When to Initiate Integrative Neuromuscular Training to Reduce Sports-Related Injuries and Enhance Health in Youth?

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Abstract

Regular participation in organized youth sports does not ensure adequate exposure to skill- and health-related fitness activities, and sport training without preparatory conditioning does not appear to reduce risk of injury in young athletes. Current trends indicate that widespread participation in organized youth sports is occurring at a younger age, especially in girls. Current public health recommendations developed to promote muscle strengthening and bone building activities for youth aged 6 yr and older, along with increased involvement in competitive sport activities at younger ages, has increased interest and concern from parents, clinicians, coaches, and teachers regarding the optimal age to encourage and integrate more specialized physical training into youth development programs. This review synthesizes the latest literature and expert opinion regarding *when* to initiate neuromuscular conditioning in youth and presents a *how-to* integrative training conceptual model that could maximize the potential health-related benefits for children by reducing sports-related injury risk and encouraging lifelong, regular physical activity.

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1537-890x/1003/157–166
Current Sports Medicine Reports

Introduction

Over the past decade, the total number of participants in organized youth sports has increased, although the relative number of boys and girls involved in these programs has shown little change at 66% boys and 34% girls (1). Compared with inactive youth, children and adolescents who regularly engage in physical activity have higher levels of musculoskeletal strength, enhanced cardiorespiratory function, and reduced risk of sports- and other activity-related injuries (98,104). Moreover, sustained enjoyment and participation in activities designed to improve physical fitness and health during childhood and adolescence may be effective in prompting regular physical activity as an ongoing lifestyle choice into adulthood (91,93). In an effort to more comprehensively and effectively address health and fitness promotion for children and adolescents, current public health objectives now aim to increase the number of youth aged 6 yr and older who regularly participate in "muscle strengthening" and "bone strengthening" activities (104).

Current trends indicate that widespread participation in organized youth sports is occurring at a younger age (1). The combination of recent recommendations targeted to promote youth involvement in strength and conditioning activities along with earlier involvement in competitive sport activities has raised interest and concern from parents, clinicians, coaches, and teachers regarding the optimal age to encourage and integrate more specialized physical training into youth development programs (5,27,78,79). Many parents ask whether it is safe for their child to "lift weights" or want to know the "best age" for their child to start regular participation in structured conditioning activities. This underscores a long-standing concern regarding the appropriate starting age for specialized physical training (*e.g.*, strength and conditioning, performance enhancement, or injury-prevention training).

This issue is particularly important for aspiring young athletes who may be ill-prepared for the physical demands of sports practice and competition. While many factors can contribute to sports-related injuries in youth (*e.g.*, previous injury, muscle imbalances, nutritional deficiencies, improper footwear), poor conditioning seems to play a primary role. Insufficient readiness for sports practice and competition may be a consequence of the contemporary decline in unstructured physical activity among children and adolescents in the United States (78,79). Based on accelerometer-determined steps per day, almost 42% of U.S. boys and 21% of U.S. girls are sedentary, and the decline in physical activity appears to progress steadily after age 6 for both sexes (103). Basterfield and colleagues reported low levels of habitual physical activity and high levels of sedentary behavior in an initial group of 405 7-yr-old boys and girls. At 2-yr follow-up, the then 9-yr-olds demonstrated even more relative sedentary time with measurably lower physical activity levels (4). This troubling trend underscores the importance of initiating efforts to avert this decline during this developmental period and encourage regular participation in age-appropriate moderate-to-vigorous physical activity beginning in childhood (4).

Many experts agree that one's level of physical activity is influenced by extrinsic factors (*e.g.*, environment, family, peers, socioeconomic status, culture, and self-efficacy) that can affect a child's desire and ability to be physically active. However, adequate development of fundamental motor skills and enhanced confidence and competence to perform these activities is cited as a primary underlying determinant for increased physical activity among youth (97). Therefore, as more children and adolescents participate in sports and conditioning activities in schools, fitness centers, and private clubs, it is important to establish age-appropriate guidelines for the initiation of integrative training activities that are purposely designed to enhance neuromuscular function, muscular strength, and capacity specific to sport-like activities. This review synthesizes the latest literature and expert opinion regarding *when* to initiate neuromuscular conditioning in youth to maximize the health-related benefits through reduced sports-related injury risk and encouraging lifelong participation in a variety of physical activities.

