial training facilities advertise 'proprioceptive training' as if it is newer and more effective balance training for preventing injuries. Clinicians for the recovery of the sensorimotor function originally suggested the idea of proprioceptive training. Two main misconceptions were caused while adopting this clinically-originated concept to general training. One is the belief that proprioception is a key factor for the improvement of balance in every occasion. Balance control is an intricate motor control process (18) affected not only by the neuromuscular function but also by the cognitive and environmental factors. Even though balance and proprioception cannot be used interchangeably, researchers have measured balance to evaluate proprioceptive function (9,12,14,30). This may confuse understanding of the role of the proprioception in balance control (11). Another misconception is the premature assumption that proprioception can be improved with physical training (2). Nevertheless, investigators have reported that proprioceptive responses were improved as a result of exercise (19,20,22,26,30). The proprioceptive exercises in many of these studies were either perturbed balance training or plyometrics, agility, or strength training with emphasis on balance component (19,20,26,30). These studies may also lead to confusion, because little explanation about the difference between regular balance training and the proprioceptive exercises were provided in these studies. Moreover, some of these studies reported balance improvement as an outcome measure (9,12,14,30), which makes it unclear if the effect was the improvement of the proprioception per se. In this context, the purpose of this review is to clarify the concept of 'proprioceptive training', and to discuss the feasibility as well as practicality of current application of this concept to general training programs. Without thoroughly comprehending the concept of proprioception and balance, it is difficult to understand the controversy regarding the proprioceptive training. However, previous authors have used slightly different definitions when explaining these two concepts (19,37). Therefore, this review will begin with meticulous overview of the concepts of balance and proprioception. Then, based on neurophysiological and motor control perspectives, the low feasibility of improving proprioception through physical training is discussed. Following this discussion, more practical approach of training balance will be introduced.

Definition of balance and proprioception

Balance is a mechanical term describing the state of an object when the resultant loads acting upon it are zero (37). In a static situation, an object is in balance if the vertical line from the center of gravity (COG) falls within the base of support (BOS). Human balance, which is better defined as 'postural control', is different from the mechanical terminology because of our inherent ability of controlling relative position of COG and the center of pressure (COP) (37,49). Because the gravitational force constantly challenges postural stability, movement of COG and COP is ineluctable; even during the quiet standing (49). A mechanical definition of stability is the inherent ability of an object to remain in or return to a state of balance (37).

Stability can be achieved either by moving the line of gravity (LOG) back into the BOS or by forming a new BOS. In the case of an in-animated object, when the LOG deviates outside of the BOS, the object falls, and the new BOS is formed (37). However, dynamic nature of human body allows marginal instability without falling. Humans can recover the state of balance from the instable position through reflexive and cognitive movement; such as swaying and stepping (19). In other words, temporary deviation of LOG outside of the BOS does not always result in falling. Moreover, the deviation of LOG outside of the BOS is often necessary for dynamic human movement. In this sense, postural stability can be defined as an inherent ability to recover the position of LOG within BOS in order to keep the upright position during both static and dynamic situations.

Human balance can be further defined considering three challenges to the postural stability: maintenance of a specified posture, movement between postures, and reaction to an external disturbance (19). Maintenance of the postural stability in all of these situations necessitates not only a voluntary but also a reflexive control of movement. In fact, Kavounoudias et al. (25) classified human balance as both cognitive and reflexive motor control activity. In summary, a reasonable universal definition of human balance can be the inherent ability of cognitively and reflexively controlling relative position of COG and BOS in order to maintain postural stability against both intrinsic and extrinsic disturbances.

Proprioception is often roughly defined as sensory information about limb, trunk, and head position and movement (28). Goldscheider (2) was one of the first to systematically quantify the awareness of body segment positions and orientations, later defined as 'proprioceptions' Over 100 years ago, Goldscheider systematically measured and compared the smallest joint rotations that could be detected at different joints in the body. Sherrington (26) later defined this awareness of the body position and movement as 'proprioception', and further explained the proprioception as a perception not necessarily perceived consciously but contributes to conscious sensations such as muscle sense, total posture, and joint stability. According to Sherrington's definition, proprioception is the afferent information from the proprio-ceptors. Proprio-ceptors are peripheral sensory receptors located in the proprio-ceptive field (the term 'proprio' from the Latin *propius*, meaning 'one's own). Proprioceptive fields are areas within the joint and deep tissues which are capable of delivering the perception of self-position and movement.

