Integrative Neuromuscular Training and Injury Prevention in Youth Athletes. Part I: Identifying Risk Factors

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ABSTRACT

PART I OF THIS REVIEW DESCRIBES THE MOST IMPORTANT NEUROMUSCULAR SPORTS INJURY RISK FACTORS IN YOUTH ATHLETES: MUSCLE FATIGUE, ALTERED TIMING AND MAGNITUDE OF MUSCLE ACTIVATION, STRENGTH DEFICITS, PREDOMINANCE OF FRONTAL PLANE CONTROL STRATEGIES, NEUROMUSCULAR IMBALANCES BETWEEN LIMBS, INADEQUATE MUSCLE STIFFNESS, DEFICITS IN POSTURAL STABILITY, ALTERED PROPRIOCEPTION, AND FEED-FORWARD CONTROL. THE SECOND PART OF THIS REVIEW PROVIDES A FLEXIBLE APPROACH TO INTEGRATIVE NEUROMUSCULAR TRAINING WITH THE GOAL TO IMPROVE INJURY RESILIENCE AND TO ENHANCE SPORT AND MOTOR SKILL PERFORMANCE.

INJURIES IN YOUTH ATHLETES

Recent data indicate that approximately 8.2 million youths between the ages 6–12 participate in organized sport in the United States (112). However, recent data indicate that participation in organized sports activities does not ensure that youth meet physical activity (PA) recommendations (59,93). This high participation in youth sports has an inherent risk of injury (4). Many injuries in youth result from traumatic incidents; however, 30–50% of injuries are estimated to result from overuse during sport participation (96). Thus, it may be important to emphasize the correct development and training of sport skills to improve participation outcomes in youth, as the development and execution of incorrect motor patterns during sports activities may increase the potential risk of sport injury (74).

Relative to adults, the rate of sport injury in youth athletes is lower (10), but consequences are more adverse; therefore, sports injuries in youth can become a barrier to long-term PA throughout the lifespan (15,24). Inadequate PA, in turn, is associated with high morbidity and long-term disability (112,119), and injuries that disrupt PA represent a considerable social and economic burden (19). Furthermore,
previous injury in youth may result in a loss of enthusiasm for PA stemming from fear of injury or reinjury (10,29). For example, an investigation into the risk factors associated with injuries that resulted from physical education, leisure time PA, and sports participation in 9–12 year olds indicated that gender, age, and, most importantly, previous level of PA were all significantly related to injury. Thus, the researchers concluded that PA promotion efforts should include a focus on injury prevention (10).

Given the negative effects of injury in youth both acutely and throughout the lifespan, injury prevention strategies should be implemented early to avoid negative consequences. Sports injuries in youth athletes have been associated with growth and development (48,85), low levels of physical fitness (10), inadequate physical preparation (56), diminished motor abilities (1), and deficits in fundamental movement skills (77). Therefore, optimal levels of physical conditioning and neuromuscular coordination are important factors to address in youth athletes, especially in situational or team sports (89,91,110). Moreover, some of the most modifiable risk factors in youth athletes are abnormal movement patterns (e.g., dynamic valgus of the knee during landing maneuvers) during execution of sport skills (81). Deviations from desirable movement patterns are usually associated with deficits in neuromuscular control strategies (Figure 1). Current research indicates that neuromuscular risk factors associated with sports-related injuries can be modified through effective integrative neuromuscular training (INT) programs to directly reduce the incidence of injury in young athletes (6,25,78). INT entails a training program that incorporates general and specific strength and conditioning tasks with the goals of improving injury resilience and enhancing sport and motor performance skills (77).

Although there is no consensus regarding optimal neuromuscular training programs, evidence supports the use of such programs to prevent injury (113–116). This review of neuromuscular risk factors in youth athletes may provide a flexible approach to optimize the design of INT programs. This article is Part I of a two-part review. Part I aims to synthesize the latest literature with regard to neuromuscular risk factors for injury to optimize targeted INT programs in the youth sports population. Part II aims to provide practical applications for coaches to implement INT to reduce injury risk and improve performance in the youth sports population.

