Integrative Neuromuscular Training in Youth Athletes. Part II: Strategies to Prevent Injuries and Improve Performance

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ABSTRACT

THE SECOND PART OF THIS REVIEW PROVIDES A FLEXIBLE APPROACH TO INTEGRATIVE NEUROMUSCULAR TRAINING (INT) WITH THE GOALS TO IMPROVE INJURY RESILIENCE AND TO ENHANCE SPORT AND MOTOR PERFORMANCE ABILITIES IN YOUTH POPULATIONS. THE PROPOSED MODEL OF INT IN THIS MANUSCRIPT PRESENTS 6 ESSENTIAL COMPONENTS: DYNAMIC STABILITY (LOWER LIMB AND CORE), STRENGTH, PLYOMETRICS, COORDINATION, SPEED AND AGILITY, AND FATIGUE RESISTANCE. THE DEVELOPMENT OF THESE 6 CAPACITIES ARE INTEGRAL IN ESTABLISHING AN IMPORTANT FOUNDATION BY INITIALLY DEVELOPING FUNDAMENTAL MOVEMENT SKILL COMPETENCY BEFORE BUILDING UPON THESE SKILLS TO ENRICH SPORTS-SPECIFIC AND ACTIVITY-SPECIFIC SKILL SETS. FOR A VIDEO ABSTRACT OF THIS ARTICLE, SEE SUPPLEMENTAL DIGITAL CONTENT 1 (SEE VIDEO, http://links.lww.com/SCJ/A190).

INTRODUCTION

As presented in part I, 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 (81,84,87). For the purpose of this article, the terms youth and young athletes refer to both children (Tanner stages 1 and 2 of sexual maturation; 10–12 years) and adolescents (Tanner stages 3 and 4 of sexual maturation; 13–18 years) (83). Youth fitness and motor abilities vary directly with maturational status. Some authors suggest that there exists a critical “window of opportunity” during the developmental years, whereby...
youth are more sensitive to training-induced adaptation (3,63). The central nervous system experiences a massive increase in myelination in the first 2–5 years of life, and this process is not concluded until sexual maturation or even adulthood (11,56,107). Given this information, training that promotes neural adaptations may be beneficial, especially before puberty and continued through the important adolescent years.

INT is defined as a conceptual training program that incorporates general (e.g., fundamental movements) and specific strength and conditioning tasks (e.g., resistance, balance, agility, plyometric) with the goal to improve injury resilience and to enhance sporting and motor skill performance (79,80). This training intervention model also intends to develop athletes’ perceptual and cognitive abilities during sporting situations to achieve a more integrative perspective of sport performance and injury prevention. Practitioners are encouraged to adopt an INT approach as an effective strategy to counter the current trend of young athletes placing greater emphasis on success in specific organized competition rather than developing optimal movement strategies and skills related to long-term injury resilience. Although INT emphasizes injury prevention training, physical adaptations from training also account for heightened sport performance skills and abilities (27,38,82). Performance improvement will generally be the primary motivation of young athletes to train over injury prevention goals (60).

INT programs promote prevention of acute injuries that result from complex sport actions (55). Previous evidence indicates that reduction in acute injuries should entail the following steps (a) identifying athletes’ specific neuromuscular deficiencies and (b) incorporating targeted exercises to promote physiological adaptations to improve neuromuscular control and coordination skills associated with the identified deficiencies (48,50). For instance, INT interventions that generate heightened coordination abilities may also result in beneficial structural adaptations of muscle and tendon structures, reducing the risk of overuse injuries (91).

The majority of studies in youth examining neuromuscular training strategies to improve performance and injury prevention include multiple components (e.g., balance, strength, plyometrics, agility, speed, coordination) (30,84). Thus, it is difficult to assess the contribution of each component. Based on the scientific evidence and the experience of the authors, this review classified INT programs in youth in 6 essential components: dynamic stabilization, coordination, strength, plyometrics, speed/agility, and fatigue resistance (Figure 1). These 6 components are integrated across the long-term athlete development model, which is an accumulation of various seasons, practices, and training sessions. Moreover, evolving communication with sport coaches can optimize development by reducing unnecessary repetition that leads to training inefficiencies and overtraining.
INT should first lay an essential foundation by developing fundamental movement skills (FMS). FMS are elementary units of movement and are commonly categorized as locomotor (e.g., running, jumping, hopping), manipulation or object control (e.g., catching and throwing), and stability skills (e.g., balancing and twisting) (42). These skills lay a necessary foundation for more complex activities including sport-specific movements (e.g., tennis serve, golf swing, basketball dribbling). Physical activity in youth contributes to increased energy expenditure, but more importantly, creates a repository of FMS also known as fundamental movement competence (FMC) (89). Children who are not exposed to activities with opportunities to enhance FMC tend to be less active during adolescence, which may manifest into sedentary lifestyle habits during adulthood (48,50,55). FMC enables youth to achieve specialized movement sequences required for participation in many organized and nonorganized physical activities (6). Thus, one can infer that there is an interdependent relationship between FMC and physical activity. FMC also facilitates physical ability and reduces the risk of activity-related injury (101). As children and adolescents grow, they require a greater range of FMS to perform more complex and demanding physical activities such as competitive sports participation. It is essential to foster this relationship to maintain physical fitness and reduce risk for injury. INT should enable children to be confident and competent with FMS before progressing to more challenging and sport-specific skills (SSS) (Figure 1). After an individual demonstrates correct and robust performance of FMS, practitioners can build upon these skills by appropriately progressing to more complex, yet safe, neuromuscular training tasks (66). The age to develop FMS and SSS depends on ability to demonstrate precursor exercises of each child; the authors recommend that ideally FMS are first optimally developed in childhood and then refined during SSS development in adolescence (76). The present commentary is directed to practitioners working with young athletes to provide a flexible guide to implement INT concepts and guidelines to reduce the risk of sports-related injury and to promote performance improvements. The intention of this review is to present a methodology of INT programs to be adapted by professional instructors and practitioners for training athletes of all ages, sporting backgrounds, levels of ability, and previous training experience to reduce injury risk and enhance performance in their athletes.