Muscle spindle, Golgi-tendon organ (GTO), and joint capsular and ligament receptors are the proprioceptors (28). The perception of joint location in space was specifically termed as 'joint position sense', and sensation of joint movement direction and velocity was termed as 'kinesthesis' (26). The proprioceptive information is delivered to central nervous system (CNS) through the afferent neural pathways to produce awareness of limb, trunk, and head position and movement, which contributes to reflexive and cognitive motor response (2,6,44). Even though proprioception does not directly affect movement production, it is important in accurately achieving a movement goal (28). Researchers have evidenced that both surgical and non-surgical removal of proprioception resulted in decrease of the accuracy and the coordinative control of the movement and alteration of the movement onset timing (28,47,48). In understanding functional role of proprioception, it is important to distinguish proprioception from tactile senses. Tactile sense is afferent information from skin mechanoreceptors related to pain, temperature, and movement. Functional characteristics of tactile sense and proprioception are very similar because both contribute to movement accuracy, consistency, and force adjustment. Moreover, tactile feedback can be used to augment proprioceptive feedback to estimate movement distance (28). However, proprioceptors and mechanoreceptors are two distinctive organs (26), and it is important not to confuse these two terms. In sum, proprioception is the self-perception of body's segmental position and movement, which contributes accuracy, consistency, and coordinative control of reflexive and cognitive human movement.

Origin of proprioceptive training

Clinicians originally proposed 'proprioceptive training' as one of the rehabilitative exercise concepts. They modified typical weight bearing exercises by making surfaces unstable on which the exercise was performed (26). Unstable surface was assumed to create a proprioceptively enriched environment that progressively challenges the proprioceptors and nervous system (42). For example, unipedal balance tasks was performed; first on a firm floor, then on a compliant surface such as a foam pad, and then on a reduced base of support such as an ankle disc training device (26). This reflects therapeutic approach of rehabilitating motor performance through the recovery of proprioception deficits (42). The need for recovery of proprioception seems to be justified by the clinical observations of pathologic functional joint instability. For example, functionally instable ankles (FIA) experience sensation of "giving way" and are susceptible to recurrent ankle sprains (18). This ankle instability exists following recovery from ligament injury such as ankle sprain (39). Researchers investigated what contributes to this functional instability of the ankle even after the tissue was already healed completely. They observed that balance deficit was commonly shown among population with FIA (18,39). Under the condition that there was no strength deficit on FIA, it was reasonable to speculate that balance impairment of this population might have been caused by the alteration of the sensorimotor function (26). The only sensory function might have been affected by the ankle sprain was somatosensory function because this injury normally does not damage the CNS, vision, or vestibular system. Most prevalent sensory receptors in the ligaments are joint receptors that are proprioceptors (26). In this reason, researchers hypothesized that ligament injury results in alteration of proprioception. In fact, the alteration of proprioception was observed in FIA in the research studies (18,34,39). In a logical sense, improvement of balance should indicate recovery of proprioceptive deficit under the assumption that diminished proprioceptive function was the only cause of the balance impairment. Studies actually showed that proprioceptive balance training not only improved balance but also reduced repetitive ankle injury rates (13,29,40). This evidence gave clinicians and researchers hope that there is a possibility to recover deterioration of proprioception through physical training (2). However, neurophysiological mechanism underlying the improvement of the balance through proprioceptive training is still not well defined, and even clinicians are very careful about acknowledging the trainability of the proprioception (2). It seems like the misconception about the proprioceptive training occurred as it was adopted in commercialized training facilities. Many of the personal trainers and strength conditioning coaches name single leg balance training on the foam pad as proprioceptive training (Fig. 1). They advertise that such training can enhance balance and even prevent athletic injuries. It is important to re-emphasize that proprioceptive training is loosely termed, and refers to concept of any training methodology that respects various proprioceptive feedback within the motor control process (26). That being said, the single leg balance training is not the representative form of the proprioceptive training. Moreover, premature assumption that one can train proprioception simply by stimulating proprioceptors, and that proprioceptive improvement will enhance balance ability as a whole can seriously mislead training regimen. It is important to keep in mind that the feasibility of proprioceptive training is greatly challenged due to the lack of neurophysiological evidence.

