THE PHYSIOLOGICAL DEMANDS OF YOUTH ARTISTIC GYMNASTICS; APPLICATIONS TO STRENGTH AND CONDITIONING

ABSTRACT

The sport of artistic gymnastics involves a series of complex events that can expose young gymnasts to relatively high forces. The sport is recognized as attracting early specialization, in which young children are exposed to a high volume of sports-specific training. Leading world authorities advocate that young athletes should participate in strength and conditioning related activities in order to increase athlete robustness and reduce the relative risk of injury. The purpose of this commentary is to provide a needs analysis of artistic gymnastics, and to highlight key issues surrounding training that practitioners should consider when working with this unique population.

KEY WORDS

Youth, Training, Gymnastics, Physical determinants, Performance,

INTRODUCTION

The sport of gymnastics possesses a range of sub-disciplines, including rhythmic, trampolining, tumbling and acrobatic, with an estimated 50 million participating world wide (29); however, artistic gymnastics is one of the most popular in terms of participation rates among children and adolescents (29, 36). Despite certain similarities, the demands of artistic gymnastics differ for males and females. Women's artistic gymnastics consists of four events (vault, uneven bars, balance beam, and the floor exercise), while men's artistic gymnastics comprizes six apparatus (floor, pommel horse, rings, vault, parallel bars, and high bar). The physical abilities necessary to perform successfully on each apparatus vary considerably in the required neuromuscular power, strength, flexibility, speed, co-ordination, balance, and energy system demands (47), and are summarised in *figure 1*. The development of these physical qualities in children and adolescents is non-linear due to interactions of growth, maturation, and training (112). Consequently, the development of physical components in young gymnasts can be complex (62) as the timing, tempo and magnitude of development will differ markedly between individuals of the same age (62). In addition to understanding the science behind the training process, practitioners working with young artistic gymnasts should also consider the key principles surrounding pediatric development to better understand the potential trainability and adaptability of gymnasts at different stages of development.

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PHYSICAL FITNESS REQUIREMENTS FOR ARTISTIC GYMNASTICS

Strength, power and speed

Strength. The sport of artistic gymnastics requires high levels of strength and power in the upper and lower limbs to successfully, and safely perform a dynamic and diverse set of movement skills in sequence (36). While these movements will invariably involve a combination of eccentric and concentric actions, the importance of isometric strength and body tonus should not be underestimated (18) as artistic gymnasts are judged by, and conditioned to, hold a sequence of technical shapes in both dynamic and static conditions (37). Thus, the ability to effectively recruit motor units in order to exert force at variable movement velocities appears to be an important determinant of performance for gymnasts from an early age. For example, during a routine on the floor, gymnasts are required to execute movement patterns that use various segments of the force-velocity curve and involve all types of muscular actions (74, 78).

Take-off characteristics for a double back somersault on the floor have reported vertical velocity of the centre of mass was 4.2 ± 0.46 m.s^{-1} for males, and 3.54 ± 0.85 m.s^{-1} for females at take-off (33) while a planche requires high levels of isometric muscular force (51). Furthermore, kinetic analysis of take-off forces during a straight back somersault tumbling series, revealed mean maximal vertical forces and maximal rate of force development were 6874 ± 1204 N, and 6829 ± 2651 N.s respectively (78). Specifically for boys, moving in and out of different positions with control is particularly important on apparatus that is upper body dominant (e.g. the rings, pommel horse) (18). Gymnasts also rely heavily on lower-limb eccentric strength, as they are frequently exposed to landing forces from varying heights, velocities and rotations (34). Researchers have shown that when simulating the impact velocities female gymnasts experience during dismounts from the balance beam and uneven bars (drop landings from 0.69 m 1.25 m and 1.82 m), the gymnasts were required to tolerate vertical peak forces that exceeded nine times their body weight (75). Those able to absorb such forces in an aesthetic manner obtain less deductions, which results in a higher overall score. Therefore, it is evident that gymnasts must manipulate the impulse-momentum relationship to maximize force production for skill execution and to safely tolerate landing forces to avoid injury.

Power. Similarly, peak power is considered to be an essential component of successful gymnastics performance (47). Gymnasts with higher concentric and eccentric strength and power are able to produce more forceful muscle actions at higher velocities (32), enabling the execution of more challenging acrobatic skills. Researchers have shown that resistance training programs can improve relative power-to-mass ratios in gymnasts through increasing peak power outputs during both countermovement and squat jumps (46% and 43% improvement respectively), and reducing fat mass whilst increasing lean muscle mass. The authors stated that as a result of these adaptations, the gymnasts were able to jump higher, providing increased flight time in which to perform more advanced technical skills, thereby increasing their score potential (32).