Operational Definitions

For simplicity, the term "youth" refers to children (Tanner stages 1 and 2 of sexual maturation; approximately up to age 11 yr in girls and 13 yr in boys) and adolescents (Tanner stages 3 and 4 of sexual maturation; approximately ages 12 to 18 yr in girls and 14 to 18 yr in boys). The term preadolescent refers to boys and girls who have not yet developed secondary sex characteristics. Although the terms "resistance training" and "weightlifting" sometimes are used synonymously, the term resistance training refers to a specialized type of conditioning that involves the progressive use of a wide range of resistive loads and a variety of training modalities, whereas the term weightlifting refers to a sport that involves lifting maximal amounts of weight in competition. Integrative neuromuscular training is a conceptual training model that is operationally defined herein as a supplemental training program that incorporates general (*e.g.*, fundamental movements) and specific (*e.g.*, exercises targeted to motor control deficits) strength and conditioning activities, such as resistance, dynamic stability, core-focused strength, plyometric, and agility, that are designed to enhance health and skill-related components of physical fitness. The cornerstone of integrative neuromuscular training is age-appropriate education and instruction by qualified professionals who understand the fundamental principles of pediatric exercise science and genuinely appreciate the physical and psychosocial uniqueness of children and adolescents. Integrative training is designed to help youth master fundamentals, improve movement mechanics, and gain confidence in their physical abilities, while participating in a program that includes variety, progression, and proper recovery intervals (27,69).

Is Motor Competence Modifiable During Youth?

While there is no single gene that codes for motor performance in children, there are nervous system limits that differentiate among each child's opportunity to exploit critical maturational thresholds for the development of dynamic interceptive actions (*i.e.*, physical acts for which the body or an implement must be moved into the right place at the right time in order to accomplish a task) (18,90). Shenk described the intricate interaction of genetics and environment, stating that "Contrary to what we have been taught, genes do not determine physical and character traits on their own. Rather, they interact with the environment in a dynamic, ongoing process that continually refines an individual" (96). Skill-related fitness may not be an innate functionality hardwired at conception or gestation. Rather, it is more likely to be an accumulation of developed skills driven by the interaction between genes and the environment. Tryon's artificial selection experiment on maze-running ability in rats supports the theory that environment can indeed influence motor performance. After raising several generations by breeding the best and worst maze-running rats, generations of rats were produced that provided two distinct lines of maze-running ability (101,102). The offspring of each of these lines consistently performed as did their parents with good performance from the "bright" offspring and poor or reduced performance in the "dull" line of rats, even though the offspring were raised in identical environments. Notably, this distinct difference in performance ability between breeding lines, which was demonstrated for multiple generations, disappeared in one generation when the rats were raised in enriched (*i.e.*, more activity-based and social interaction) environments.

Genetic epidemiologists frequently observe that certain diseases such as obesity cluster in families, but individual family members sometimes do not demonstrate that common phenotypic expression (87). Likewise, children may inherit sensitivity to the effects of limited physical activity (*i.e.*, sedentary environments) that can trigger reduced motor development during youth (35). In adolescent youth, multidisciplinary interventions that incorporated progressive and periodized resistance training were vital to improving health in previously sedentary adolescents (35). Multidisciplinary integrative training models provided to

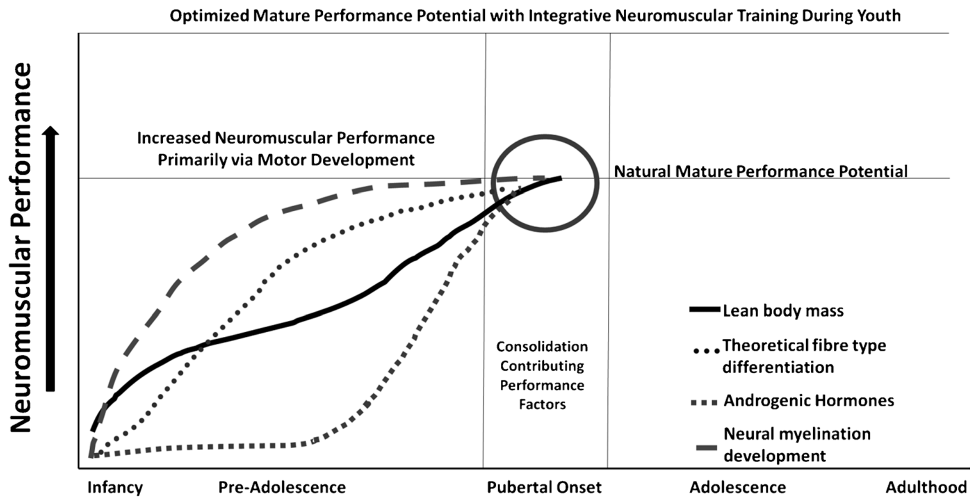

Figure 1: In youth, several factors contribute to motor control and strength expression. In children, motor control and strength may be less related to hypertrophy and more likely associated with neural development. It is proposed that integrative neuromuscular training focused on skill-related fitness (*e.g.,* agility, reaction time, coordination, power, speed, and balance) can maximize neural development during preadolescence and optimally prepare youth to capitalize on the consolidated factors that contribute to motor performance following the onset of puberty. [Adapted from Kraemer WJ, Fry AC, Frykman PN, Conroy B, Hoffman J. Resistance training and youth. *Ped. Exer. Sci.* 1989; 1:336–50. Copyright © 1989 *Ped. Exer. Sci.* Used with permission.]

