Neuromuscular Control of Trunk Stability: Clinical Implications for Sports Injury Prevention

Bohdanna Zazulak, DPT
Jacek Cholewicki, PhD
N. Peter Reeves, PhD

Perspectives on Modern Orthopaedics articles provide an objective appraisal of new or controversial techniques or areas of investigation in orthopaedic surgery.

Dr. Zazulak is Doctor of Physical Therapy and Research Associate, Yale New Haven Hospital, Yale University School of Medicine, New Haven, CT. Dr. Cholewicki is Walter F. Patenge Professor, Osteopathic Surgical Specialties, Michigan State University, East Lansing, MI. Dr. Reeves is Research Assistant Professor, Osteopathic Surgical Specialties, Michigan State University.

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Reprint requests: Dr. Cholewicki, Michigan State University Center for Orthopedic Research, Ingham Regional Orthopedic Hospital, 2727 South Pennsylvania Avenue, Lansing, MI 48910.

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Abstract

Recent prospective evidence supports the hypothesis that impaired trunk control is a contributing factor to sports injuries of the spine as well as to segments of the kinetic chain. The current concepts regarding neuromuscular control of trunk stability are best described from a systems engineering perspective. In the analysis of current neuromuscular training protocols for sports injury prevention, these principles are applied to identify components that optimize neuromuscular control of trunk stability. Current perspectives of neuromuscular learning can be applied clinically to aid in the formulation of injury prevention strategies.

As a human neonate grows, the development of trunk neuromuscular control precedes coordinated, controlled limb motion. Neuromuscular development begins with prone posturing, as the neonate develops strength and coordination in the neck and upper back extensor muscles as a result of resisting gravity, then progresses to supine development of trunk flexors.[1] This is followed by learning to sit via cocontraction of trunk flexors and extensors.[1] Once trunk neuromuscular control is achieved, the infant begins to use the upper extremities for reaching, grasping, and transferring. Generally, by age 1 year, the infant has progressed to upright posture control and walking.

This temporal sequence of neuromuscular trunk muscle activity that precedes extremity muscle activity is evident during athletic maneuvers. Trunk muscle activity occurs before the activity of the lower extremity musculature, just as it occurs with neuromuscular control in the developing infant.[2,3] The central nervous system (CNS) creates a stable foundation for movement of the lower extremities through cocontraction of the abdominal as well as the back muscles, with the relative contributions of each muscle continually changing throughout the functional task.[4,5]

Is this temporal relationship of muscle activation important? Could poor trunk control compromise lower extremity function? Theoretically, from the systems engineering perspective, the answer to these questions is yes. Several recent studies provide direct evidence in support of the link between trunk motor control and musculoskeletal injuries.