**INTEGRATIVE NEUROMUSCULAR TRAINING TO REDUCE RISK OF INJURY IN YOUTH ATHLETES**

Research indicates that neuromuscular and biomechanical risk factors can be modified by INT programs (52,82,84,90). These programs have been shown to directly reduce the incidence of injury in athletes (41,52). In addition, there is an established age-related association between INT program implementation and reduction in anterior cruciate ligament (ACL) injuries (86). This association indicates that the effects of puberty on the neuromuscular system can be mitigated. Puberty is characterized by major musculoskeletal developments that usually are not accompanied with sufficient corresponding neuromuscular adaptation, and this may result in the development of abnormal mechanics during sport actions (49,103,121). Consequently, it may be optimal to initiate INT programs in the pubescent athlete to establish movement patterns that can limit the development of motor deficits that may result from puberty.

Neuromuscular control during sport actions depends on the proper functioning of the sensorimotor system. This complex system incorporates afferent and efferent nervous system signals, as well as central integration and processing components involved in maintaining dynamic joint stability (104). Although definitions vary (49,103), this review will operationally define neuromuscular control as the precise muscle activation that allows for a coordinated and efficient action (37). Figure 2 provides a schema depicting the relationship between training, the sensorimotor system, joint stability, and neuromuscular control, and the effect of each on injury risk. An improvement in the sensorimotor system through task-specific training leads to increased neuromuscular control, which can then improve dynamic joint stability during intense sports maneuvers. The concomitant improvements in neuromuscular control and dynamic joint stability can decrease the risk of injury.

**ANALYSES OF NEUROMUSCULAR INJURY RISK FACTORS IN YOUTH ATHLETES**

As previously mentioned, the optimization of INT programs in youth athletes arises from the knowledge of mechanisms by which neuromuscular risk factors underlie subsequent sports injuries. This review will focus on the most commonly injured areas of the body in youth athletes: the ankle and the knee (1). The current literature emphasizes the following neuromuscular risk factors of injury (36): muscle fatigue (11,67), altered timing and magnitude of muscle activation (31,70,126), strength deficits (38,42,100), predominance of frontal plane control strategies (dynamic valgus) (5,68), neuromuscular imbalances between limbs (16,76), inadequate muscle stiffness (39), deficits in postural stability (99), altered proprioception (105), and feedforward control (9) (Figure 1). Table 1 provides an overview of INT strategies that can be used to target neuromuscular risk factors in youth athletes.

**MUSCLE FATIGUE**

Muscle fatigue is defined as a progressive decrease of maximal force and power capacity of muscles, which means that submaximal contractions can be sustained after the onset of muscle fatigue (26). Fatigue is associated with changes in neuromuscular control strategies during sport tasks and decreases in dynamic joint stability in lower limbs (11,18,67). Moreover, fatigue is
associated with reduced coordination, altered proprioception, and changes in lower limb biomechanics, such as decreased knee and hip flexion, increased dynamic valgus at the knee, increased ground reaction forces, and increased time to joint stabilization (12,17,33,109). Decreased neuromuscular control resulting from fatigue is associated with an increase in risk factors for sports injuries such as ACL ruptures (12,17) and ankle sprains (33). Importantly, different sexes respond to neuromuscular fatigue in different ways (55). Female athletes suffer greater consequences related to injuries compared with male athletes (46), so sex is important to consider when creating INT programs. High-intensity training of neuromuscular tasks is likely important, especially under conditions of fatigue, to mimic sport conditions and train the neuromuscular system to perform in a safe and efficient manner while fatigued.