preadolescent (both nonobese and obese) youth also may enrich their motor learning environment during this period of time (Fig. 1). Environments augmented with integrative neuromuscular training may not only help youth overcome genetic limitations (17), but also may help children achieve a level of motor competence that is beyond their expected adult potential without such training (Fig. 2).

Although speculative, a child in a nonenriched environment that is deficient in opportunities to regularly engage in activities that enhance fundamental motor skills may suffer long-lasting detrimental effects on health and disease risk later in life. This view is supported by the recent work of Lopes *et al.* (2010) who found that 6-yr-old children with low and average levels of motor coordination had lower levels of physical activity 5 yr later compared with children with high motor coordination (58). Further, in a 10-yr, longitudinal study of 630 adolescents, the participants first became involved in organized youth sports clubs between the ages of 6 and 10 yr (52). Interestingly, those who reported becoming members of a sports team at an even earlier age were more physically active as adults than adolescents who initiated sports involvement at older ages

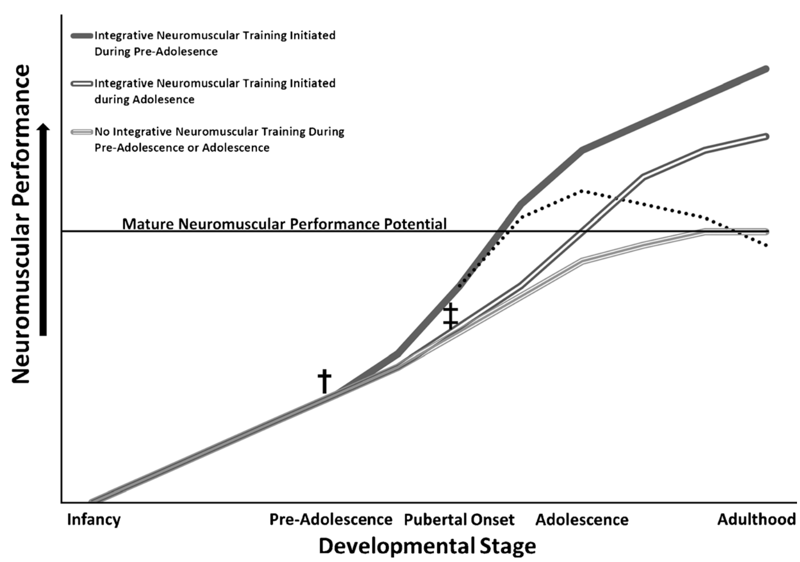

Figure 2: Conceptual model that compares the effects of integrative neuromuscular training initiated at different times in youth. The initiation of these integrative training techniques during preadolescence (†) and adolescence (‡), which will likely improve motor capacity and performance beyond natural adult potential (without such training). It is suggested that integrative neuromuscular training initiated in preadolescence and maintained into adolescence will maximize the potential to achieve optimal adulthood motor capacity. Dotted lines indicate potential detrimental effects of overtraining youth without structured recovery periods included as an integral component of the integrative training model.

(52). It has been proposed that the high degree of plasticity in neuromuscular development during preadolescence, combined with appropriately timed implementation and progression of integrative neuromuscular training, may allow for strengthened physical, mental, and social development that contributes favorably to their athleticism during adolescence. It also is possible that the improved motor competence developed through adolescence facilitates the establishment of desired behaviors and habits that may carry over into adulthood (Figs. 1 and 2) (52). On the basis of motor skill learning, preadolescence may provide an optimal window to train and develop long-lasting fundamental movement skills in boys and girls (36,59). Following maturation, young adult's corticomotor plasticity and potential for learning dynamic interceptive actions may be strongly diminished (38,89,90). Although speculative, children who do not regularly participate in this type of neuromuscular training in physical education classes, recreation programs, and youth sport centers may never reach their true genetic potential during adulthood.

When Is Motor Competence and Skill-Related Fitness Most Modifiable in Youth?