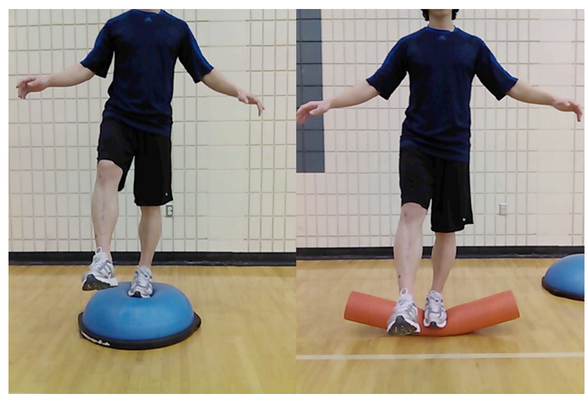

Figure 1. Faulty use of the term 'proprioceptive training': balance training and proprioceptive training should not be used interchangeably.

Proprioception; can it be improved?

Neurophysiological conduction of the proprioceptive information is composed of three different stages: acquisition of the mechanical stimulus, conversion of the mechanical stimulus into the neural signal, and the transmission of the neural signal to the CNS (26). Therefore, in order to evidence the trainability of the proprioception, we need to prove that balance training can enhance either the sensitivity of the proprioceptors responding to mechanical stimulus or the neurophysiological efficiency of signal conversion and transmission. In this case, the sensitivity is better termed as 'acuity' (2). The velocity of the signal conversion and