The ability to produce high levels of muscular power is salient upon the type of muscular action involved and researchers have shown that when a muscle performs an eccentric action prior to a concentric action, greater power outputs are produced compared to a concentric action in isolation (55). This sequencing of an eccentric contraction followed immediately by a concentric contraction is referred to as the stretch-shortening cycle (SSC) (55). Research has shown that SSC utilization of both upper and lower limbs are key performance indicators for young gymnasts aged 8 to 15 years old (11, 12). For example, research has shown that young gymnasts with an explosive take-off from the board (short repulsive board contact time and high take-off velocity) had increased post-flight times, which resulted in fewer deductions and higher scores in vaulting performance (11). Evidence suggests that during the floor exercise, explosive tumbling involves take-offs with contact times between 115 ± 10 to 125 ± 11 ms (73), underlining the importance of fast-SSC actions (ground contact times < 250ms) for performance (12). However, recently researchers have found that young elite male gymnasts had unexpectedly poor fast-SSC actions when tested during a 30 cm drop jump protocol (107). The authors suggested that the gymnasts were not effective in their execution of the drop jump due to an over-reliance of sprung surfaces and longer take-off foot contacts during training of tumbling and vaulting performance (107). The findings could also indicate that gymnasts are very proficient at gymnastics skills which require SSC actions, but have not experienced the use of drop jumps in their training on non-sprung surfaces (58).

Speed. The phase of running prior to the point at which an individual reaches their maximum velocity is referred to as the acceleration phase. The ability to accelerate effectively requires the application of high resultant ground reaction forces in a horizontal direction, relative to body weight (80). Maximal velocity usually occurs between 15-30 metres in young athletes (76), and refers to the point at which external forces are no longer changing the velocity. The approach to the vault in gymnastics requires rapid acceleration up to 25 m to facilitate an explosive take-off from the springboard (10). Achieving a high speed during the approach and subsequent power output for the aerial phase is directly associated with improved scores on the vault (12). Elite male gymnasts demonstrate speeds of up to 10.9 $m.s^{-1}$ during competition (3). In young national standard female gymnasts, average speeds of over 18 m were 6.07$m.s^{-1}$ (8-10 years old), 6.31$m.s^{-1}$ (11-12 years old) and 6.20 $m.s^{-1}$ (13-14 years old), respectively (12). Interestingly, the results indicate a reduction in sprint speed together with an increase in body mass and height of gymnasts aged from 11-12 to 13-14 years old. As the natural development of speed throughout childhood and adolescence is thought to follow a non-linear process (66), the results could reflect a period of ‘adolescent awkwardness’ whereby a temporary disruption in motor co-ordination occurs due to growth (8). Furthermore, a fast vault run-up speed and resultant take-off velocity from the spring board were found to be strong predictors (r^2 >.64) of floor tumbling ability (12), demonstrating the importance of developing high running speeds for artistic gymnastics.

Balance and stabilization

The aptitude to balance and stabilize the body is a complex process involving sensory information from the vestibular, visual and proprioceptive systems (31), to maintain the body's centre of gravity over the base of support (44, 87). Gymnasts' requires the ability to balance and maintain postural control via the upper and lower extremity, during both static and dynamic movements. Factors that affect young gymnasts' ability to stabilize their bodies during such tasks include; the size of the base of support, centre of gravity height, and number of limbs in contact with the apparatus (40). Unique to the sport of artistic gymnastics, the equipment's mechanical properties affect the stability of the apparatus which also influences the difficulty of the tasks (16). For example, the handstand is a fundamental skill for male and female gymnasts which has considerably different demands to maintain stability when performed on different apparatus such as the floor, beam, parallel bars, and rings (16, 40). A recent review concluded that when aiming to retain stability during a handstand, the 'wrist strategy' can be adopted to maintain the position, providing the gymnasts body remains in a vertical position (40). The 'wrist strategy' involves increasing the centre of pressure in the fingers or wrists depending on the movement direction of the centre of gravity (105). However, if the area of support is smaller for example on the uneven bars, the "shoulder strategy" may be required to maintain balance (40).