Studies investigating the trainability of youth with resistance and integrative-type training protocols have demonstrated significant improvements in selected performance measures in children and adolescents following progressive training programs (19,25,29–31,75,81,86,94,95,105). The observable benefits of this type of training are greater than those attributable to normal growth and development alone. These gains stem largely from neuromuscular adaptations (*i.e.,* more comprehensive and synchronous firing of muscle units) during preadolescence. In contrast, measurable training-induced gains prompted by increased fat-free mass are observable during adolescence, owing to testosterone and other hormonal influences on muscle hypertrophy that are operant during and after puberty (Fig. 1) (53).

Pubertal female athletes (12 yr old) who self-reported previous participation in resistance training demonstrated a 13.4% improved lower extremity control from the first to second year of testing, compared with an average decrease of 21.7% in the other groups of pubertal and postpubertal (14 yr) girls who did not report participation in resistance training in the previous year. In addition, hamstring strength was significantly greater in both the pubertal and postpubertal groups who participated in resistance training exercises. Ultimately, the athletes who participated in resistance training during earlier stages of development (early maturation, before 12 yr old) demonstrated the greatest benefits from participation in resistance training, as evidenced by reduced lower extremity deficits (32). Moreover, regular participation in a progressive integrative training program has been found to positively influence several other measurable indices of health and fitness (5,24,72,75). Regular participation in an integrative or multifaceted resistance training program with qualified instruction also can provide an opportunity for children and adolescents to learn proper exercise technique, receive basic education on program design, learn about healthy lifestyle choices, and gain confidence in their abilities to be physically active.

Children purportedly are born with a predetermined level of skill-related fitness capacity (18). Without an environment enriched with opportunities and encouragement to participate in integrative training during this developmental period, children and adolescents will be less likely to reach their true skill-related fitness potential (Fig. 2) (18). Kraemer and colleagues suggested that a consolidation of performance factors (*e.g.,* increased neural myelination and androgenic hormonal influence) create an optimal opportunity to expose youth to an enriched environment of integrative training before the onset of pubertal maturation (Fig. 1) (53). Integrative neuromuscular training is vitally important for youth whose cognitive and motor capabilities are highly "plastic" and amenable to age-appropriate interventions, and may be even more beneficial to youth with a decreased genetic potential for motor development and competence (38,83). Considering the potential for motor skill learning, along with the need to capitalize on the consolidation of factors that contribute to enhanced motor skill performance during preadolescence (Fig. 1) (53), regular participation in integrative neuromuscular training as part of physical education, recreational fitness training, or preparatory sports conditioning should begin during middle childhood (about age 7 to 10 yr, depending on maturity) and continue through adolescence (Fig. 2). On this basis, integrative neuromuscular training that is designed to enhance development of fundamental movement skills during this optimum period may provide the most lasting benefits during adolescence and possibly adulthood (36,59).

Does Maturity (Somatic or Psychosocial) Affect *When* to Initiate Integrative Neuromuscular Training?

While chronological age may historically be used for initial participation and grouping of sports teams, it is clear that maturity-related differences in body size exist around 6 to 7 yr of age (62). Somatic maturational assessments are traditionally the best way to identify rapid adolescent growth (61). Individually determined percentage of adult height also may be used as a relatively quick and noninvasive indicator of maturity status (62). The Khamis-Roche method of estimated adult stature was developed from the Fels Longitudinal Study (51) and uses individual stature, mass, age, and midparental stature in a regression equation for boys and girls. Peak height velocity (PHV) is the maximum growth rate during the adolescent growth spurt and occurs at approximately age 12 in girls and age 14 in boys (92,99). A potential window of opportunity may exist for the optimal initiation of integrative neuromuscular training based on measures of somatic maturity. Specifically, it seems most beneficial and thus desirable to initiate integrative training programs during preadolescence *prior to* the period of PHV when youth are growing the fastest. Children with earlier somatic maturation (growth) may particularly benefit from earlier participation in integrative neuromuscular training.

Although there is no minimum age for participation in integrative neuromuscular training programs, all participants must be able to follow coaching instructions and be able to handle the attention demands of a training program. In general, a child who is deemed ready for structured sports participation (about age 7 or 8 yr) would typically be ready for some type of resistance and other integrative training (5,24). However, regardless of the starting age, all youth should receive instruction on safety concerns, including sensible starting weights, repetitions, and jumping heights, for example. Proper handling of equipment and safe spotting procedures when appropriate also are imperative. This is particularly important in schools and recreation centers because untrained youth tend to overestimate their physical abilities, and this may increase their risk of injury (84). While somatic maturation helps define periods that are optimal to gain motor competence with integrative training, ultimately the child's psychosocial status (ability to follow coaching instructions, adhere to safety rules, and handle the attention demands of a training program) is paramount in the decision process regarding his or her participation in a structured integrative neuromuscular training program.