**INTEGRATIVE NEUROMUSCULAR TRAINING RECOMMENDATIONS FOR YOUTH**

Neuromuscular training programs should be individually designed to consider a number of factors including level of maturation, training age, technical competency, individual neuromuscular deficits, practiced sport activities, sex, genetics, and motivation. Instruction and supervision by qualified practitioners are essential for safe, effective, and enjoyable INT participation by youth. It is critical that instruction and feedback are developmentally appropriate, enthusiastic, and consistent with an individual’s needs, goals, and abilities (79). It is also valuable to ensure an individual’s mastery of movement technique in fundamentals before progressing to more intense exercise variations and derivatives. In other words, an athlete should not be progressed in exercise intensity based on time in a program nor the performance of their peers, but solely on their own technical ability. Thus, training progressions are limited by the ability of an individual to first demonstrate sound, consistent technique of precursor exercises. For example, fundamental movement skills are necessary before performing high impact actions such as the drop vertical jump (a plyometric that involves a drop from a box, immediately followed by a maximal vertical jump). This exercise has been suggested as an excellent plyometric activity to improve power and technique to reduce injury incidence in youth (88). If fundamental landing competency is not first acquired for lower level exercises (e.g., squat jump, hopping), athletes should not be instructed to perform a more advanced exercise such as the drop vertical jump. As a consequence of performing higher-level tasks too early, the task may elicit incorrect movement strategies (e.g., dynamic valgus during landing), leading to a potentially harmful absorption of impact force with a related higher risk for injury (4,86).

INT sessions are characterized by short bursts of physical activity interspersed with brief rest periods (80). Although the World Health Organization (WHO) recommends that youth should engage in 60 minutes or more of physical activity daily (112), it has been suggested that high-intensity INT should only be performed 2–3 times per week and on nonconsecutive days to allow for sufficient recovery time between training sessions (35,78). INT session duration can vary between 30 and 90 minutes, depending on individual characteristics and previous training experience. Nevertheless, for physical education, there is evidence that less time is effective as well (e.g., 15 minutes) (33). Although published INT interventions have demonstrated favorable outcomes in terms of injury prevention (84,88), it is still essential to program training periodization that considers the specific needs, limitations, and goals of an athlete.

**COMPONENTS OF INT FOR YOUTH**

The current review will focus on the 6 components (Figure 1) of INT to develop neuromuscular control with principal goals of improving sport performance and reducing sports-related injuries. The 6 components of INT include: dynamic stabilization (focusing on lower limb and core), coordination, strength, plyometrics, speed/agility, and fatigue-resistance (e.g., cardiorespiratory and repeated bout endurance). We present a flexible practical application guide of these components, with an initial focus on...
achieving fundamental movement skill competence as the basis of INT, then progressing to learn sports-specific skills in a safe and fun environment. INT should emphasize correct training methodology for FMS and SSS exercise progressions independently and also consider training that incorporates both general and specific skills that function simultaneously. For example, racquet sports movements, such as a backhand swing, require correct kinematics and kinetics of the lower extremities (24,100) and core stability (77) for optimal performance and injury resilience. In this case, optimal performance of this skill is especially dependent on the ability of one to execute an explosive upper body displacement while orienting the body in timely, correct positions to generate an optimal task outcome and to avoid injuries to the lower extremities and lower back (1,104). In INT, it is valuable to incorporate a variety of fundamental skills to optimize versatility and movement strategy decisions for a given sports-specific situation with various parameters (e.g., position of the ball, opponents, and teammates).

Table 1 indicates the principal methodological parameters to focus on in each of these 6 essential components.

### DYNAMIC STABILITY

Muscle pattern recruitment plays a critical role in joint stability, which depends on the coordination of sensorimotor strategies to stabilize the center of body mass and the joints around the body while performing dynamic tasks (93,94). For this component, we focus on (a) lower limb and (b) core dynamic stability training.

#### Lower limb dynamic stabilization

Current literature describes 3 categories of progression when training to improve dynamic joint stability: static balance, dynamic balance, and dynamic stabilization (44). Static balance is defined as the ability to maintain center of mass over a static base of support and stationary supporting surface (18). This ability is highly influenced by the correct function of sensory information obtained from the somatosensory (especially proprioception), visual, and vestibular systems (49). It is noteworthy that proprioceptive sensibility has been suggested to be the most modifiable by neuromuscular training (49,94). Secondly, dynamic balance is defined as the capacity to maintain center of mass over a fixed base of support under a challenge; specifically, motion of other limbs and