Expectedly, researchers have shown that gymnasts have superior balance ability when compared with controls (2, 15), and various other sports (19, 44). Recent findings from a large data-set of children aged 5 to 14, found that scores from the balance error scoring system (BESS), significantly improved with increasing age (39). Given the effects of gymnastics-specific training on balance (2, 15, 19, 44), and the natural improvements in balance that manifest during childhood (39), devoting large amounts of time to balance training during young gymnasts' strength and conditioning provision may not be warranted. Instead, warm ups and injury prevention sessions would serve as the opportune time to incorporate exercises that enhance postural/trunk control, stability, and that emphasize high quality (force absorption) landing tasks.

Energy demands of gymnastics

The duration of performance within artistic gymnastics varies amongst activities; the vault exercise can last approximately five seconds, while the beam and floor exercises can last up to 90 seconds (47). Both the explosive nature of the sport and short duration of the disciplines dictate that the main supply of adenosine triphosphate (ATP) in gymnastics is via the ATP-PCr and anaerobic glycolytic energy systems. Researchers have shown peak blood lactate concentrations (L_{max}) above 4 mmol/l for elite males and females on all apparatus, with the exception of the vault (2.4-2.6 mmol/l) (69). Owing to the variety in duration, intensity and tempo of artistic gymnastics activities and the variability of muscle contraction types during competitive routines, gymnasts never reach a "steady state" in performance (47). Therefore, estimating energy costs from the relationship between VO_2 and HR is likely to be invalid when drawn from laboratory testing of the athletes (47).

According to longitudinal data regarding the aerobic capacity of gymnasts, typical maximal oxygen uptake (VO_{2max}) values have remained around 50 ml/kg/min over the last five decades (49). It would appear that aerobic capacity is not a key determinant of performance for artistic gymnasts. This is perhaps unsurprising considering gymnasts are conditioned to perform short, explosive routines, relying predominantly on anaerobic metabolism. However, this is not to say that possessing some level of aerobic capacity is unnecessary (47), as it has been shown that adolescent female gymnasts attain VO_{2max} profiles as high as 85% (relative to body mass) following competitive routines, such as the floor exercise (69). Additionally, heart rate data of elite gymnasts has been investigated during each apparatus for both males and females (49, 69). Maximal HRs were found to be approximately >180 ± 11.33 beats per minute, with the exception of the vault (and the rings as HR data was not included in the study) (49, 69), demonstrating the high intensity nature of the sport. It would appear from the aforementioned data that during competitive routines, elite gymnasts work close to their metabolic thresholds (46), indicating the need for high-intensity based conditioning programs. Crucially, gymnasts that are able to recover more efficiently between a series of skills or different events, are more likely to sustain a higher level of performance, and reduce their relative risk of injury through fatigue. Therefore, while it may not be a primary training emphasis during the developmental years (62), strength and conditioning programs for youth gymnasts should not eliminate aerobic conditioning as a training stimuli, especially when trying to optimise recovery during repeated bouts of exercise.

Childhood physiology: an increased ability to recover from high-intensity exercise

Balancing fatigue during intense training sessions and technical competency of difficult skills is essential to optimize the safety of young gymnasts (47). Performing highly skillful routines in a fatigued state may increase the risk of injury (97). Thus, it is important that young gymnasts are able to facilitate a fast recovery from high-intensity exercise. Researchers have shown that children recover more quickly from high intensity exercise than adults (28). From a mechanical perspective, children are unable to generate relative power outputs to the same magnitude as adults (95), which is likely to result in less relative fatigue (28). Similarly, researchers have shown that children's type II muscle fibres are similar or smaller in cross-sectional area than their type I fibres (113), which suggests an extensive underuse of type II motor units during the pre-pubertal years (21). Thus, children's neuromuscular immaturity may impact on their ability to maximally recruit higher-order, type II motor units. This indicates a greater reliance on lower-order type I motor units that facilitates a faster resynthesis of energy substrates, resulting in a faster recovery (28). Additionally, faster PCr resynthesis has been attributed to children's greater reliance on oxidative metabolism and lower dependence on glycolytic metabolism (21). Children also produce lactate at a lower rate than adults during maximal exercise, resulting in reduced lactate accumulation, though their rate of lactate removal appears to be the same (21). Thus, when aiming to develop anaerobic capacity in young gymnasts, practitioners should consider the influence of growth and maturation on the trainability of this system. Furthermore, young gymnasts will require a certain degree of aerobic conditioning to recover from the high-intensity exercise that the sport demands. It is therefore important for coaches' to encompass both anaerobic and aerobic conditioning stimuli in artistic gymnasts programming.