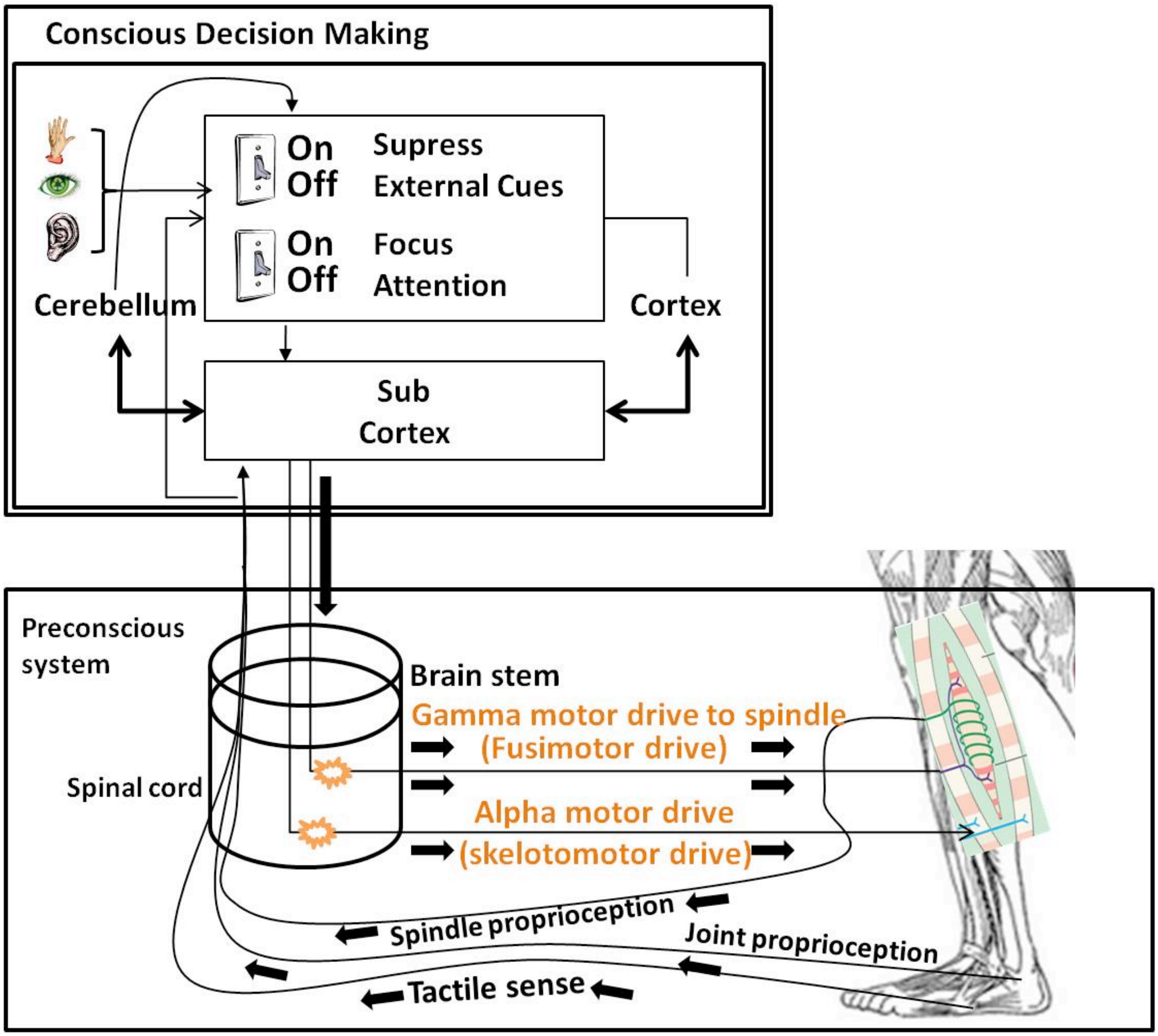

Figure 2. Possible volitional modulation of spindle acuity: Muscle spindle is the only proprioceptor that can be modulated efferently due to the fusimotor drive.

transmission is known to be fixed (41). Therefore, possible trainability of the proprioception can only be explained by the modulation of the acuity of the proprioceptors (2). It was speculated that muscle spindles may be the only possible proprioceptors of which acuity might be systematically modulated through the gamma motoneuron (2).

The schematic process of the theoretical modulation of spindle acuity is described in figure 2. Theoretically, spindle acuity can be volitionally modulated through task-dependent muscle contraction (2). A slight increase in spindle fusimotor drive, along with increased skeletomotor drive, has been observed during visually-guided manual tracking tasks which required increased precision (46). Participants significantly increased spindle output as they tensed the muscles within which the muscle spindles were located (15). The increase of the spindle output can be explained as a volitional alpha-gamma coactivation during the voluntary stiffening of the muscles (16). However, this is not the evidence of an increase in proprioception per se, because the related experiments were not designed to test a hypothesis that increased fusimotor firing rate results in increase of proprioception. With the muscles being stiffened, the CNS increases the fusimotor drive to the spindles, which possibly increase the size of the ensemble response of the primary spindle afferents (16).

It is known that increased ensemble responses of afferents assist in improved discrimination of muscle length changes than the response of a single afferent (5). Therefore, in order to ideally test if training of a specific motor task results in improvement of proprioceptive acuity, the study should measure size of ensemble responses. In addition, plausible investigation of proprioception should measure the degree of correlation between intensity of fusimotor activity and ensembles of afferents. However, no such studies have been conducted, likely because the feasibility of such studies on human participants is low because of its invasive nature (2). Research comparing the ability of detecting joint position without involving voluntary motor task before and after specific motor training can be an alternative approach (2). However, randomized controlled prospective trials used passive position sense did not consistently show that exercise training improved proprioception at the injured ankle (20,31). Therefore, at this point, there is little evidence that supports the hypothesis that proprioception can be improved through training.

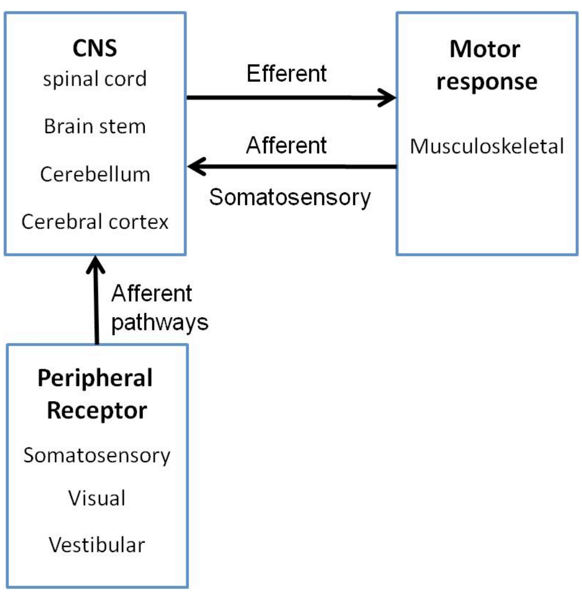

Figure 3. Closed-loop control system.

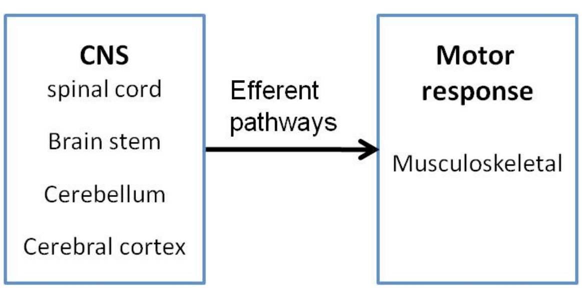

Figure 4. Open-loop control system.