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<th>Table 1</th>
<th>Principal methodological parameters to develop the different components of INT programs</th>
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<td><strong>Content of INT programs</strong></td>
<td><strong>Methodological parameters for the creation of tasks</strong></td>
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<td>Dynamic stability</td>
<td>Balance training on stationary supporting surface and static base of support</td>
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<td>Lower limb dynamic stabilization</td>
<td>Balance training on stationary supporting surface under perturbations of different characteristics</td>
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<td>Core dynamic stability</td>
<td>Balance training that includes dynamic actions (SSS)</td>
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<td></td>
<td>Balance training on the knees (stimulus focused on trunk and hip muscle stabilizers by no bearing the weight directly on feet)</td>
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<tr>
<td>Coordination</td>
<td>Develop basic and specific skills (FMS and SSS)</td>
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<td></td>
<td>Variety of movements and multitasking</td>
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<td></td>
<td>Unanticipated reactions with sound technique</td>
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<tr>
<td>Strength</td>
<td>Develop appropriate strength capacity to perform FMS and SSS</td>
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<td></td>
<td>Functional overload</td>
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<tr>
<td>Plyometric training</td>
<td>Development of stretch shortening cycle ability, focusing on elastic energy, and reflexive muscle activity mechanisms</td>
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<tr>
<td></td>
<td>Ensure proper movement mechanics (e.g., avoid knee valgus or emphasize soft landing)</td>
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<tr>
<td>Speed/agility</td>
<td>Development of skills at maximum speed</td>
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<td></td>
<td>Integration of COD actions</td>
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<td></td>
<td>Training closely related coordination</td>
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<td>Resistance to fatigue</td>
<td>Development of skills under fatigue conditions</td>
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<td></td>
<td>Stimulus provoking cardiovascular, metabolic and neuromuscular fatigue resistance</td>
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COD = changes of direction; FMS = fundamental movement skills; SSS = sport specific skills.
body segments, or unanticipated disturbance to supporting surface (26). This perturbation stimulus can be controlled or unpredictable, and multidirectional forces can be applied to integrate training regimens to improve dynamic balance (103). Finally, dynamic stabilization, the most challenging category, is defined as the ability to maintain equilibrium during dynamic actions (the body is under some kind of displacement), bringing the requirement of balance to the kind of joint stability involved in sport-specific skills (79). In fact, many sports-related injuries occur when an athlete loses balance during dynamic actions such as jumping (72,95,111). Several published investigations have shown a decrease of injuries and injury-risk factors (28,71) and an improvement in sport performance (41) through balance training interventions. Thus, developing a strong foundation of proprioceptive sensibility during the developing years is essential to promote long-term athletic success and health.

It is critical to emphasize instruction and feedback on the correct flexion of the trunk-hip-knee-ankle complex during proposed exercises that target training lower limb dynamic stability. Closed kinetic chain exercises of the lower extremities have been related to greater coactivation of the quadriceps and hamstrings and less dynamic valgus (62). These 2 neuromuscular adaptations are considered to decrease risk factors associated with anterior cruciate ligament injury (46). Corrective training can help the player to achieve the right automatisms and consequently allow the player to better transition from coactivation to inhibition strategies to achieve maximal explosive actions (61). Practicing correct mechanics and activation may result in improved movement strategies becoming more automatic to translate to sport scenarios. In addition, training can improve stabilization during dynamic tasks such as jumping and landing. Recent studies suggest feed-forward control of the ankle and knee stabilizers during the preparatory phase before touchdown on landing or stopping to be the most significant factor in improving dynamic stabilization (12,54). With the aim to improve feed-forward control mechanisms in sporting situations, training programs should introduce a high variety of progressive tasks that also integrate unanticipated actions and conditions. Table 2 shows some practical suggestions to implement these principles when training lower limb dynamic stabilization in youth.

Balance training comprises numerous progressions that depend on maturation stage and neuromuscular performance ability (44). Despite this, there is a scarcity of scientific literature on optimal balance training progressions intended to improve performance and prevent injuries in youth (29,43,71,81,113), the present review will present an evidence-based guide for balance training progression. Dynamic stabilization in youth should begin with static balance exercises emphasizing the correct posture and lower limb alignment. After an athlete demonstrates correct performance of static balance, instructors can progress to more complex balance tasks such as dynamic balance and dynamic stabilization exercises. Training modes in novice athletes should focus on static balance (e.g., single-leg balance exercises on stable surfaces). At this stage, we can also introduce easy dynamic balance exercises (e.g., double-leg stance on a BOSU) and dynamic stabilization exercises (e.g., soft landings in a stable surface). Once competency is achieved, intermediate athletes will continue dynamic balance skills (e.g., single-leg balance unstable surface with or without perturbations) and more challenging dynamic stabilization exercises (e.g., single-leg hops on a BOSU). As the athlete matures and improves, neuromuscular performance and balance dynamic exercises can be progressed to more challenging actions that include unanticipated actions and conditions (e.g., single-leg hops on a BOSU) while catching a ball and with a partner perturbations. Figure 2 provides an example progression of exercises to improve dynamic stabilization of the lower limb in young athletes. Because many sports activities entail forces to be applied to the body in off-balance situations, unstable resistance training (e.g., squat on a BOSU) has been demonstrated to facilitate greater neuromuscular adaptations (e.g., more trunk muscles activation, more cocontractions, and more limb muscle activation) compared with stable resistance training (7). In addition, instability training is beneficial because it allows high muscle activation with

### Table 2

<table>
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<tr>
<th>Examples of practical applications progressions to train dynamic stability</th>
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<tr>
<td>Static balance → dynamic balance → dynamic stabilization</td>
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<tr>
<td>Low → high amplitude movement</td>
</tr>
<tr>
<td>Open → closed eyes</td>
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<tr>
<td>Without shoes → physical training shoes → specific sports shoes</td>
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<tr>
<td>Variability of perturbation types: instable surfaces, manipulative or object control, opposition, vibration…</td>
</tr>
<tr>
<td>Without → with external load</td>
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<tr>
<td>Slow → fast short-stretching cycles</td>
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<tr>
<td>Without → with cognitive load/decision making</td>
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<tr>
<td>Expected → unexpected actions</td>
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<td>Without → with fatigue</td>
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less stress on joints. On the other hand, unstable resistance training can lead to decrease in the force output and increases in antagonistic activity that may be detrimental to absolute strength gains when resistance training. The positive effects of instability training on sports performance have yet to be quantified. To the best of our knowledge, when implementing a resistance training intervention for young athletes, both stable and unstable exercises should be included to enhance both high force (stable conditions) and stressors to the neuromuscular system (unstable conditions) (8).