Does Sex Affect *When* to Initiate Integrative Neuromuscular Training?

Children with low motor competence are less able and sometimes less willing to participate in many sports and recreational activities typically enjoyed by their more well-coordinated peers. For both boys and girls, motor competence is associated with improved fitness measures (39). Adolescent boys commonly outperform girls in measures of physical performance, and these motor competence measures are related to better health outcomes in adults. Boys demonstrate power, strength and coordination increases with increasing chronological age that correlate to maturational stage, while girls show significantly smaller changes throughout puberty (10,61). For example, vertical jump height (a measure of whole-body power) increases steadily in boys during puberty, but not in girls (50,61,85). Hewett and colleagues demonstrated that as boys mature, they use a more efficient strategy for muscular dampening of forces (45). The improved motor control likely reflects natural adaptive changes in contraction patterns of the adductors and abductors of both the hip and the knee (57,100). Brent and colleagues demonstrated that hip abduction strength relative to body mass in boys improves with each subsequent age group (11 to 17 yr). In contrast, hip abduction strength does not change in girls across the same age range. These findings may indicate that integrative neuromuscular training protocols should include hip abduction strengthening exercises and should be implemented for girls before age 11 when the gender-specific reduction in relative hip strength diverges (14).

Musculoskeletal growth during puberty, in the absence of sufficient corresponding neuromuscular adaptation, may facilitate the development of abnormal mechanics during certain activities (33,42). These intrinsic risk factors, if not addressed at the proper time, may continue through adolescence into maturity and predispose women athletes to increased risk of a variety of musculoskeletal injuries (46,70). In a recent longitudinal study, Ford and colleagues noted that pubertal girls have an increased change in abnormal landing mechanics over time (34). In addition, important contributing risk factors for knee injury were significantly greater across consecutive years in young postpubertal female athletes compared with men. Integrative neuromuscular training programs have been successful at reducing these abnormal biomechanics (48,73–75) and appear to decrease injury rates in female athletes. Integrative neuromuscular training utilized to enrich the motor learning environment in early youth also may initiate adaptation and help children with low motor competence "catch up" with their peers in these measures (17,38,89,90). Preliminary data indicate integrative neuromuscular training protocols implemented in preadolescence (Tanner 1) and early adolescence (Tanner 2) may artificially induce the "neuromuscular spurt" (defined as the natural adaptation of increased power, strength, and coordination that occurs with increasing chronological age and maturational stage in adolescent boys), especially related to relative posterior chain strength postural control and neuromuscular power which is often reduced as young female athletes mature (67). An induced neuromuscular spurt may decrease differences in neuromuscular control of the lower extremity between adolescent male and female athletes and has the potential to reduce the risk of sports-related injury in adolescent female athletes (41,43,48,71). These data provide further support that preadolescence may be an optimal time to institute programs aiming to reduce these deficits that accelerate during maturation and lead to increased musculoskeletal injury risk.

What Are the Risks Associated With to Initiate Integrative Neuromuscular Training During Preadolescence?

As with any exercise or sports-related activity, youth participation in integrative neuromuscular training activities involves some degree of inherent risk of musculoskeletal injury. However, when children and adolescents are appropriately supervised and the training program is consistent with individual needs and abilities, risk of injury can be much less than in other sports and recreational activities in which children and adolescents regularly participate (28,108). Zariczyj and colleagues evaluated the incidence of sports-related injuries (based on accident reports) in school-aged youth over a 1-yr period and found that resistance training resulted in 0.7% of 1,576 injuries, whereas American football resulted in 19% of all injuries, or a nearly 30 times greater relative incidence (108). Many of the sustained forces and impulse loads that youth are exposed to in sports and recreational activities are greater in duration and magnitude than properly prescribed and performed resistance and plyometric exercises. For example, during certain dynamic sports activities characteristic of recreational or competitive play, athletes can expose their lower extremity to ground reaction forces reaching five to seven times their own body mass (20,47,64). Impulse ground reaction loads can be tremendously magnified and compounded during running and other single-limb stance plyometric activities inherent in some sports. Thus appropriate integrative neuromuscular training protocols pose less of a risk to children and adolescents than traditional recreational and competitive sport activities (28,69).