The role of CNS in balance training

Commercialized training facilities often emphasize the benefit of balance training in preventing athletic joint injuries and falling. However, it is important to note that injury prevention requires more than proprioceptive improvement. Isolated improvement of proprioception is not the practical balance training strategy because the mechanism of the balance improvement involves not only neuromuscular and musculoskeletal factors, but also task dependent motor learning. In this section, the attention will be paid to the CNS adaptation-induced motor learning, and to theoretical principles on how the exercise should facilitate the CNS adaptation.

In order to discuss the importance of the CNS adaptation in injury prevention oriented balance training, it is necessary to understand situational limitation of proprioceptive feedback. The degree of proprioceptive contribution within motor control process changes in accordance with the different control systems employed differently task by task (2,28). Afferent information is best utilized during the closed-loop control system in which feedback is compared against a standard or intended goal during the course of action (28) (fig. 3). As demonstrated in figure 4, an open-loop control system is a one-way system in which the CNS plans and delivers all the information needed to carry out an action to the musculoskeletal system (28). In this context, proprioception is thought to be most important in the closed-loop control of slow to moderately fast conscious and reactive movements (2). For example, static single leg balance or a slow dynamic balance tasks such as walking on a balance beam require active contribution of proprioceptive feedback. However, closed-loop postural reflex against unexpected disturbance is not effective enough to avoid injuries during time-critical tasks (2). For example, during impact movement like running, the ground reaction force reaches to the injurious level within less than 50 milliseconds which is enough time to force the ankle to invert more than 17° (33). Closed-loop postural movement strategies triggers at 100 milisecond in response to an external perturbation (28), unbalanced emphasis on slow and controlled closed-loop movement training is not an effective strategy in preventing athletic injuries. Alternative and more effective protective movement strategies should focus on prevention of the injurious joint position rather than aftermath reaction. Anticipatory preset of muscle stiffness is known to be an effective protective mechanism by enhancing joint stability and fusimotor drive (2).

Since there is not enough time available to effectively utilize afferent feedback during the time-critical situation, the movement is more likely to be