Core dynamic stability. Core dynamic stabilization (core stability) is essential to maintain spinal integrity and lower extremity control during sports activities (2,77,109). Although this term is broadly present in specialized literature, there is no single universally accepted definition for core stability. Kibler et al. (57) defined this term as the ability to control the position of the trunk over the pelvis, allowing for optimum production, transfer, and control of force and motion to the terminal segment in integrated kinetic chain activities that involve the spine, hips, pelvis, proximal lower limb, and abdominal structures. Panjabi (90) described 3 subsystems that can work together to maintain core integrity: (a) the central nervous subsystem (control), (b) the skeletal subsystem (passive), and (c) the muscular subsystem (active).

Although scientific literature provides support for the benefits of core training on performance and injury prevention (31,70), the evidence is scarce and sometimes contradictory for both adult and youth populations. Nonetheless, available literature presents valuable core training programs and recommendations for athletic populations (2,9,52,77,109). Before initiating a core focused training regimen, it is important to use appropriate screening tools to identify any underlying injuries or deficits to the core structure that inhibit function (e.g., low back pain disorder) (2,70). If an underlying injury is suspected, an individual should seek professional medical examination before performing core exercises and some exercises may worsen an adverse condition. For example, back injuries link with specific changes in muscle recruitment strategies used by the central nervous system to control the spine. This type of injury usually involves impaired activity of deep muscles (e.g., transversus abdominis and lumbar multifidus) often in association with hyperactivity of superficial muscles (e.g., rectus abdominis and latisimus dorsi) (70). Specific core exercises are useful in rehabilitation and injury prevention that aim to integrate deep and superficial muscle activities during functional tasks (53). For example, exercises that target motor pattern relearning of inhibited deep muscles can be beneficial for individuals with deficits from prior injury or lack of primal level core strength (92). Athletes that pass screening examinations can focus on functional core exercises to ensure regular participation in daily living tasks and sports physical activity (52,109).

From our experience and review of current literature, core dynamic stabilization programs in novice athletes should consider starting with basic postural stability and consciousness activation exercises (e.g., quadruped or “big-dog” exercise or diaphragmatic breathing) on static surfaces (see Figure 3A–C). These exercises comprise “low threshold” postural movements that primarily demand endurance and motor control (52,70). Another objective of these exercises is to activate deep muscles of the trunk and hip girdle (2) while maintaining a neutral spine posture (70). Intermediate youth athletes should progress through stability,
muscle endurance, and reactivity exercises (see Figure 3D–G). There are numerous methods to progress stability and strength with core exercises. Some of the more common exercises proposed in the literature to develop core strength and stability are variations of the plank (front, side, and reverse) and bridge exercises. These higher load exercises should be executed predominantly with the spine in a neutral position, which represents posture during speed and change of direction movements characterized by youth sports (44,70). These exercises can be further challenged in the athlete by adding unstable surfaces. As performance advances, functional exercises should progress with incorporation of strength and power components (see Figure 3J and 3K). Depending on the athlete’s abilities, these more challenging exercises can emphasize rotations, accelerations, and deceleration movements (43). On the other hand, these movements have been attributed to spinal injuries and are also characterized by most sports. Because of these reasons, twisting movements in youth athletes should be performed under limited load and range of movement and performed with a neutral and braced spine (70). The proposed progression is important to ensure correct motor patterns during specific sport actions in youth athletes, where spine acceleration and deceleration movements occur in multiple axes and planes. In addition, stable and unstable training have their place in core training program progressions, and they should not be isolated (8). Unstable core exercises (e.g., plank exercises using a BOSU or a stability ball) have been used on the premise that greater instability will stress the neuromuscular system and also increase activation of core muscles to a greater extent than similar activities performed on stable surfaces. Core exercises that incorporate an unstable surface (e.g., BOSU) can also inhibit force, power and range of motion, which are necessary in youth athletics (9).

Moreover, it is important to note that both types I and II muscle fibers must be stimulated to ensure spinal integrity during sports and daily life activities in youth (39). Therefore, it is necessary to program a variety of core stability exercises ensuring both static (i.e., isometric) and dynamic exposure. In addition, when training for proper core activation, it may be advantageous to stimulate the core muscles when the athlete is in a quadruped position, on their knees, or lying supine position to eliminate balance assistance provided from the lower extremities (e.g., ankle joints). For example, core stability exercises that have the athlete sit on their knees on unstable surfaces (e.g., Figure 4) can be implemented to effectively train for deep tissue activation and core balance.