Integrative skill-related movements may be required to positively influence motor adaptations in youth that can prepare them to meet the demands of recreational and sport activities. Regular participation in integrative neuromuscular training programs that include weightlifting exercises (*e.g.*, modified cleans, pulls, and presses) and plyometric exercises (single- and double-leg hops and jumps) with qualified instruction and sensible progression have been found to enhance functional biomechanics and abilities and reduce the number of sport-related injuries in young athletes (43,63,75). Although some organizations and observers do not support participation in weightlifting or maximal load lifting until physical or skeletal maturity (2,66,107), others suggest that childhood may be the ideal time to develop the coordination and skill technique to perform these lifts correctly (5,24,53,82). However, unsupervised and poorly performed weightlifting, resistance and plyometric exercise should not be performed under any circumstances, because of the potential for accidental and musculoskeletal overload injury (11,76,88) In preadolescent populations (aged 8 to 13 yr), two thirds of all reported injuries during resistive and integrative training are to the hand and foot and are related to "dropping" and "pinching" (76). The authors conclude that the majority of youth resistance training injuries are the result of accidents that are potentially preventable with increased supervision and stricter enforced safety guidelines (76).

If appropriately supervised and sensibly progressed, integrative neuromuscular training programs can be safe, effective, and enjoyable for children and adolescents (5,6,19,24,60). However, because unsupervised and poorly designed training programs can be injurious, qualified professionals should design individualized exercise programs that are consistent with the needs, interests, and abilities of each participant and closely supervise all training sessions For example, without quality supervision and instruction, youth are more likely to attempt to lift weights that exceed their capabilities or engage in other risky behavior in the training center (28,49,76). Adults who teach and coach youth should have practical experience working with children and adolescents and a philosophy about training youth that is consistent with the needs, interests, and goals of younger populations.

Integrative Neuromuscular Training During Preadolescence to Reduce Risk of Sports-Related Injuries in Youth — Is it Effective?

While the total elimination of sports-related injuries in youth is an unrealistic goal, appropriately designed and sensibly progressed integrative neuromuscular training programs may help to reduce the likelihood of sports-related injuries in young athletes (28,40,43). By addressing the risk factors associated with certain youth sport injuries (*e.g.,* low fitness level, muscle imbalances, and errors in training), acute and overuse injuries could be reduced by 15% to 50% (65). Lehnhard and colleagues significantly reduced injury rates with the addition of a strength training regimen in male soccer players (56). Cahill and Griffith incorporated resistance training into preseason conditioning for adolescent football teams and, over four competitive seasons, reported a reduction in overall knee injuries, including the incidence of knee injuries that required surgery (16). Likewise, Emery and Meeuwisse found that integrated neuromuscular training was protective of all injuries, including acute onset injury in young soccer players (21). Notably, protocols that incorporate resistance training into preseason and in-season conditioning programs reduce anterior cruciate ligament (ACL) injury risk factors and ACL injury incidence in female athletes (40,43). Although only a small minority of young athletes participate in integrative neuromuscular conditioning programs before sports participation (15), these data indicate that such multifaceted conditioning programs may indeed reduce sports-related injuries in adolescents and that similar results would be observed in preadolescent populations if such programs were applied (19,37,41).

How to Initiate Integrative Neuromuscular Training During Preadolescence

Rather than prolonged periods of aerobic exercise, which may be less appealing for children, recent findings indicate that integrative neuromuscular training that incorporates intermittent-type activities into a well-designed plan may offer more effective health and fitness value to aspiring young athletes (Fig. 3) (40,43,59,68,69,72,74,75). Integrative neuromuscular training is characterized by short bursts of physical activity interspersed with periodic brief rest periods. The intermittent rather than continuous nature of integrative neuromuscular training is more consistent with how youth move and play (3). It also includes a variety of training modalities that are sensibly prescribed and progressed over time.

Adding integrative neuromuscular training to the total exercise dose of young athletes (*i.e.,* sports practice, sports competition, and free play) should be carefully considered, as this could contribute to the chronic repetitive stress placed on developing musculoskeletal systems. The risk of overload or overuse injury unduly increases if the intensity, volume, or frequency of training or competition greatly exceeds the ability of the participants to tolerate the load, perform technically sound movements, or to sufficiently recover from prior activity bouts (8,9,12). An effective approach could be to integrate resistance, power and speed training into a progressive conditioning program in which the volume and intensity of training periodically change throughout the year (*i.e.,* periodization). The systematic structuring of program variables, along with sufficient individual effort, qualified instruction, and adequate recovery are key interrelated determinants of effective progressive integrative neuromuscular training (Fig. 4). Adequate recovery between challenging training and competition sessions is often overlooked in youth conditioning programs that seem to be primarily focused on overload and progression. Safe and effective training of athletes at any age involves balancing the demands of training with the need for recovery to minimize