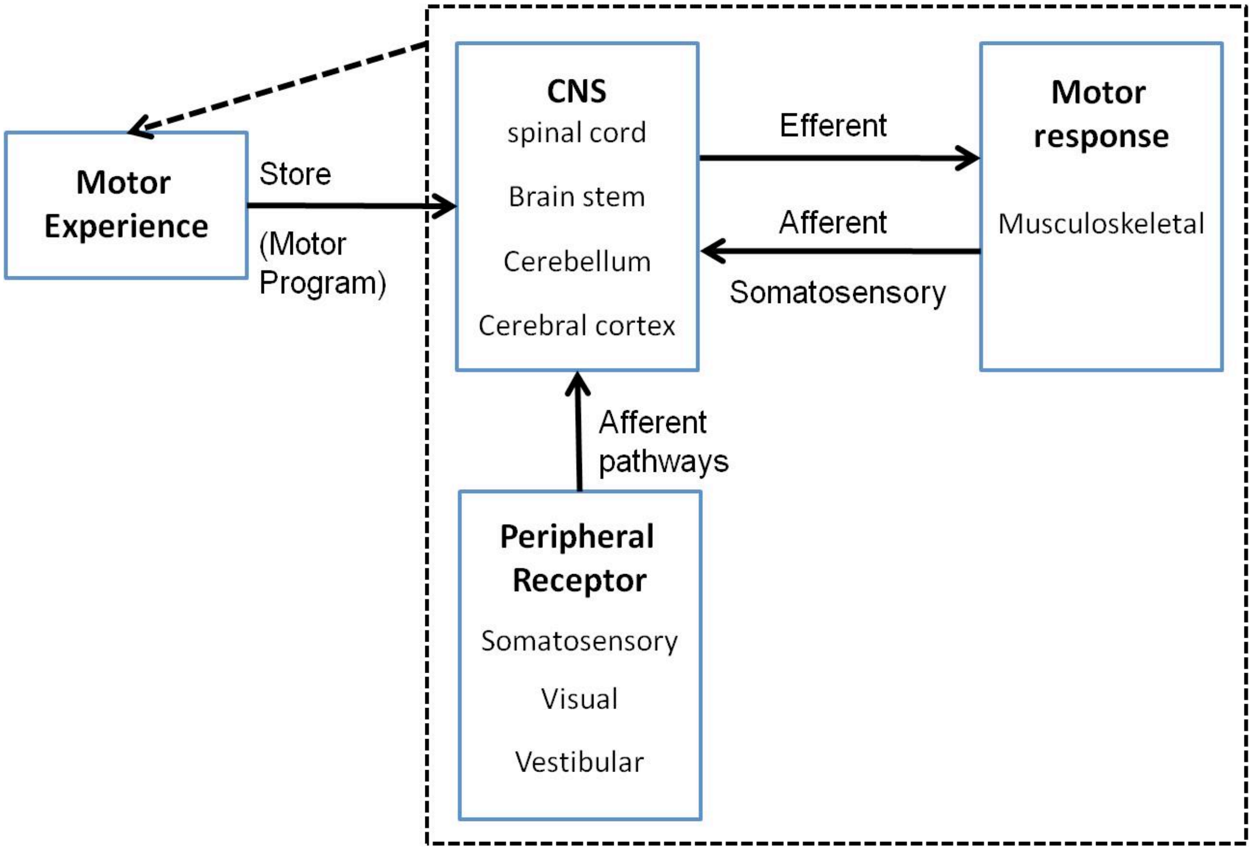

Figure 5. Motor program-based motor control.

initiated via open-loop control system (2). The role of the CNS is very important in open-loop system (28), and successful avoidance of the injury depends on appropriateness of the movement instruction prepared by the CNS for the musculoskeletal system. In fact, it has been suggested that protective motor behavior can be developed through the CNS adaptation (24). Experience of motor tasks helps the CNS updating internal models used for open-loop controlled movements, and thereby may help protect joints in time-critical situations by increasing their resistance to sudden disturbances (2). This hypothesis can be related to central neuronal plasticity that is supported by the evidence of the CNS adaptations that facilitate recovery from an injury (1,7,22). These adaptations include dynamic reorganization of brain areas, "re-discovery" of previously recognized pathways, and increased synaptic connections between neurons (3).

Exercise program facilitating CNS adaptation

Establishment of an adequate motor behavior through the CNS adaptation is necessary in successful avoidance of athletic joint injuries and falling. There are two evidence-based theoretical frames about how behavioral pattern of the movement is generated. Motor program-based theory explains that nervous system coordinates movement components differently in accordance to the relative importance given to movement instructions specified by the CNS (28). According to this theory, the CNS stores motor programs for each set of movement pattern, and retrieve the programs when needed (41) (fig. 5). The most acceptable motor program-based theory is Schmidt's generalized motor program (GMP) theory (28). GMP is a set of memory-based motor program of a class of actions that have common unique set of features called invariant features (41). Invariant features, such as relative timing and speed of segmental movements, are the "signature" of a specific class of the movements and form the basis of what is stored in memory (41). These features inherently remain consistent from one occasion of movement to another.

The dynamic pattern theory is another motor control theory of which concept opposes motor program-based theory. According to this theory, movement coordination is instantly controlled based on information in the environment and the dynamic properties of the body and limbs (28). This approach emphasizes the ability of nervous system to self-organize the motor pattern. Proponents of the dynamic pattern view emphasize the interaction between the performer and the task-oriented environment in which the skill is performed (28). The nervous system reacts to the environment and task demands by the movement of individual of muscles and joints, which later forms a functional synergy called coordinative structures (28). It was suggested that the coordinative structures not only exist naturally but also develop through practice or experience (43). Reactive nature of the movements generated through the dynamic pattern can be mistakenly thought of an example of closed loop control. However, dynamic pattern theory, in fact, indicates that afferent information is used not only for closed-loop control but also has an important role in open-loop system during the action preparation (2).

The CNS can use sensory information to prepare for upcoming movement demands, termed: perception-action coupling (28). The term 'perception-action coupling' is mainly used to describe the spatial and temporal coordination of vision and the limbs that enables people to perform hand-eye or foot-eye skills (8). However, CNS can use more than just visual information (such as smell or tactile sensation of the texture of the floor) for action preparation. Considering that stiffening of the muscles was observed during the movement preparation, there is a high possibility that perception-action coupling also contributes to the preset of joint stability (2).