When training core stability with young athletes, it is also important to consider sex differences. Current research shows that female athletes on average have greater lateral trunk displacement and altered trunk and hip flexion, greater ranges of trunk motion, and increased hip adduction and internal rotation during sporting maneuvers compared with males (74,77). This discrepancy should be
considered when programming and applying training exercises for female athletes. Additionally, core weakness and instability in females is considered as one of the multiple antecedents of sex-related discrepancy in anterior cruciate ligament (ACL) injuries, reflected by the 4-fold to 6-fold higher incidence of injury in female compared with male athletes (77,109). This altered neuromuscular control during sports activities can manifest in high joint loads in both lower limb and spinal structures.

**COORDINATION**

Coordination capacity has been defined in a variety of ways and encompasses various complex skills and abilities. The capacity to perform complex motor skills (67), to control and regulate motor actions (73), and to arrange body and limb motions relative to the patterns of environmental objects and events (68) are some of the ways humans can demonstrate coordination capacity. Coordination in relation to environment is of particular interest for activities where the demand for skills necessitates high levels of perceptual and cognitive qualities for performed actions (67). Scientific literature emphasizes the need for athletes to develop optimal coordination of movements to perform a motor action (117). Because of the greater neural plasticity earlier in life, initiation of coordination development training at an early age is warranted (67,117). In this sense, prepubescence is an optimal period to imprint correct coordination abilities, whereas later stages of development (i.e., adulthood) present more challenging timeframes in which to optimize skill development (63). Similarly, it is recommended that children participate in a variety of sports activities (e.g., hockey, handball, rugby, gymnastics) to maximize neural adaptations for a multitude of skill sets before sport specialization. The early work of this variety of motor patterns will give the young athlete the capacity to perform appropriate and safe responses to sport situations.

With regard to the development of coordination abilities in youth, the literature provides a wide variety of coordination classifications. In particular, Meinel and Schnabel’s (73) classification of coordination offers a comprehensive list of suitable abilities: space–time orientation, reaction, rhythm, kinesthesia differentiation, balance, adaptation or transformation motion, and coupled or combinatory motion (Figure 5). The aim of INT training is not to isolate any coordination ability, but rather to implement a comprehensive training guide to develop coordination required for fundamental movement competency and sport-specific skills based on previous literature (49,79,81). Related to this methodology, other works analyzing more complex actions as coupled skills (e.g., jumping–change direction, displacement–jumping) have also given more information about the difficulty of developing these kinds of tasks in a correct way (15,21). FMS must be developed first and then systematically combined to improve complex coordination tasks (e.g., sport specific skills).

Considering this content, variety and progression principles are the basis of effective exercise program design (14). Coordination exercise types can be integrated. For example, use of multiple stimuli (visual, auditory, kinesthetic), combination of different movements, temporal and spatial variations, simultaneous use of multiple equipment types, cognitive loads, reaction drills, and asymmetrical movements are suitable methods for manipulating the training of coordination skills. In addition, coordination work must also integrate a variety of drills, including reaction drills, to encourage reflexive coordination skills with desired technique. These exercise progressions should not compromise correct technique execution and should only progress with demonstration of correct and consistent performance.

Further, it is important to strongly consider the warm-up phase of a training session as a valuable time to train coordination skills. The warm-up can be an excellent phase of the training session to train coordination because the central nervous system is not fatigued and is thus primed to create or refine motor patterns (Figure 6).

**STRENGTH**

Scientific literature has provided evidence that resistance training has many benefits and little risk of injury for youth when a program is appropriately instructed by qualified professionals (34,37). Aside from reducing the risk of sport-related and physical activity-related injury, well-designed
resistance programs can improve muscle strength, power production, muscle endurance, motor and coordination abilities, bone mineral density, body composition, insulin sensitivity, sports performance, self-confidence, and self-image in children and adolescents (35). Injury risk related to resistance training has been primarily associated with a lack of supervision that allows for poor exercise technique and usage of inappropriate training loads (35). For

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<tr>
<th>Space-time orientation</th>
<th>• Ability to realize position of the body or its parts in space and time.</th>
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<tr>
<td>Reaction</td>
<td>• Ability to respond quickly to auditory, visual and kinesthetic stimuli.</td>
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<tr>
<td>Rhythm</td>
<td>• Ability to chronologically organize muscle performance in relation to space and time</td>
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<tr>
<td>Kinesthesia differentiation</td>
<td>• Ability to feel and perceive kinematic and dynamic features of movement, with the aim to execute the desired movement with accuracy and efficiency</td>
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<tr>
<td>Balance</td>
<td>• Ability to keep body or its parts in a relatively stable position</td>
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<tr>
<td>Adaptation or transformation motion</td>
<td>• Ability to modify motor activity by comparing or anticipating new or changing environmental conditions</td>
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<tr>
<td>Coupled or combinatory motion</td>
<td>• Ability to simultaneously coordinate partial movements together in relation to a global movement while maintaining a determined motor aim</td>
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Figure 5. Coordination abilities definitions (Meinel and Schnabel, 1987).

A. Ladder drills in multiple directions and different kinesthetic, auditory and visual stimuli

B. Rope jumps in multiple directions and different supports (e.g. regular skip (a), side to side (b), forward and back, running on the spot (c), criss-cross fit (d), double hops, scissors, one foot hop (e), rope cross-over (f)...)

C. Relay races combining different movements and equipment (e.g. Change of direction bouncing a tennis ball (a, b) + skipping on hurdles (c) + push up on a fiball (d) + balance on the knees on a fiball (e) + throwing the ball to the next partner)

D. Coordinative drill combining three tasks: 3-6 repetitions of continuous (a) defensive position in a vibration platform (2s), (b) reverse slalom at maximal speed and (c) 1 vs. 1 fighting with a fiball (5s).