One final consideration for training youth athletes is their capacity to resist muscle fatigue and their ability to recover during high-intensity

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**Figure 1.** Relationship between altered kinematics and neuromuscular risk factors (adapted with permission from Fort-Vanmeerhaeghe and Romero-Rodriguez, 2013).
intermittent exercise (23,101). Pre-pubescent children are able to resist acute fatigue better than adolescents and adults during one or several repeated high-intensity exercise bouts (101). Although the exact mechanism is not known, it is possible that because children have less muscle mass than adults, they generate lower absolute power during high-intensity exercise. In addition, there is a significant interaction between maturity and sex on fatigue resistance during high-intensity intermittent exercise after the onset of puberty. Adolescent males have greater fatigue resistance than adult males, whereas no differences between adolescent females (mid puberty 14–15 years) and adult females (23) have been found. Therefore, youth may be able to perform with greater levels of neuromuscular control when in a fatigued state compared with adults in an INT program. However, youth may need longer recovery periods than adults to ensure that adequate motor control strategies are used during training in high fatigue conditions. It is also important to note that, while children can resist acute fatigue to a greater extent compared with adults, we do not yet fully understand the potential risks of accumulated fatigue in youth.

**ALTERED TIMING AND MAGNITUDE OF MUSCLE ACTIVATION**

Alterations in muscle activation capacity during sport-specific tasks may increase the risk of injury (20,42,70). Alterations in muscle activation capacity refer to the changes in intensity of muscle activation and in time to reach the maximal activation. Investigations carried out mainly using electromyography indicate the following associations between injury risk factors and specific injuries:

**Delay in reaction time of peroneal muscles.** Although there is a lack of consensus in the scientific literature, functional ankle instability (FAI) has been associated with increased peroneal reaction time (61,70,71). A recent review evaluated whether peroneal reaction time was influenced relative to an injured or previously injured ankle (70). The authors showed a significant delay in the reaction time of peroneal muscles in the injured ankles. Conversely, another recent review studied the sensorimotor deficits associated with FAI and concluded that peroneal reaction time was not affected in FAI ankles compared with healthy ankles (71). However, the authors associated FAI with deficits in postural control and ankle joint position sense.

**Muscle activation imbalances between medial and lateral sides of the quadriceps and hamstrings.** Imbalances between the medial and lateral parts of a muscle have been described as risk factors for injury, especially in both the quadriceps (27,83) and hamstrings (106). Investigations into the activation pattern of the quadriceps in a high-risk movement pattern known to result in ACL injury in both sexes indicated that females activate a higher proportion of the lateral side of the quadriceps muscle compared with males, which may contribute to dynamic knee valgus and facilitate ACL tear (83). Moreover, this injury mechanism is compounded by predominance in activation of the lateral part of the hamstrings (106). With regard to patellofemoral pain syndrome, early evidence indicates that a lower magnitude and longer activation of the vastus medialis as compared with the vastus lateralis is associated with a higher incidence of this condition (20,27).

**Diminished muscle coactivation between agonist and antagonist muscles.** Compared with agonistic
activation in isolation, the coactivation of agonist and antagonist muscles has been associated with joint stabilization and the reduction of ligament loading due to increased joint stiffness (60). Diminished coactivation between quadriceps and hamstrings has been related to risk factors associated with ACL injuries (32,47). Moreover, the coactivation of these 2 muscles during cutting, landing, or deceleration not only provides knee joint stability but also protects from excessive anterior tibial displacement and dynamic knee valgus (32,47,60). However, current literature also emphasizes the importance of coactivation for both the transverse abdominis and multifidus muscles during functional tasks for the prevention and treatment of low-back pain (63).

**Decreased hip muscle activation.** Decreased hip muscle activation has been associated with risk factors related to ACL rupture (127) and concurrent patellofemoral pain syndrome (123). Research suggests that the decreased hip muscle activity and increased quadriceps activity exhibited by females compared with males during single-leg landings may be an important contributor to the increased susceptibility of female athletes to noncontact ACL injuries (45,127). Despite limited data about the relationship between hip muscle activation in fatigue conditions, Patrek (97) observed that gluteus medius activation did not decrease when fatigue occurred during single-leg landing. However, the activation of this muscle delayed after the protocol. Related to this last point, and from an injury standpoint, the timing of activation is more relevant than the magnitude of the activation (22). Conversely, females with patellofemoral pain have demonstrated delayed and shorter gluteus medius activation compared with females without knee pain during running (123).