Neuromuscular Control of Trunk Stability

The concept of "trunk stability" or "core stability" in the field of athlet-

Figure 1

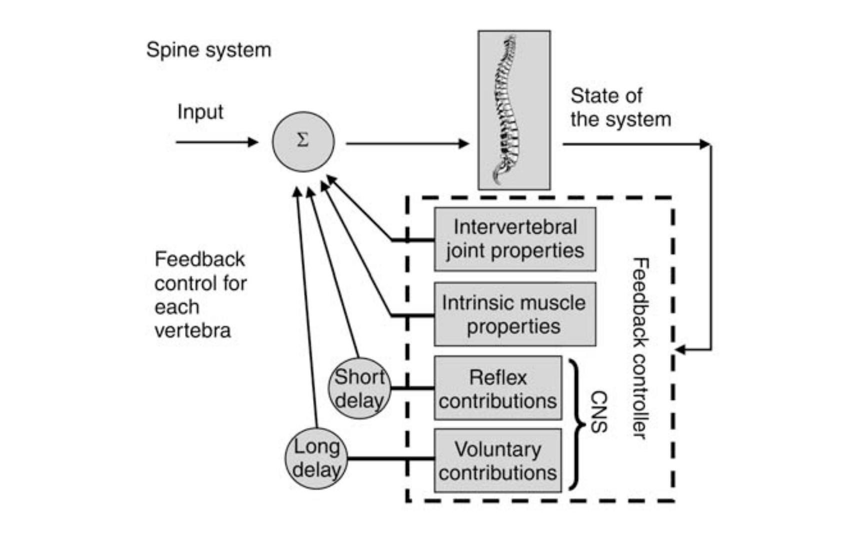

Diagram of components of the spine feedback control system. CNS = central nervous system, Σ = summation of series. (Reproduced with permission from Reeves NP, Narendra KS, Cholewicki J: Spine stability: The six blind men and the elephant. *Clin Biomech [Bristol, Avon]* 2007;22:266-274.)

ics has permeated into the vernacular of sports medicine physicians, physical therapists, and athletic trainers. Numerous definitions of core stability have emerged. The ambiguity of the definitions is not unexpected, considering that even within the disciplines of engineering, there is no absolute definition of stability.[6] It is important for the sports medicine community to choose an appropriate definition of stability that is both applicable to the musculoskeletal system and consistent with the theoretical foundations of systems engineering and biomechanics. When considering the role of the trunk in athletic function, the concepts of stability must encompass both static and dynamic conditions.[6]

Trunk stability is the term used to describe the capacity of the body to maintain or resume a relative position (static) or trajectory (dynamic) of the trunk following perturbation. During athletic movements, trunk stability is contingent upon neuromuscular feedback control in response to internal and external disturbances, including the forces generated from distal body segments as well as from expected or unexpected perturbations. In feedback control, information about the current state of the system (eg, joint position, velocity, force, pain, pressure) is fed back to the controller (CNS) to generate control input to the muscles and, in turn, to affect the joint. The controller's logic transforms the feedback information into an orchestrated neuromuscular activation pattern.

The performance of the system is another important variable to consider in understanding neuromuscular control of the trunk during athletic movements. Performance reflects how close the disturbed trajectory of the trunk remains to the undisturbed trajectory.[6] Following perturbation, the behavior of a well-performing trunk in an athlete will resemble the undisturbed behavior, suggesting that there is minimal error between the disturbed and undisturbed trajectories of motion.

For a dynamic system to be stable, three primary requirements must be satisfied (Figure 1). First, the system must be internally observable. This implies that sufficiently accurate and complete feedback information from sensory receptors about the state of the system is available to the controller (ie, CNS). This information is used by the controller to generate appropriate control input to the muscles. For example, a preexisting injury and fatigue have been shown to interfere with this part of the control process by corrupting spine position sense.[7]

Second, information must be accurately relayed to and from the CNS. This may be compromised by delays, such as those resulting from nerve injuries or neurologic disorders.

Third, the system must be controllable. This requires that actuators (ie, muscles) have sufficient power to bring about quick changes in all degrees of freedom (ie, joint motions).

Problems in any of these three areas can lead to instability, resulting in uncontrollable motions. In the context of the musculoskeletal system, this means that a joint can be unexpectedly displaced, possibly beyond its physiologic limits, resulting in injury. In a multisegmental system, forces and motions generated at one joint affect all of the remaining joints. Thus, problems in the control of one segment (or instability, in the most extreme case) may degrade the performance of the other segments to the point at which the entire system may become unstable (Figure 2).

Trunk Neuromuscular Control and Injury

Recent evidence indicates that poor neuromuscular control of the trunk, that is, observability, information relay, controllability, or any combination of these three, will affect other joints and predispose the athlete to back and lower extremity injury.

Muscle reflex response to sudden force release in trunk flexion, extension, and lateral flexion (Figure 3) was prospectively measured and analyzed in 292 collegiate varsity athletes (148 women, 144 men) who were followed for 2 to 3 years to track low back injuries.[8] Delayed trunk muscle reflex responses were identified as a significant ($P \leq 0.05$) predictor of low back injury in athletes. These neuromuscular deficits appear to be a preexisting risk factor rather than the result of prior low back injury.