Figure 6. The warm-up phase of an INT session can be an excellent moment to train coordination capacities. This figure shows examples of different coordinative tasks for a youth population.
Strategies to Improve Neuromuscular Control in Youth

these reasons, supervision from a qualified professional is essential for youth-based resistance training programs. Additionally, without guidance from a qualified instructor, athletes will not be provided with necessary corrective feedback to improve technique. Without intervention, these athletes will continue to produce poor and suboptimal technique and it will be more difficult to modify poor technique and habits later in life.

The development of muscular strength has been suggested as a priority at all growing phases for both males and females (32). Previous research has shown close associations between muscular strength capacity and running speed, muscular power, change of direction speed, plyometric ability, and endurance (63). In addition, muscle strength has been revealed as a contributing factor for successful fundamental movement competency. The methodology of strength training should first ensure correct execution of exercises (e.g., controlled movements, proper breathing) and safety education about training equipment (34,69). Some exercises will be carried out with external loads and special attention needs to be focused on postural control (core and lower limb positions and stability) and lifting technique to promote safety at all times. All sessions should begin with a dynamic neuromuscular warm-up (i.e., coordination development and dynamic stretching exercises) and conclude with an appropriate cool-down period (e.g., dynamic low-speed stretching exercises). The main part of the training session will introduce strength training that considers application of progression, variability, and specificity based on training pediatric exercise science principles (14). As previously mentioned, the high neural plasticity of young people calls for a great variety of movement skills in the training program (e.g., upper-body and lower-body, unilateral and bilateral execution, pushing, and pulling strength exercises) (83).

Related to the progression principle, resistance load and velocity of execution should increase gradually and systematically to reduce possible risk of injuries while training. It has been suggested that resistance can be added with 5–10% increments in weight when predetermined repetitions can be performed consistently and correctly (32,116). Furthermore, training programs must factor in considerations of the needs, goals, and abilities of each participant (35). Table 3 shows a guide for progression on strength training for youth based on scientific literature (10,37,43,116).

The other major parameter related to the progression of the applied loads is the acceleration and speed of execution. Initially, resistance training should focus on technique with exercises using light-to-medium loads performed at slow to medium speeds. Considering the increased neural plasticity associated with childhood, only after a young athlete achieves strong technical competency with initial low-intensity exercises, it is important to appropriately progress movement speeds and loads (63).

Muscle power is also trainable during childhood. For youth, one of the best ways to develop power is through plyometric training (stretch shortening cycles), which is further discussed in the next section. Faigenbaum et al. (34) recommended a progression during resistance training for power considering intensity (30–60% of maximum repetition and moderate to fast velocity), volume (1–3 or more sets of 1–6 repetitions), frequency (2–3 sessions per week), and type of exercises (multijoint exercises).

The variability principle of training (related to the variation of the applied load and the exercises carried out) can easily be applied when strength exercises are not directly related to sport skills. On the other hand, it is more difficult to design strength exercises that attempt to mimic specific sport actions (e.g., a forehand in tennis, a change direction in soccer). There is inherent difficulty in reproducing specific sports-related skills against resistance, but this factor will be another important step in the direction of the main goal of INT programs (i.e., the achievement of the correct neuromuscular control to prevent injuries and improve performance). Figure 7 shows this concept progressing from general to specific exercises adapted to the sport action.

Although increasing intensity and volume is an essential facet to strength training, it is equally important to ensure adequate recovery in a training program. It is suggested that the greatest adaptations occur when muscles have fully recovered (106). Therefore, excessive fatigue to the musculoskeletal system may greatly hinder an athlete’s ability to progress in a strength program and overtraining can be a serious health risk. Therefore, it is recommended to balance high-intensity and/or high-volume workouts with less intense training (LIT) (36). LIT consists of exercises that substantially decrease in resistance such as body weight exercises. Faigenbaum et al. (2006) suggest that LIT can not only promote recovery periods, but also enhance the recovery process through reinforcement of joint stability, range of motion, and specific movement patterns. LIT sessions can be part of a valuable multifaceted approach to optimizing performance and reducing overtraining risk (36).

PLYOMETRICS (STRETCH SHORTENING CYCLE)

Plyometric training has been shown to improve muscle power, enhance sport performance, and reduce injury risk in young athletes (47,65,81). This methodology of training is based on the development of stretch shortening cycle (SSC) ability, which consists of a fast action of muscle stretching (eccentric action) followed by a fast shortening phase (concentric action) (106). As a consequence of this fast movement, SSC depends on elastic energy and reflexive muscle activity mechanisms (110); both of which are believed to be trainable in youth (37,65). Despite plyometric actions being the training mode most representative of free play (e.g., jumping in
multiple directions, skipping”), some high-intensity plyometric exercises, such as depth jumps, have been described as activities that involve maximal effort and also high joint loads. Consequently, implementation of high-intensity plyometric exercise should be prescribed and supervised by qualified instructors that ensure proper movement mechanics are developing correctly.