**Deficits in trunk stability and muscle activation.** In the past, deficits of the

### Table 1

<table>
<thead>
<tr>
<th>Potential neuromuscular risk factors in youth</th>
<th>Neuromuscular training focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscle fatigue</td>
<td>Strength and power muscle endurance</td>
</tr>
<tr>
<td>Altered timing and magnitude of muscle activation</td>
<td>Strength/power (plyometric)</td>
</tr>
<tr>
<td>Diminished muscle coactivation between agonist and antagonist muscles</td>
<td>Awareness muscle activation exercises</td>
</tr>
<tr>
<td>Decreased hip muscle activation</td>
<td></td>
</tr>
<tr>
<td>Strength weakness</td>
<td>Agonist/antagonist strength balance</td>
</tr>
<tr>
<td>Overload eccentric training</td>
<td></td>
</tr>
<tr>
<td>Frontal plane knee control: dynamic valgus</td>
<td>Good technique (low limb alignment with trunk-hip-knee-ankle flexion) during landings, change of directions, and deceleration actions</td>
</tr>
<tr>
<td>Neuromuscular imbalances between limbs</td>
<td>Symmetry technique in bilateral tasks</td>
</tr>
<tr>
<td>Inadequate muscle stiffness</td>
<td>Strength</td>
</tr>
<tr>
<td>Deficits in postural stability</td>
<td>Balance → dynamic stabilization</td>
</tr>
<tr>
<td>Altered proprioception</td>
<td>Fundamental movement skills</td>
</tr>
<tr>
<td>Feed-forward mechanism</td>
<td>Training with unexpected actions</td>
</tr>
<tr>
<td>Task variability</td>
<td></td>
</tr>
<tr>
<td>Agility open tasks</td>
<td></td>
</tr>
<tr>
<td>Coordination abilities</td>
<td></td>
</tr>
</tbody>
</table>

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sensorimotor system in the body’s core (spine, hips, and pelvis) have been associated with an increase in lower limb injury (73,126). Alterations in the neuromuscular control of the trunk have been associated with increased knee valgus, and this puts the knee joint at risk for injury because of transmission of higher loads (73). Similarly, Zazulak et al. observed that decreased proprioception and neuromuscular control of the trunk could predict an increased risk of knee injuries in females, but not in males. Moreover, this sex difference is related to the aforementioned higher deficits in neuromuscular control described in females when compared with males (126). It has also been suggested that deficits in the activation of hip and trunk muscles associated with pubertal age may increase injury risk (73). As previously mentioned, the pubertal age group is especially vulnerable to neuromuscular deficits (86).

**STRENGTH DEFICITS**

Dynamic joint stability depends on passive (ligaments and articular geometry) and active (muscles and neuromuscular control) restraints of the joint. When active restraints are compromised, there may be an increased risk of injury (111). A lack of muscular strength may lead to poor neuromuscular control, which is a precursor to injury. Research indicates that strength deficits may be related to both acute (e.g., ACL rupture or hamstring strains) and chronic (e.g., patellofemoral pain) lower limb sports injuries (43–58).