In this study, the odds of sustaining low back injury increased 2.8-fold when a history of low back pain (LBP) was present.[8] It has been documented that a history of LBP results in long-lasting alterations in trunk neuromuscular control. Subjects with LBP demonstrate impaired postural control,[9] delayed muscle reflex latencies in response to sudden trunk unloading,[10,11] and abnormalities in neuromuscular recruitment patterns.[12] More specifically, athletes with a history of LBP, even after clinical recovery and return to their prior level of competition, continued to demonstrate neuromuscular control deficits.[13,14] Compared with athletes without a history of LBP, these athletes are at three times greater risk of sustaining a low back injury; this may be indicative of persistent deficits in neuromuscular control of the trunk.[15]

Recent prospective evidence also suggests a correlation between factors related to trunk neuromuscular control and lower extremity injury. Zazulak et al[16] identified significant predictors of knee injury related to neuromuscular control of the trunk. Two hundred seventy-seven collegiate varsity athletes (140 women, 137 men) without a history of knee injury were prospectively tested for core proprioception (Figure 4) and were monitored for injury over the course of 3 years. Statistically significant deficits in proprioception were observed in women who later sustained knee and ligament/meniscus injuries during the follow-up period compared with uninjured women from the same varsity sports teams ($P \leq 0.05$). No significant differences were noted in the proprioceptive measures between injured and uninjured men. For each degree increase

Figure 2

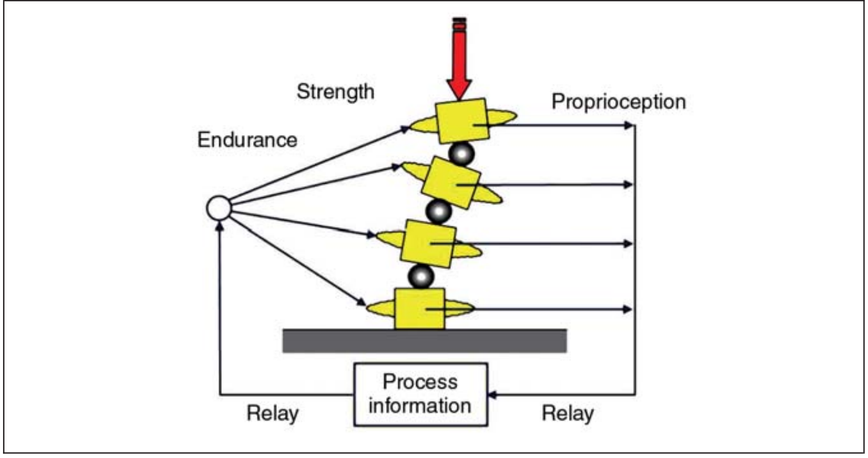

Diagram demonstrating that impairment in any of the elements of feedback control of the spine, even at the level of a single segment, will affect the remaining segments. In the most extreme case, the entire system may become unstable, leading to uncontrollable displacements.