In summary, in discussing key factors for generating motor behavior, GMP theory emphasizes the role of memory, whereas dynamic pattern theory emphasizes the interaction between performers and physical environment. Research evidence supports both of the theories; therefore, an ideal training program should respect memory function, task characteristics, and environmental effects. The distinction of motor skills based on the invariant features and separated repetition of those skills are the key factors of improving memory-based motor function. Change of the sensory environment and task goals is necessary to stimulate dynamic pattern of the movement behavior. For example, types of balance tasks can be divided into static and dynamic balance performance (single leg standing vs. balance beam walking), and these can be subdivided based on the goal of the tasks. The goal of static single leg balance exercise can be either maintaining a good joint alignment for one minute or hitting multiple targets with the non-balancing leg without falling. The goal of dynamic balance task can be either crossing a 2-meter balance beam as quickly as possible or a 2-meter tandem walk with correctly stepping on target steps. Visual environment can be altered by changing arrangement of obstacle settings or changing movement patterns of other people around a person. Sensory environment can be changed by challenging proprioceptive feedback via different sources (ground, upper body, or self-induced perturbation by voluntary movement), or changing visual or auditory information (causing distraction through a moving-wall or noise). Strength and conditioning coaches need to be not only creative in implementing adequate changes of the exercise programs, but also perceptive in finding out appropriate amount of repetition necessary for inducing motor learning.

Dual task training: overcoming the limited capacity of the CNS

In order to provide an ideal training environment for the CNS adaptation, one should also consider inherent limitation of the CNS. There is a general agreement that capability of the CNS to engage in multiple cognitive and motor activities simultaneously is limited (28). Ashton-Miller and colleagues (2) suggested that the CNS must learn to attend to what matters and to disregard irrelevant stimuli in order to selectively focus on specific environmental context features when we perform motor skills (fig. 6).

As discussed earlier, injury prevention not only requires basic static and dynamic balance abilities but also goal-oriented motor skills. Disregarding athletic events, daily movements continuously impose simultaneous cognitive and motor demands on top of the balance ability. For example, we talk on the phone, carry something, or read a newspaper when we walk on the street. Even when one does not perform secondary motor tasks, the brain engages in multiple cognitive tasks during walking. In this reason, researchers currently focus on developing balance training methods which help one to overcome dual task interference (35,36,50). According to Schmidt and Lee (2005), the term dual-task interference refers to the decrement in performance of one or both tasks when two activities are carried out concurrently.

In a broad aspect, two schools of thoughts exist from which distinctive training methodologies originate. One theory explains that the CNS overcomes dual task interference by mastering single-component task (50). With practice, a skill may become more automatic. With greater automaticity, the attentional demand of the same task is reduced. As a result, there are more CNS resources available for the secondary task. Therefore, this theory emphasizes separate practice of component tasks. Another theory discusses that practice leads the CNS to integrate different tasks together so that the CNS can perceive the two different tasks as a single higher order skill (34). This helps the CNS to overcome dual task interference because tasks that were previously recognized as dual-tasks become