Another consideration of plyometric exercise is the differences between slow and fast plyometric exercises (97) when programing and instructing plyometric training. Slow SSC exercises, such as a countermovement vertical jump, are characterized by large angular displacements of the lower limb joints with longer contraction times (>0.25 seconds) of the muscles involved. On the other hand, fast SSC, such as a triple jump action, consists of smaller angular displacements and quicker eccentric-concentric coupling (<0.25 seconds) (97,110). In the field of sports performance, slow SCC exercises are not considered adequate to maximize reflex potentiation force because of the critical window of force application threshold of 250 ms (110). Komi et al. (1997) suggests that an effective SSC requires 3 critical elements: a well-timed preactivation of muscles before the eccentric phase, a short and fast eccentric phase, and an immediate transition between stretching and shortening actions (58,110). These requisite elements can lead to a more compromised action for joints and muscles, and preparation before doing higher intensity plyometrics is essential when programing. Moreover, it is also important to differentiate between low-intensity and high-intensity exercises with regard to plyometrics (23,106). High-intensity exercises are usually related to both high-impact loads and fast SSC (e.g., drop vertical jumps, bounding, multiple box jumps). Nevertheless, it is also worthwhile to emphasize fast SSC with lower impact exercises such as skipping or jumping rope (Figure 8). Because of all of these considerations for plyometric training, exercise progression should also be optimally programed with high consideration for muscle-tendon stiffness (85). Higher stiffness increases muscle preactivation

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Strength training progression guidelines in youth population</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of exercises</td>
<td>Prepuberty or novice</td>
</tr>
<tr>
<td></td>
<td>Special focus and priority on fundamental movement exercises (squat, lunge, push-up)</td>
</tr>
<tr>
<td>Range of movement</td>
<td>Generally, full movement range on the major exercises, however, to reduce the risk of injury, moderate movement range on some complex exercises</td>
</tr>
<tr>
<td>Muscle groups trained</td>
<td>Exercises should include all major muscle groups. Focus on maintaining strength muscle balance: symmetry between limbs and agonist–antagonist equilibrium. Special attention should be paid to common strength weaknesses (e.g., lower back, rotator cuff or hip abductors muscles)</td>
</tr>
<tr>
<td>Intensity</td>
<td>10–15RM, moderate velocity (emphasis on controlled movement)</td>
</tr>
<tr>
<td>Volume</td>
<td>1–2 sets</td>
</tr>
<tr>
<td>Rest intervals</td>
<td>Although it is known that rest intervals should be between 1 and 3 min between sets, these parameters must adapt to each participant, session, repetition, level of fatigue, and aim of training.</td>
</tr>
<tr>
<td>Frequency (days × week)</td>
<td>2–3 (on nonconsecutive days)</td>
</tr>
<tr>
<td>Type of adaptations</td>
<td>Neuromuscular</td>
</tr>
<tr>
<td>Special recommendations</td>
<td>Technique and postural control is the priority. Make training enjoyable</td>
</tr>
</tbody>
</table>
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and consequently allows the muscle to tolerate and absorb high impact loads in a more efficient way during the ground contact phase (110). Consequently, progression should be developed in sport players starting with lower intensity and slower velocity drills and progressing to higher intensity and faster velocity exercises (65).

Lloyd et al. (2011) described a 6-stage model progression of plyometric training in youth (65). Basic progression recommendations focus on training intensity (from low-intensity to high-intensity exercises), volume (one to multiple sets of 6–10 repetitions), frequency (2 sessions per week on non-consecutive days), velocity, and recovery (60–180 seconds). Another consideration for progression relates to the kinematics of the action, starting with fundamental movements (e.g., body weight squat, lunges) progressing to low-intensity plyometric exercises (e.g., jumps in place), medium-intensity tasks (e.g., multiple bilateral hopping and jumping, box jumps) and high-intensity exercises that are more complex and entail high impact load (e.g., bounding unilaterally, depth jumps) (Figure 8). A key to heightened performance in sports situations is the ability to quickly change direction. Direction change is not only dependent on vertical forces; this ability is predominantly performed in multiple planes and axes. In fact, it is also necessary to develop plyometric capacity to improve this ability. Emphasis should be placed on elastic and reflex actions for optimal change of direction, consequently adapting the SSC within movements inherent to the sporting situations (108,114).

**SPEED AND AGILITY**

Speed and agility training are vital components of neuromuscular training in youth and can be considered a manifestation of coordination capacity at high speeds of performance (13). The definition of speed is related to the rate of change of position with respect to time and results from the product of stride length and frequency (5). Speed, in context of situational sport, can be linked to agility, which is a more multifactorial concept defined as the capacity to allow rapid whole-body movements while changing direction in response to a stimulus (99). This definition links agility to the ability to change direction and physical qualities such as strength and power. In addition to these abilities, rapid deceleration has been also defined as an essential skill that is closely linked to agility and multidirectional movement training (51,59). Agility, especially in situational sport (e.g., opponents, teammates, a ball and a shared field of playing), also includes the development of cognitive components such as visual-scanning techniques and anticipation (115). In addition, the ability to properly change direction is related to other cognitive and perceptual capacities, such as decision-making processes (98,108).

With regard to INT programs, when training change of direction ability at high speeds, special attention should focus on lower limb biomechanics. In particular, altered control of knee joint biomechanics in the frontal plane during cutting maneuvers is considered a major risk factor for knee injuries such as ACL ruptures (46). The load...
of the ligament in change of direction (COD) is increased when associated with fatigue and/or decision-making processes (15). This effect is even greater in female adolescents who typically demonstrate greater dynamic valgus than males during unanticipated cutting actions (40). It has been shown that the most effective activation pattern to stabilize the knee is achieved when the hamstrings and quadriceps muscles generate flexion or extension moments (62). As mentioned previously, kinematics must be preserved to reduce high joint loads when agility is initially implemented in INT programs with a focus on correct alignment and flexion of the lower limb (trunk-hip-knee-ankle complex). Attention should also be placed on lower limb patterns during open or unplanned conditions of tasks with the intention of reducing the risk of injury during similar sport scenarios. For example, in Australian Football, it has been observed that ACL ruptures occur during COD maneuvers such as sidestepping (37%), landing (32%), landing and stepping (16%), stopping/decelerating (10%), and crossover cutting maneuvers (5%) (22). This information emphasizes the need to develop agility training in INT programs with a large variety of COD, as sidestepping, crossover cutting and deceleration lead to change of direction actions. Agility training should start with closed and preplanned drills to promote technical competency before progressing to more open and unplanned conditions. Figure 9 shows an example of speed and agility training by specific sport skills in young tennis players. 