Figure 3

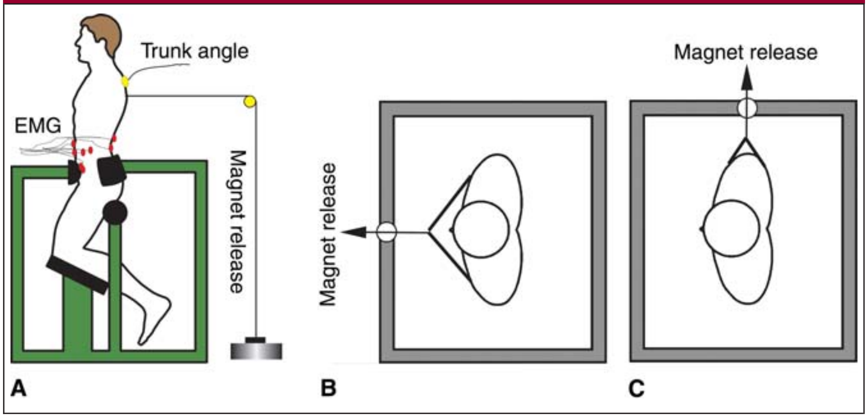

Diagram demonstrating a subject positioned in a multidirectional, sudden-force-release apparatus. Flexion **(A)**, extension **(B)**, and lateral bending **(C)** loads were applied via a system of pulleys. A cable attached to a chest harness at approximately the 5th thoracic vertebra was held with an electromagnet and served as a resisting force for isometric exertions. The resisted force was suddenly released when the electromagnet was deactivated at random time intervals after the target force was reached. Muscle reflex latencies (ie, muscle shutting off and switching on) were recorded with surface electromyography (EMG) from 12 major trunk muscles. In addition, angular trunk displacements that occurred 150 ms after the release and maximum displacements were recorded and averaged across five trials in each direction. (Reproduced with permission from Cholewicki J, Silfies SP, Shah RA, et al: Delayed trunk muscle reflex responses increase the risk of low back injuries. *Spine* 2005;30:2614-2620.)

Figure 4

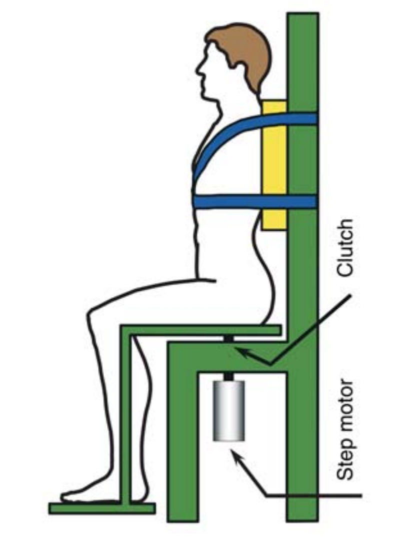

Illustration of an apparatus for testing core proprioception in the transverse plane. Subjects were positioned on this apparatus so that the vertical pivot axis extended through the L4-L5 vertebrae. Subjects were rotated 20° away from the neutral spine posture (2 deg/s) and briefly held in that position for 3 seconds. After the clutch was disengaged from the motor drive, the subject rotated himself or herself and stopped the apparatus by pressing a switch when he or she perceived being back in the original, neutral position. (Reproduced with permission from Cholewicki J, Shah K, McGill KC: The effects of a three-week use of lumbosacral orthoses on proprioception in the lumbar spine. *J Orthop Sports Phys Ther* 2006;36:225-231.)

in average proprioceptive error, there was a 2.9-fold increase in the odds ratio of knee injury and a 3.3-fold increase in the odds ratio of ligament/meniscus injury. This proprioceptive measure predicted knee injury status with 90% sensitivity and 56% specificity in female athletes.[16]

These 277 collegiate athletes were also prospectively tested for trunk displacement following sudden force release (Figure 3). Angular trunk displacements that occurred 150 ms after the release and maximum displacements were measured and averaged across five trials in each direction. Trunk displacement was greater in athletes who later sustained knee, ligament, and anterior cruciate ligament (ACL) injuries during the follow-up period than in uninjured athletes. History of LBP was also a significant predictor of knee injury.[17] A logistical regression model, consisting of proprioception, trunk displacements, and history of LBP, predicted knee ligament injury with 91% sensitivity and 68% specificity. This model predicted knee, ligament, and ACL injury risk in female athletes with 84%, 89%, and 91% accuracy, respectively. History of LBP was the only significant predictor of knee ligament injury risk in male athletes. Thus, factors related to core stability predicted the risk of knee, ligament, and ACL injuries with high sensitivity and moderate specificity in female athletes.[17]

In a recent prospective study of more than 900 athletes, female athletes who subsequently suffered an ankle injury demonstrated greater medial-lateral body sway than did uninjured athletes.[18] In contrast, predictors of injury in male athletes were related to ankle range of motion, not measures of proprioception. This study corroborated the findings of Greene et al,[15] Cholewicki et al,[8] and Zazulak et al,[17] in that it also found history of prior injury to be a strong predictor of future injury along segments of the kinetic chain in both men and women, further suggesting the possibility of a preexisting neuromuscular deficit or one incurred from injury.