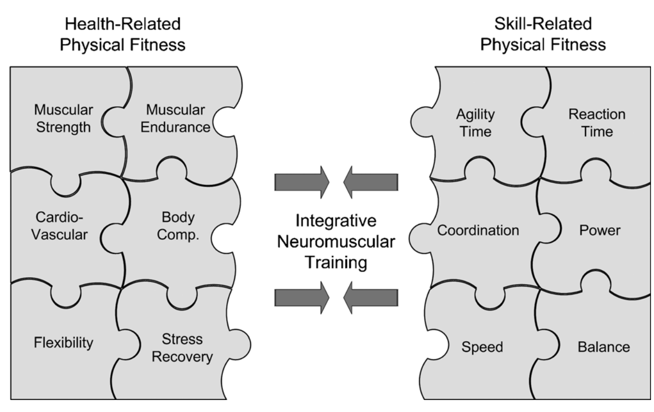

Figure 3: Integrative training model indicating a focus on the development of fundamental motor skills through activities that consolidate skill- and health-related fitness may maximize efficacy of neuromuscular conditioning during pre-adolescence.

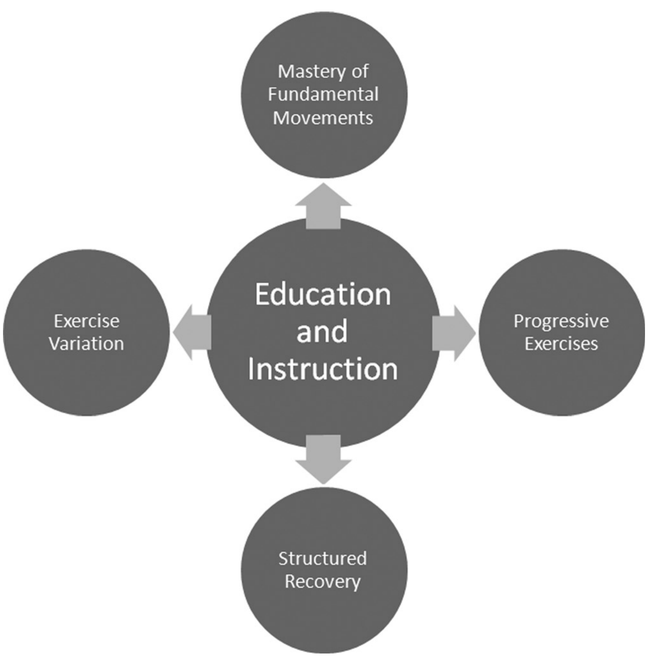

Figure 4: Education and instruction are the key components for effective implementation of integrative neuromuscular training. [Reprinted from Myer GD, Faigenbaum AD, Chu DA, *et al.* Integrative training for children and adolescents: techniques and practices for reducing sports-related injuries and enhancing athletic performance. *Phys. Sports Med.* 2011;39:74–84. Copyright © 2011 JTE Multimedia. Used with permission.]

injury risk and achieve training adaptation goals. This is particularly important for young athletes who represent different sports teams or participate in extracurricular sport activities at private training centers and in the community.

Children and adolescents should engage in 60 min or more of physical activity daily (104). However, high-intensity training should be performed only two to three times weekly on nonconsecutive days, to allow time for sufficient recovery between training sessions (24). When young athletes participate in strength and conditioning activities more than 3 times weekly, factors such as the overall training volume, training intensity, exercise selection, and nutritional intake should be considered carefully, as these factors directly influence the ability to recover from and appropriately adapt to the training program. As training programs and level of competition become more advanced and activity bouts are more frequent, proper exercise technique should be closely monitored by qualified professionals. Moreover, youth coaches should be cognizant of the signs and symptoms of overtraining (*e.g.*, muscle soreness that lingers for several days, decrease in performance, increased perception of effort during exercise, frequent upper respiratory tract infections, sleep disturbances, loss of appetite, mood disturbances, shortness of temper, decreased interest in training and competition, decreased self-confidence, inability to concentrate) and should realize that some children with relatively immature musculoskeletal systems cannot safely tolerate the same amount of exercise that many of their teammates can endure (12,106).

The prescribed exercises, sets, and repetitions for an effective integrative neuromuscular exercise program should be individualized and attainable for each athlete, and also modified as needed. Initial volume selection should be low to allow the athlete to learn how to perform each exercise with proper technique. Volume (or resistance, when applicable) should be increased after the athlete can perform the exercise properly at the prescribed volume and intensity. The professionals who supervise young athletes should be skilled in recognizing proper technique and should provide constructive feedback during the learning and development process, especially when improper technique increases injury risk. Once the young athlete becomes proficient with all exercises within a progression phase, she or he can advance to the next successive phase. Young athletes should participate periodically in less intense training (LIT) sessions to encourage and reinforce learning of specific movement patterns (26). Accordingly, high-intensity and/or high-volume training sessions should be regularly balanced with LIT sessions, as well as other recovery strategies to maximize training adaptations while minimizing the risk of overtraining (106).