Flexibility and mobility

Unlike other sports which require optimal ranges of motion for skill acquisition and mechanical advantage (62), artistic gymnastics is an aesthetic sport which demands large ranges of motion to achieve certain positions and techniques for the purpose of scoring (37). For example, following appropriate preparation, male gymnasts perform dislocation elements on the high bar and rings (48), underlining the extreme ranges of motion required by the sport. Furthermore, in women's gymnastics, the Code of Points penalises gymnasts that do not attain 180 degrees of splits during leaps, jumps and acrobatic skills (37). It is essential to note that while the ability to achieve these limb positions relies heavily on extreme ranges of motion, these movements must be supplemented with appropriate levels of muscle strength throughout the range of motion (18, 48).

TRAINING CONSIDERATIONS FOR YOUNG ARTISTIC GYMNASTS

Growth, maturation and training

Intuitively, gymnastics coaches may favour the selection of late maturing individuals and those that are genetically predetermined to have shorter and slighter statures (particularly in women's gymnastics). However, children develop biologically at different rates, particularly around puberty whereby they experience rapid fluctuations in growth (106). Chronological age is not a valid or reliable indication of maturational status (4). While technical competency will always be a key determinant of training prescription, it is imperative that consideration is given to biological maturation when training young gymnasts within the same competitive age group. Predicting somatic maturity may be a useful and practically viable marker for coaches to monitor gymnasts' growth and maturation (63). For example, owing to the influence of stature on performance and the high representation of later maturing youth (108), practitioners could determine the percentage of predicted adult stature (53), which offers a practical and reasonably accurate measure of estimated maturity for youth populations (53).

With a clear understanding of biological maturation, practitioners working with young gymnasts should be better placed to prescribe and coach developmentally appropriate training strategies that meet the specific needs and goals of the individual (7, 58, 60). For example, by collecting basic anthropometric data on a quarterly basis, practitioners can identify with reasonable accuracy when a gymnast is experiencing a growth spurt, and can tailor training accordingly. From a physical perspective, when working with youth who are undergoing rapid periods of growth, coaches should spend time addressing any decrements in range of movement (foam rolling soft tissue, unloaded stretches) and balance, due to the changes in the height of centre of gravity (static and dynamic balancing/stabilizing activities). Furthermore, coaches must individualize programmes to target deficits in strength resulting in muscle imbalances (89). There are numerious training strategies available to practitioners to develop the physical performance characteristics of young artistic gymnasts, which can be seen in *figure 2*. The challenge of working with youth who are experiencing a growth spurt is exacerbated when sport-specific training loads are high, which are common in youth gymnastics (90). This scenario can lead to high amounts of accumulated fatigue at a time when young gymnasts' are experiencing significant biomechanical alterations (e.g. increased limb length, reduced relative strength) as a result of growth. Data suggest that the growth spurt poses an increased risk of injury in young athletes as a result of musculoskeletal vulnerability (70), especially with respect to overuse (14), and acute traumatic (111) injuries. Due to the heightened injury risk during this stage of development, routine screening of basic anthropometric data, and some form of movement screening (e.g. the tuck jump assessment or drop jump testing for knee valgus during landings). Similarly, practitioners are also advised to make use of some form of health and well-being questionnaires to monitor sleep, fatigue, muscle soreness, mood, levels of social interaction, and any onset of pain that could be associated with musculoskeletal injuries (58). Furthermore, coaches must carefully monitor training loads (both volume and intensity) and closely monitor the total loads experienced by young gymnasts. This requires a quantification of training load during strength and conditioning training, sport-specific training, and competitions to reduce the risk of; overuse-type injuries, non-functional overreaching, overtraining syndrome, and burnout (20). Practitioners should adopt an integrated approach to quantigy training loads, using a combination of both internal and external load metrics to provide insight into the total stress placed on the athletes (9).

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A holistic approach to training

Research from numerous reports in various sports have suggested that children specializing in a single sport prior to puberty may be disadvantaged at a later stage (45, 81, 83). Historically, gymnastics coaches prioritise the implementation of traditional gymnastics-specific conditioning programs from a very early age (6, 92), which often involves circuits of body weight exercises and repetitions of skills. However, while such training programs typically only involve the development of specific physical qualities and movement patterns for gymnastics, it is recognized that well-rounded athleticism should be developed in all youth (58). It is proposed that integrative neuromuscular training (INT), which uses a combination of general and specific strength and conditioning activities to enhance health and skill-related components of fitness (41) could be an advantantagous addition to gymnasts programs to enhance performance and reduce the relative risk of sport-related injury. Crucially, training provision for youth should be programmed in a holistic and integrated manner in order to provide a variety of training stimuli to develop multiple fitness components and overall athleticism (44).