Using reproducible and precise laboratory measurement techniques, these prospective studies addressed trunk proprioception (observability),[16] trunk muscle reflex response (observability and information relay),[8] trunk displacement following perturbation (observability, information relay, and controllability),[17] and postural control (observability, information relay, and controllability).[18] The following findings from these studies provide valuable insight into the role of trunk neuromuscular control during athletic activity. (1) Delayed trunk muscle reflex response is predictive of back injury in males and females. (2) Poor trunk proprioception is predictive of knee injury in females. (3) Postural sway is predictive of ankle injury in females. (4) Trunk displacement following perturbation is predictive of knee injury in both females and males. (5) Prior injury predisposes athletes to future injury throughout segments of the kinetic chain in both males and females. (6) The combination of several factors related to trunk control provides a highly predictive model for both back and lower extremity injury in athletes. What then is the mechanism underpinning the relationship between control of the core and injuries to various segments of the kinetic chain?

A Possible Link Between Control and Injury

A simple exercise can be performed to aid in understanding the link between control and injury. The task involves balancing a broom in the palm of the hand (Figure 5, A). When the center of mass of the broom is directly under the base, the system is balanced (ie, in a state of equilibrium), and no corrective forces are required. When the broom starts to fall, the hand will move to catch it. The size and speed of the hand movements are related to the size and speed of broom displacement, with larger/faster broom displacement requiring larger/faster hand movements. Moreover, larger/faster hand displacements require greater forces to accelerate the hand. Broom balancing can be performed with the eyes open and closed. Vision provides additional feedback about the position of the broom, thus allowing for better control. With better control, less displacement occurs, and less force is required to maintain a stable system.

The broom balancing task also can be performed by holding the base of the broomstick with the hand (Figure 5, B). It is helpful to add a small weight to the top of the broom to increase the destabilizing mass. The upright position of the broom (ie, equilibrium) is maintained by exerting moment (ie, torque) to the base. This moment is proportional to the size and speed of broom displacement. When the mass added to the broom is sufficient to eventually produce fatigue in the forearm muscles, control becomes more difficult. With impairment in control, more displacement occurs, and more force is required to maintain stability. These simple exercises clearly illustrate the point that greater forces from segments acting on the broom are necessary to maintain system stability when the quality of proprioception or muscle force control is deteriorated.

The broom balancer example is analogous to the trunk and lower body segments (Figure 5). Impaired control of any segment will result in larger forces and/or displacements throughout the system. Impairment in trunk control requires that other segments (eg, lower extremities) exert higher forces and possibly undergo larger displacements to maintain stability. Greater forces and displacements transmitted through the kinetic chain (eg, lumbar spine, hip, knee, ankle) make the system susceptible to injury. Injury will likely occur at the weakest link, where the joint position is compromised or the forces are close to tissue failure (eg, the knee in Figure 6). Under static conditions (eg, standing), small control impairments may not result in any appreciable forces or displacements. However, under dynamic conditions (eg, jumping, landing, cutting), which magnify destabilizing forces acting on the system, these forces and displacements are likely to increase, rendering the system with compromised control more susceptible to injury.