Previous research indicates that strength deficits are related to both antagonist/agonist and contralateral strength imbalances. Despite the abundance of literature on strength imbalances around the knee, evidence regarding their contribution to ACL and hamstring injuries remains inconclusive (2,44,92). Research indicates that a hamstring-to-quadriceps ratio lower than 60% can predispose an athlete to ACL injury (44,80). Lower levels of hamstring strength compared with quadriceps strength during landing and cutting maneuvers increases anterior shear stress on the tibia, which increases the load on the ACL. Another major risk factor for ACL injury is strength asymmetries between limbs (47,88,94). Research shows that bilateral differences of 15% or more in concentric and/or eccentric actions of the hamstrings increases the risk of injury to these muscles (21). Similarly, a concentric hamstrings/quadriceps strength ratio (on at least one leg) of less than 0.47–0.45 and a mixed ratio of eccentric hamstring/concentric quadriceps strength ratio lower than 0.80–0.89 (measured by an isokinetic device) also increase the risk of hamstring injury in soccer players (21). However, it is important to mention that, in addition to imbalances, both absolute and relative strength should be considered (122). An appropriate hamstring/quadriceps ratio is irrelevant if the athlete displays inferior strength. Conversely, gaining absolute strength without the development of antagonistic muscle action may further propagate imbalances that increase inherent risk factors (80).

In addition to such deficits, it is important to note that there is a possibility that decreased eccentric muscle strength may lead to injury. This assertion is supported by research that connects eccentric strength deficits in the quadriceps muscle to tendinopathies in athletes (102). The forces necessary to resist knee extension and start hip extension during maximal sprints could surpass the tolerance of the muscle-tendon unit when these ratios of strength are not achieved because of hamstring strength deficits (3). The previously reported threshold for the critical difference between legs is 10–15% measured using isokinetic strength and vertical jump data (50,62,72,88,95). Although knee strength deficits are critical, it is also important to note the relationship between hip muscle strength deficits and sports injury. Deficits in strength combined with hip abduction, hip external rotation, and hip extension are risk factors associated with patellofemoral pain syndrome (97), ACL injury (53), and iliotibial band syndrome (38). Furthermore, the achievement of an eccentric hip adduction/abduction strength ratio of more than 90% has been suggested to play an important role in the treatment and prevention of groin injuries in soccer players (117).

Finally, deficits in power have also been associated with an increased rate of injury (124). Low levels of power may underlie increased electromechanical delay, and this causes a decrease in muscle reaction speed in the context of sports actions.

**FRONTAL PLANE KNEE CONTROL: DYNAMIC VALGUS**

Altered knee joint biomechanics, especially those that lead to lack of control strategies in the frontal plane of the knee during landing, cutting, and deceleration, are considered major risk factors for knee injuries, including ACL rupture (47,95) and patellofemoral pain (75,79). The implications of biomechanical abnormalities in the knee differ depending on sex. Female athletes exhibit a 4-fold to 6-fold increase in incidence of ACL injuries over male athletes (46). Other research on male and female youth athletes (11–19 years old) has demonstrated a predominant dynamic knee valgus during actions at high risk for injury, including landing (5,87,108). However, it is important to isolate the relationship between dynamic valgus and age. In the prepubescent population, the number of injuries may be lower because younger athletes have less body mass, shorter joint lever arms and do not generate as much power, and, therefore, do not exhibit such dynamic valgus load as their more mature counterparts. As a result, sport actions are developed at a lower power in younger athletes than in older athletes. This may account for the lower rate of injury in younger athletes (10,120) and reaffirms the notion that INT programs should be initiated during...
prepubescence to establish proper technique before athletes begin to generate enough power to increase their risk of injury (85).

**NEUROMUSCULAR IMBALANCES BETWEEN LIMBS**

Neuromuscular asymmetry of the lower limbs is associated with injury and can be used as a predictive tool to detect athletes who may be at risk for injury or reinjury (94,107). Although lower limb asymmetries are normal in healthy athletes, research suggests that a difference in strength and power greater than 10–15% between legs is the threshold to consider for increased risk of injury (50,62,72,88,95). Similarly, it has been shown that differences between limbs of <15% in the single-leg vertical jump should be considered as the physiological norm in youth (16,35). It is important to note that lower limb asymmetries in strength, coordination, and postural control are more common in female athletes than male athletes, especially during adolescence (30,34,76). Testing procedures to identify and track neuromuscular asymmetries should be implemented to detect at-risk athletes, and INT programs can help guide corrective strategies to address asymmetries and potentially reduce the risk of injury.