Conventionally, gymnastics coaches' conditioning programs are largely skill driven owing to the specific demands of the sport (50). Training specificity cannot be underestimated in this sport and can be used to prepare gymnasts effectively, providing training is progressively load. However, the broader field of strength and conditioning may offer additional benefits to the physical preparation of gymnasts (32, 38, 68, 91). Indeed, the challenge for the strength and conditioning coach working with young gymnasts is to safely provide an effective training stimulus that is different to that which they experience during their sport-specific training, yet is still relevant to their athletic development. Young artistic gymnasts will likely be accustomed to experiencing high ground reaction forces during activities such as tumbling or vaulting (54, 103). For example, pre-pubescent female gymnasts have been shown to endure vertical ground reaction forces of 2-4 times body weight at the wrist, and 3-8 times body weight at the ankle, on the floor apparatus (13). A major role of the strength and conditioning coach is to increase the robustness of the child to repeatedly tolerate these ground reaction forces safely and effectively, in both a fatigued and non-fatigued state. Frequent exposure to specific movement patterns whereby the application of force is not varied may result in chronically overstressing the musculoskeletal system (5, 20). Strength and conditioning coaches working within early specialization sports should be particularly aware of the benefits that movement variability provide for motor skill development and reducing the risk of overuse injuries (5, 58). The strength and conditioning coach has a role to play in developing general levels of athleticism in the young child that will facilitate their lifelong participation in sports and activities outside of gymnastics. In the event that a young gymnast decides to disengage from the sport, it is important that they are physically prepared for the demands of other sports or physical activities (58), not just attempting to maximize specific abilities for gymnastics. Finally, coaches should be mindful that strength and conditioning provision with young gymnasts should be fun, challenging, and enjoyable, to optimise athlete buy-in and long-term adherence to programmes.

Strength and power training

Traditional fears that resistance training induces excessive muscle hypertrophy, resulting in increased body mass has anecdotally discouraged some gymnastics coaches from using this training modality, particularly with young females (32). However, the adaptations from resistance training in youth prior to the onset of puberty are likely to be neuromuscular in nature (35), meaning that large increases in muscle cross-sectional area are unlikely (62). Consequently, increases in strength during this stage of development - especially in the early stages of the training intervention - will be as a result of improved neuromuscular qualities (motor unit recruitment, synchronization & firing frequency) as opposed to hypertrophic adaptations (60). Following the adolescent growth spurt, both neurological and morphological adaptations may also occur as a result of training (62). However, as the goal for most gymnasts would be to develop relative strength, appropriate training prescription (lower repetition ranges, higher intensities, and longer rest periods) should result in myofibrillar hypertrophy and increased functional mass, as opposed to sarcoplasmic hypertrophy and increased non-functional mass (102). Sex differences in the rate of muscular growth are apparent following the onset of puberty, with males displaying accelerated gains in strength (66) and females a reduction in strength and power production (88). Decrements in neuromuscular strength during this stage of development may increase females' risk of certain injuries, especially those involving the anterior cruciate ligament (ACL) (30, 93), an injury which is highly prevalent during landings in gymnastics (43). Gymnasts are required to 'stick' landings following certain skills and dismounts to avoid large deductions and to optimize performance (37); therefore, the need to develop eccentric strength to assist in force disspaction strategies is necessary. Programs which specifically focus on the development of eccentric strength in highly trained athletes improve power, velocity and jump height characteristics, compared to controls that trained without an accentuated eccentric load (104). However, there remains a lack of literature that has specifically examined the effects of eccentric strength development in young athletes. Short term neuromuscular training interventions which focus on 'soft' landings with an emphasis on knee and hip flexion, significantly improved adolescent female athletes' biomechanics during landings (82), which could be a beneficial strategy for gymnasts to adpopt for dismounts and 'sticking' landings. Given that gymnasts may develop greater activation in their knee extensor muscles due to a gymnastics-training induced adaptation prior to puberty (77), and females are predisposed to deficits in hamstring strength following the onset of puberty (42), integrated neuromuscular training programmes (84, 86) targeting hamstring strengthening should be incorporated into pre-pubertal and adolescent young gymnasts training programmes.