Identifying Neuromuscular Control Deficits in Athletes

Trunk stability requires feedback control,[6] which demands muscle recruitment patterns that differ between athletes and between athletic tasks. The sudden release protocol offers insight into neuromuscular control and trunk stability through description of muscle activation patterns and measures of trunk displacement and stiffness[8,17] (Figure 3). The proprioception apparatus, as described by Taimela et al[7] and Cholewicki et al,[8] is useful in identifying deficits in active and passive position sense, and motion perception (Figure 4). Unfortunately, these apparatus are not readily available to clinicians and trainers for the identification of deficits in neuromuscular control in athletes. Instead, the clinician or trainer must rely on assessment of single-leg stance, postural sway on stabilometers, and visual observation of neuromuscular deficits through global movement abnormalities during athletic maneuvers (Figure 6, A). Clinical tests for the identification of spinal instability have yet to be validated in the context of motor control.[19,20]

Athletes with identified trunk neuromuscular deficits and those with a history of previous injury are candidates for neuromuscular control training. Ideally, problems in neuromuscular control of the core should be diagnosed based on observability, information relay, or controllability. In reality, such a determination often is not possible. Therefore, much of the neuromuscular training will challenge the entire feedback control system, with the goal of improving control through enhanced proprioception, reaction time, and functional strength.

Figure 5

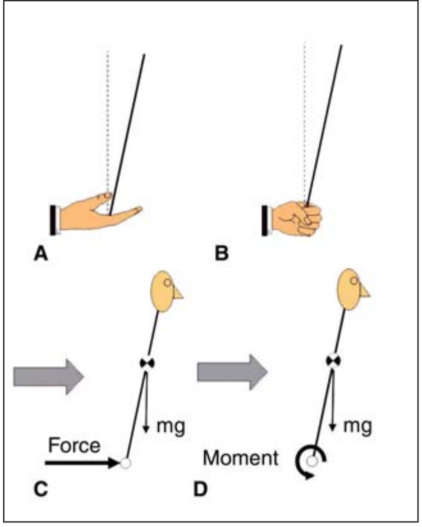

Illustration of the broom balancing task, which demonstrates a link between control and injury. **A,** When balancing the stick, the hand will have to move to catch it. **B,** Alternatively, stick balancing can be accomplished by exerting a moment at the base. The required force **(A)** or moment **(B)** is proportional to the size and speed of broom displacement. Similarly, greater forces **(C)** and moments **(D)** from segments acting on the trunk are necessary to maintain its stability when the quality of proprioception or muscle force control has deteriorated. mg = upper body mass

Neuromuscular Control Training

The human nervous system has considerable plasticity and potential for learning. Interventions may be developed to enhance neuromuscular control of trunk stability in order to reduce the risk of injury.[21-25] Strategies for neuromuscular control training include techniques to cognitively train deep intrinsic spinal musculature and to enhance sensory input from the trunk musculature. As a result of the findings from studies on trunk stability and muscle recruitment, neuromuscular control training has focused on first restoring control of the deep trunk musculature

Figure 6

Photograph **(A)**, illustration **(B)**, and schematic **(C)** demonstrating the vulnerability of the kinetic chain components in the presence of deficits in trunk neuromuscular control. Greater forces are exerted and larger displacements occur in an attempt to maintain the system's performance and stability. Injury will likely occur at the weakest link, where the joint position is compromised or the forces are close to tissue failure. In this instance, the knee may be the weakest link.

Figure 7

This jump-and-hold training drill challenges neuromuscular control as the athlete's trunk follows a trajectory of approximately 45° to a final held single-leg stance athletic position. The athletic position is a functionally stable position with the knee flexed, shoulders back, eyes up, and body mass balanced over the balls of the feet. (Reproduced with permission from Myer GD, Ford KR, Hewett TE: Rationale and clinical techniques for anterior cruciate ligament injury prevention among female athletes. *J Athl Train* 2004;39:352-364.)

before proceeding to functional activities and demanding situations. Recent evidence suggests that healthy persons subjected to sudden loading appear to select a natural muscular activation pattern appropriate to maintain trunk stability. Conscious, voluntary overdriving of this natural pattern results in impaired neuromuscular performance.[26,27] Thus, trunk stiffness that is not optimal for a given dynamic task (eg, too much or too little stiffness) will require larger motions and greater muscular forces to control the trunk.