**INADEQUATE MUSCLE STIFFNESS**

Muscle stiffness, defined as a muscle’s ability to resist lengthening and contrary to compliance (26), is essential for both the maintenance of joint stability (40) and the ability to generate power (14). To better understand this concept, it is important to differentiate between active and passive stiffness (40). At low applied loads, the passive structures of the joint (e.g., ligaments, capsules) provide enough stability. However, during sport activities, joint forces go beyond the stabilizing capacity of the joint capsule and ligaments and muscles are recruited to stabilize the joint (39). Active muscle stiffness is considered an essential component of joint stability during functional and sporting activities, preventing against musculoskeletal injuries (111). Moreover, active muscle stiffness is related to active joint stiffness, which can be voluntarily controlled through muscle recruitment (40).

The relationship between active stiffness and injury is still unclear because of a lack of research (14). There is some evidence to suggest that there is an “optimal” amount of stiffness. Low levels of stiffness have been associated with soft tissue injuries (40). However, too much stiffness may be related to high levels of peak forces and loading rates, which can be associated to bony injuries (14). In terms of performance, an athlete with greater muscle stiffness in the lower extremity more efficiently uses and reuses stored elastic energy during stretch-shortening cycle exercises (jumping, running, and hopping) (13).

Recent evidence demonstrates that females have reduced muscle stiffness compared with males of the same age (125). Power and strength training are needed to improve motor unit recruitment and, consequently, to improve muscle stiffness (69). To further improve muscular stiffness, neuromuscular training for youth should emphasize explosive power and eccentric loading.

In addition, muscle stiffness depends on maturation/developmental status. As previously mentioned, puberty is accompanied by hormonal changes, which lead to an increase in muscle stiffness, especially in men (98). In this case, concomitant training methods to improve muscle stiffness and compliance should be applied (13).

**DEFICITS IN POSTURAL STABILITY**

Postural stability, also known as dynamic balance, is dependent on the integration of perceptual information and neuromuscular control strategies to regulate the stability of the body’s center of mass during dynamic tasks (103,104). Currently, the relationship between balance and risk of lower extremity injury is unclear. Although some research indicates that there is no relationship between the 2 (7,66), most research has found significant correlations between deficits in postural stability and injury incidence (64,99,118), especially in individuals with history of injury (66,95). The high variability of methods used to assess postural stability could partially explain the contrasting results in existing research.

In youth athletes, an individual’s inability to control and maintain postural stability during static and dynamic tasks has been associated with risk of injury and reinjury, especially in the ankle (64,99) and knee (95,99). Plisky (99) showed that high school players with a greater balance capacity (a superior score in anterior and lateral distances performing the star excursion balance test) were 2.5 times less likely to sustain a lower limb injury. This finding demonstrates the importance of incorporating balance training into strength and conditioning programs in youth athletes.

**ALTERED PROPORCIPITION**

The proprioceptive system is a part of the sensorimotor system that incorporates afferent and efferent signals and serves as a conduit for the integration of sensorimotor control during the maintenance of functional joint stability (103). Although visual and vestibular input contributes to the performance of athletic actions, the peripheral mechanoreceptors are typically influenced most by injury and are thus the most modifiable from a training perspective (49). There is currently no consensus on the exact definition of proprioception in the literature (49,103,105). For the purposes of this review, we will define proprioception as the type of sensorimotor sensitivity that contributes to the maintenance of dynamic joint stability, achieved by the detection of pressure, tension, and length variations of the different muscles and articular tissues (37).