Despite the lack of scientific literature regarding agility training in youth, Lloyd et al. (64) recently developed an example progression for each stage of technical competency based on fundamental movement skills, change of direction speed (CODS), and reaction agility training (RAT). In this review, change of direction speed is considered to be a closed and preplanned skill in nature, contrary to reactive agility, which incorporates open and unplanned changes of directions. These authors proposed that both children and adolescents should be exposed to all 3 training components; however, the distribution of time for each training component should vary according to stage of development/technical competency. For example, with prepubescent and technically incompetent children, the primary focus should be on FMS development with secondary focus to CODS and RAT; whereas, with a technically competent adolescent, greater emphasis can be placed on RAT development while maintaining FMS and CODS competency.

Figure 8. Example of plyometric exercises progression in youth.
training) were the most efficient in postpeak height velocity participants. These authors suggested that it is difficult to quantify the effects of different training methods because of the limited knowledge in this area. Based on scientific literature, when training youth for speed improvement, the first level of training should focus on developing correct running kine- matics and technique. This can be accomplished through specific dynamic drills such as A-skips, B-skips, high knees, or ankle-quad grabs. Functional mobility is another element to be considered to improve running form, especially mobility of the ankle and hip. As youth improve running kinematics, attention can focus on power, strength, and sprint-specific training development (64). Classic sprint training in youth consisted of straight line sprinting (around 5–30 meters) with passive recovery (105). Other forms of specific sprint training have been studied in youth such as resisted sprint training (e.g., sprinting uphill or sprinting while using weighted sleds) or assisted sprint training (e.g., supramaximal or overspeed running like downhill running) (96). Nevertheless, it is important to emphasize agility training (speed with change of direction) over linear sprints because a majority of sports demand quick, multidirectional movements (115).

**FATIGUE RESISTANCE**

In team and racquet sports, one of the keys to successful performance is the ability to develop repeated high-intensity actions; which are reliant on neuromuscular and cardiorespiratory efficiency to reduce the negative effects of fatigue. This ability plays an important role not only in performance but also in injury prevention because neuromuscular fatigue is considered one of the higher risk factors for sports injuries (17,21). Recently, high-intensity interval training (HIIT) has become one of the most effective and commonly used methods for improving cardiorespiratory, metabolic and neuromuscular components of fitness in youth and adult athletes (19,45). Methodologically, HIIT involves repeated high-intensity efforts. To study fatigue resistance competency with repeated bouts of high-intensity activity, the effects of SSG were studied in youth team sports (16,25). SSG is a more real sport scenario of HIIT that incorporates coordinative and tactical specific skills to the development of fatigue resistance. It can be assumed that athletes who are
better able to resist a sport-specific amount of fatigue can more favorably handle potentially injurious scenarios. It is accepted that SSG can substitute aerobic interval training to train specific energy systems during the competitive period in athletes (102), and some aspects related to performance level (time spent performing high-intensity actions during a match) have improved by this kind of work (75). But, when implementing this type of training, it is important to note that game-based training has been related to a higher traumatic risk of injuries because of the higher number of contacts (with the other players) and the high variability of the game (unexpected actions) (20). Moreover, it has been suggested that lower-skilled players may profit less from SSG compared to classic HIIT training (45).

Borotikar et al. (2007) indicates that central fatigue has shown important effects on the decrement of the ability to perform complex tasks in sports. The authors present the possibility of introducing complex and challenging decision-making tasks during training to train the athlete to generate optimal movement strategies in various sport situations to reduce injury risk. There are also recommendations that training programs train movement strategies under fatigued conditions to simulate realistic scenarios when injury risk is greater (15).

Given current evidence related to efficacy and approaches to training for fatigue resistance, aerobic fitness should be progressed throughout the development stage considering both maturation and technical skill (45). From our experience and review of current literature, tasks implemented to improve fatigue resistance in novice athletes should be enjoyable and focus on technical skill acquisition during aerobic and interval-based tasks that include gameplay. As an athlete matures into later development stages, greater emphasis can be placed on high-intensity SSG to improve aerobic fitness and technical skills. Once young athletes have progressed to a sufficient competency level to pursue specific sport skills performance, a combination of SSG and classic HIIT training is recommended (45). Figure 10 shows an example of different methods (RST, classic HIIT, and SSG) to improve fatigue resistance with the aim to improve cardiorespiratory, metabolic, and neuromuscular capacities in youth populations.

SUMMARY
The proposed model of INT programs in this manuscript presented 6 essential training components: dynamic stability, strength, plyometrics, coordination, speed and agility, and fatigue resistance. This review emphasizes a flexible approach to INT with goals to improve injury resilience and to enhance sport and motor performance abilities in youth populations. INT in youth should first build an important foundation by developing FMS competency and then build upon these skills to enrich sports-specific and activity-specific skill sets. The key to a well-designed INT program is to integrate all of these components in an individualized manner and to design and deliver training in an enjoyable fashion to motivate youth to incorporate and retain optimal movement strategies.

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