Evidence indicates that, with training, reaction time and other neuromuscular control parameters may be enhanced in the trunk and lower extremity. The most extensive research in this area is in ACL injury prevention programs. Although specific trunk stability training in the prevention of this type of injury has not been well studied, the programs that incorporated trunk neuromuscular exercises appear to be effective.[28-30] The key components of these successful interventions include proprioceptive training and the plyometric jump-and-hold exercise, combined with sport-specific biomechanical analysis and technique training[31] (Figure 7). Balance and trunk control training using unstable surfaces (eg, wobble boards, roller boards, exercise balls) and pro-

Figure 8

A B C

A through **C,** Drills to enhance trunk neuromuscular control are performed on a balance device that provides an unstable surface while maintaining the athletic position. As the athlete improves, the training drills can incorporate ball catches, kicking, kneeling, and perturbation training to improve trunk neuromuscular control. (Panels A and B reproduced with permission from Myer GD, Ford KR, Hewett TE: Rationale and clinical techniques for anterior cruciate ligament injury prevention among female athletes. *J Athl Train* 2004;39:352-364.)

prioceptive activities (eg, single-leg stance) are components of these effective interventions (Figure 8).

Improvements in performance may be gained by incorporating perturbations of various sizes on unstable surfaces.[32] An additional component of effective interventions is plyometric training, which trains the neuromuscular system to quickly and effectively carry out the stretch-shortening cycle and focuses on proper technique and body mechanics (Figure 9). Such an approach addresses observability, information relay, and controllability requirements for maintaining stability of the entire system. Stable balancing during athletic maneuvers (Figure 7) demands effective control of all joints in the kinetic chain, including the trunk. Conversely, deficits in any of the control aspects (observability, information relay, controllability), even at a single joint, will result in decreased performance or, in the extreme case, loss of stability. In the context of athletic performance, such deficits may result in injury to any of the joints in the entire kinetic chain.

Clinical Implications

Neuromuscular control training for athletes has traditionally focused on resistance exercises for trunk musculature. It is important for the trunk musculature, as the actuator or effector of the system, to satisfy the demands of athletic tasks with sufficient strength. However, these exercises not only induce potentially injurious loads to the spine but are also nonfunctional in that they do not consider the role of the controller to satisfy the demands of internal and external forces of athletic maneuvers. Therefore, injury prevention programs should emphasize a dual focus of muscle capacity and neuromuscular control.[33] Athletes with trunk neuromuscular deficits should be targeted for retraining to restore normal movement control.

Summary

Impaired trunk neuromuscular control appears to increase the risk of back and lower extremity injury in athletes. Athletes may be evaluated

Figure 9

Broad jumps further challenge trunk neuromuscular control when the horizontal momentum of the trunk is quickly transformed into vertical momentum and the trajectory of the trunk is redirected. (Reproduced with permission from Myer GD, Ford KR, Hewett TE: Rationale and clinical techniques for anterior cruciate ligament injury prevention among female athletes. *J Athl Train* 2004;39:352-364.)

for control deficits of the trunk before competition and targeted for specific active neuromuscular training. The implementation of interventions that incorporate trunk neuromuscular training, including proprioceptive exercise, perturbation, and correction of body sway, has the potential to reduce the risk of injury in the athlete. The reliability of clinical assessment of these biomechanical parameters must be established to identify athletes who are at increased risk of injury. Future research should focus on well-controlled, prospective longitudinal studies of defined populations of athletes followed through multiple sports seasons to correlate changing trunk neuromuscular control parameters (eg, trunk proprioception, trunk muscle reflex latencies, trunk displacement response to perturbations, postural sway) to injury risk.

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