Diminished proprioception has been associated with abnormal biomechanics, which, in turn, predispose
athletes to injury. Diminished proprioception has been shown to be a risk factor for many injuries, including ACL ruptures (46,126), patellofemoral pain syndrome (4), and chronic ankle instability (65). In addition, impaired proprioception in previously injured joints predisposes athletes to reinjury (95,99). To ensure the establishment of proper technique and to decrease the risk of injury in youth athletes, proprioception training should be the first step in the implementation of INT programs. A strong base in proprioception will provide the foundation to progress athletes to more challenging, intense, and sport-specific actions. Proprioception training will be a prominent point of discussion in part II of this commentary.

FEED-FORWARD MECHANISMS
The dynamic stabilization of the joints during sport activities depends on both feedback (reflex response) and feed-forward (preactivation or anticipation) neuromuscular control mechanisms (8,9,103,104). Feedback control is characterized by a continual processing of afferent information, which provides a reflexive muscle response on a moment-to-moment basis (103). During sport activities, especially in team or situational sports where the context is continuously changing, feedback control plays a limited role in injury prevention. Although less understood as a process for injury prevention in fast-paced situations, feedback control is necessary for maintaining posture and protecting joints during slower, more predictable actions (37).

Conversely, feed-forward (i.e., prospective) control has been described as anticipatory actions taken before sensory detection of a homeostatic disruption (103). That is, muscle preactivation has the ability to protect joint structures from a potentially injurious load. This neuromuscular control mechanism depends on previous movement experiences, previous exposures to external stressors, and learned perceptual-motor relationships (28). The continuous information provided via the feed-forward mechanism facilitates the motor learning process and provides an opportunity to make adjustments to avoid injury.

Although feedback control is related to mechanoreceptor detection of altered support surface, feed-forward control is related to anticipatory actions from previous experience and learned relationships between the athlete and the environment (28,103). This indicates that the feed-forward control allows for the necessary activation of the muscles stabilizing joints during the preparatory phase of movements before potential injury. For this reason, feed-forward is considered as the most important factor in maintaining dynamic stabilization during landing, deceleration, and cutting movements (9,51,103).

Current research emphasizes the importance of unanticipated movements that function to prompt the maintenance of appropriate biomechanics during the execution of high-risk tasks that may cause injury, including landing and cutting maneuvers (8,51,57). Cutting maneuvers performed without adequate planning (unanticipated actions) increase risk factors for noncontact knee ligament injury compared with predetermined actions (7,9). These risk factors include increased external varus/valgus and internal/external rotation torques applied to the knee. In addition, Ford et al. (31) showed greater altered kinematics in female adolescent athletes compared with similar male athletes and suggested that differences in kinematics may contribute to the greater rate of ACL injury documented in female athletes. Other research on unanticipated actions has shown that the inclusion of an opponent during cutting and landing actions increased the mechanical load in the knee (57,68). Furthermore, research indicates that feedback control of peroneus muscles is not affected in the presence of chronic ankle instability, indicating that the burden of negative effects falls mainly on feed-forward control (51). Consequently, when designing INT programs, it is essential to progress to unanticipated and opposed tasks to train the feed-forward system, especially in youth athletes because of their high neural plasticity (11).

CONCLUSIONS
This review of the risk factors provides important background information that is needed to design neuromuscular tasks that can be adapted to each athlete and sport, which will be useful to coaches, strength and conditioning professionals, and physiotherapists. Research indicates that neuromuscular risk factors can be modified through INT programs. Although the optimal training methods adapted from each specific population are untested, evidence exists to support the implementation of interventions to prevent, treat, or return youth athletes to sport after certain lower limb injuries. When implementing an INT program for youth athletes, it is important to progress exercises in intensity and difficulty while maintaining an emphasis on the correct lower limb biomechanics to minimize joint loads during sport-specific actions. During INT development, it is important for individuals creating INT programs to select appropriate tasks for each athlete and to provide constant feedback about how the athlete is executing each exercise. Finally, the current evidence indicates that prescreening with valid and reliable tests can help identify neuromuscular risk factors that will benefit from targeted training and can help optimize the efficiency and effectiveness of INT programs in youth.

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Integrative Neuromuscular Training in Youth

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