While participation in organized school- and community-based youth sports programs provides an excellent medium to increase physical activity and improve health in youth, participation in organized sports activities does not ensure that youth meet the recommended requirement of at least 60 min of moderate-to-vigorous daily physical activity (7,55,80). Moreover, a recent meta-analysis on youth resistance training indicates that improved muscular strength is dependent on adequate volume to provide sufficient adaptive stimulus (6). Distefano and colleagues modified traditionally effective training programs previously used for adolescents (41,63,74) into a 9-wk "integrated injury prevention program" for use as an additive training regimen during the warm-up period in young soccer players (aged 10 to 12 yr). The addition of integrative injury prevention training program into standard soccer training influenced improvements in balance ability and vertical jump height in the young soccer players (19). Clearly, participation in physical activity should not begin with competitive sport but should evolve out of well-rounded preparatory fitness conditioning that is sensibly progressed over time. With addition of integrative neuromuscular training into existing practice activities, coaches can be better equipped to ensure that youth will see greater gains in skill-related fitness and health with likely reductions in risk of sports-related injury.

While there is not one combination of exercises, sets, and repetitions that has proven to optimize training adaptations, it appears that multifaceted and integrative programs that increase muscle strength, enhance movement mechanics, and improve functional abilities appear to be the most effective strategy for reducing sports-related injuries in young athletes (40). Integrative neuromuscular training that is focused initially on fundamental skill mastery in early childhood may improve the capacity to achieve sport-related and dynamic interceptive skills during adolescence. Likewise, fundamental movement skills competency in children and adolescents can increase physical activity, improve cardiorespiratory fitness, and enhance body composition (BMI z-score) (59). Although there are many approaches to potentially reduce youth sports-related injuries (*e.g.*, coaching education, safe equipment, proper nutrition), enhancing physical fitness as a preventive health measure is considered a cornerstone of multi-component programs for school-aged youth. This is an important consideration for health care providers who often perform preparticipation physical examinations in order to assess a young athlete's readiness for sport (47). In addition to the medical examination (including a musculoskeletal assessment), health care providers should inquire about a patient's participation in physical activities over the past few months. Since training errors (*e.g.,* "too much, too soon") are a common theme in many sports-related injuries in youth (65), there is an ongoing need to ensure that aspiring young athletes participate in integrative neuromuscular conditioning programs before the start of the sport season and continue training in a modified program throughout the competitive season (13,27,28).

Proper education and instruction are paramount for safe, effective, and enjoyable integrative neuromuscular training (Fig. 4). However, initiation of integrative neuromuscular training during preadolescence also must be challenging and enjoyable to keep the children interested and motivated in continuing participation (22,24). Age-appropriate education and qualified instruction are essential to successfully integrate different components related to the mastery of fundamental movements, program variation, exercise progression, and structured recovery. Because a growing number of school-aged youth are exposed to strength and conditioning activities in physical education classes and community recreational and sports training programs (24,54), the importance of qualified and enthusiastic instruction that is consistent with individual needs, goals, and abilities is critical. Children and adolescents who participate in integrative neuromuscular training programs should be knowledgeable of the potential risks and concerns associated with exercise equipment (*e.g.,* treadmills, weight machines, barbells) and should be aware of the potential risk of injury if they do not follow established training guidelines and safety procedures. Ultimately, education and instruction will determine the levels of success that can be achieved within each component of an integrative neuromuscular training program (Fig. 4).

Conclusion

Regular participation in organized youth sports does not ensure that youth are adequately exposed to fitness regimens and activities that sufficiently improve health and sports-specific fitness to minimize risk of injury and promote lifelong health and fitness. Accordingly, participation in physical activity should not begin with competitive sport, but should evolve out of regular participation in a well-rounded preparatory conditioning program. Integrative neuromuscular training programs that incorporate a variety of fundamental movements designed to enhance both health and skill-related fitness may be most beneficial if initiated during preadolescence. Moreover, integrative neuromuscular training is more likely to have long-lasting effects if qualified professionals focus on the process of developing fundamental motor skills rather than the product of enhanced sports performance. Integrative neuromuscular training maintained throughout childhood and adolescence will likely improve movement biomechanics, minimize the risk of sports-related injury, and promote positive health outcomes during adulthood. With a program based on the physical and psychosocial uniqueness of children, integrative neuromuscular training that is sensibly progressed over time and consistent with individual needs, goals, and abilities can be integral to development and promotion of a health-oriented approach to lifelong physical activity.

Acknowledgments

Funding was provided by National Institutes of Health Grants R01-AR049735, R01-AR055563, and R01-AR056259.

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