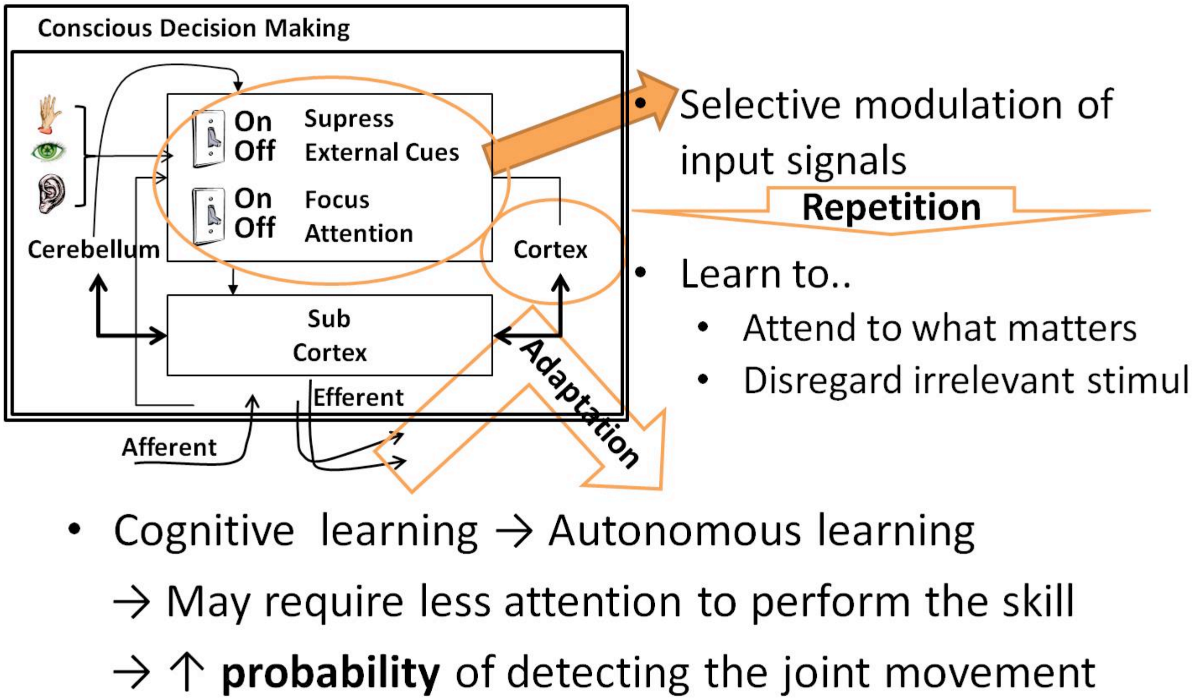

Figure 6. Theoretical motor cortex adaptation through training: As the CNS repeats selective modulation of input signals, the CNS learns to attend to disregard irrelevant stimuli in order to attend to more meaningful afferent information. As a result, motor skill becomes autonomous.

recognized as single-tasks. Therefore, this theory emphasizes simultaneous dual task training.

Silsupadol et al. (45) combined the two theories mentioned above and created a dual task balance training methodology of which effect can be transferred to real life situation. They compared three different balance training methods: a single task balance training, a combined balance and cognitive task training under a fixed-priority instructional set, and a combined balance and cognitive task training under a variable-priority instructional set. Single task balance training included body stability, body stability plus manipulation, body transport, and body transport with manipulation. For the combined task training they added cognitive tasks to the single task training. Examples of cognitive tasks were auditory discrimination tasks, simple calculation, spelling the words backward, remembering things, etc. During the fixed-priority instructional set, participants were directed to maintain attention on both balance and cognitive tasks at all times. Participants in the variable instructional set group focused more on balance task during the half of the session, and paid more attention on cognitive tasks during the rest half. Participants were randomly assigned to one of the three training groups, and participated in 45-minute training sessions 3 times a week for 4 weeks. Balance performance with novel cognitive tasks was used to measure the outcome. Novel cognitive tasks were the ones that were not directly trained during the intervention period. Only the participant who trained under variable instructional set showed improvement of balance during the balance performance with novel cognitive tasks, and this benefit was maintained for 3 months (45). This result indicates that simultaneous training of dual task with intentional shift of attention between balance and cognitive tasks is most effective in transferring the training effect to real life multiple task situations.

Application of dual task training.

Dual task training is not always the best methodology of training motor skill. Appreciation about the best timing of the implementation of dual task training is just as important as comprehension about the method of training. Researchers suggest that skill focused attention is important during the initial stage of motor learning, but becomes counterproductive for the experienced individuals (4,17,32,38). Researchers showed that multiple task training (motor + cognitive demands) were more effective for performance developments of experienced athletes (4,32). Intuitively, this indicates that cognitive attention is productive for training novice but certain amount of distraction from it is necessary to help experienced individuals proceed to more advanced level. Circumstantial evidence can be found in performance of professional athletes. Their practice and competition are full of continuous secondary cognitive and motor task on top of the balance performance. For example, professional figure skaters or gymnasts have to constantly focus on the rhythmic beats of the background music and the timing of the next movement at the same time they maintain balance in an unstable position. These multiple tasks continuously give dual task interference challenge to the CNS. As athletes repeat the practice, the CNS finally learns how to maintain balance despite multiple environmental distractions.

CONCLUSION

Emergence of proprioceptive training in industrial training facilities seems to reflect current effort of applying therapeutic concept of proprioceptive recovery to general training program. While it is encouraged to continue such efforts, correction of mythical beliefs is necessary for more suitable application. Proprioception is sometimes mistakenly considered as a key factor for the balance improvement and injury prevention. However, there is no neurophysiological evidence that proprioception can be trained through physical training, and proprioception is effectively used only during the slow closed-loop control of movement. In addition, overemphasis on proprioception may cause training program to ignore the role of the CNS in carrying out motor abilities and skills. Training program should be able to facilitate the CNS adaptation that is a key factor for development of motor abilities and improvement of skill performance. In order to create an ideal learning environment for the CNS, an exercise program should distinctively train different motor skills with adequately changing task goals and visual environment. Also, training should help CNS to overcome its limited attentional capacity by adequately imposing multiple task demands.

Acknowledgement

We would like to sincerely thank Dr. Alison Oates for her constructive advice and support.

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