Irrespective of the stage of development, resistance training for gymnasts with a low training age and low levels of technical competency should begin with exercises that are low to moderate in intensity (e.g. body weight) and technically simple (85). The primary focus should centre on building a base level of muscular strength and developing a broad range of robust movement patterns (58). Over time, gymnasts will become proficient at body weight exercises and will ultimately require a new stimulus to overload the body for further adaptation (99). Intensity (or load) can be increased with minimal or no equipment, by altering the body's position against gravity. Additional external load in the form of free weights, elastic resistance bands and medicine balls, has been shown to be a safe and effective means of enhancing young athletes' strength within resistance training programs (58). Unfortunately, very few studies have investigated the effects of resistance training programs with artistic gymnasts. Recently, one study in elite pre-pubertal female gymnasts found that a 16-week training intervention, combing high impact plyometrics with heavy resistance training, was more effective in improving various parameters of drop jumps (e.g. fight time, contact time, flight-contact ratio, and estimated mechanical power) than habitual skill training (68). As a result, the authors recommended a reduction in time spent on technical routines and repeatedly performing gymnastics movements, and the inclusion of 2 to 3 intense strength and power workouts per week (68), prescription guidelines that are in line with existing youth resistance training guidelines (23, 60). Furthermore, a recent meta-analysis in well-trained young athletes has concluded that on the premise that technical competency has been suitably developed, the most effective dose-response relationship occurs with; conventional resistance training programmes of periods > 23 weeks, 5 sets per exercise, 6–8 repetitions per set, a training intensity of 80–89% of 1 RM (56). This underlines the need for progressive overload even in youth, in order to ensure ongoing neuromuscular adaptation.

It should also be stressed that when technical proficiency is evident, young gymnasts will likely require exposure to larger external loads, typically elicited through barbell related activities such as squatting, deadlifting, lunging, and weightlifting exercises (including their derivatives) to promote further adaptations. Resistance training should be implemented as alternative training session to gymnastics training, and not merely as an addition. Regular resistance training should form part of young gymnasts' training programs to develop/maintain levels of muscular strength, avoid detraining of neuromuscular qualities, and to prevent over-use injuries associated with high volumes/intensities of sports-specific training (20, 23, 25, 26, 60, 110). One to three resistance training sessions per week are recommended for young athletes, providing that adequate time for rest and recovery is integrated into the gymnasts' periodized plan (60).

Gymnastic performance is characterized by powerful muscle actions, the type of training must acknowledge the principle of specificity for optimal adaptations, with high contractile velocities are appropriate training modalites (32). As training age and technical competency increases over time, resistance training exercises and weightlifting movements can be performed more explosively to promote appropriate neuromuscular adaptations (52). French et al. (32) utilised a power-specific resistance training programme in elite female gymnasts, which significantly enhanced whole body muscular power capacities. The training included exercises which focused on applying as much force as possible in the shortest period of time which is an important factor for performance in gymnastics (32). This resulted in an increased level of performance, as demonstrated in their competition scores (especially on the floor), due to improvements in leaping and tumbling (32). Furthermore, a recent study investigated the effects of a 6-week resistance training program on jumping performance in pre-pubertal rhythmic gymnasts using sport specific (three repetitions of ten dynamic exercises wearing a weighted belt that was 6% of body mass) and non-specific (a moderate load/high repetition resistance training program with dumbbells) interventions (91). While both strength training programs increased lower limb explosive strength by 6-7%, only the non-specific training intervention significantly improved flight time in the hopping test which assessed leg stiffness (91). Drop jumps are a highly complex task for young athletes to develop proficiency in (6), however importantly, they are primarily used as a training tool to target fast or slow SSC function through progressive overload. Cueing shorter contact times during drop jumps typically encourages faster SSC activity, while cueing athletes to prioritise maximimum jump height may result in slower SSC actions (65). An increase in leg stiffness may result in reduced ground contact times, leading to a more efficient utilization of the SSC (1, 55). Shorter contact times with rapid amortization periods have been shown to result in greater reutilization of elastic energy (115). While gymnasts need increased leg stiffness for fast SSC actions, the optimal amount of leg stiffness is task specific (71). Certain skills in gymnasts will require a more compliant system involving longer contact times and slower SSC actions, resulting in greater jump heights (1). Plyometrics have been shown to enhance leg stiffness in young boys (59) as well as promote improvements in rebound jump height, vertical jump performance, running velocity, and rate of force development (61), all of which are highly relevant to gymnastics.

However, as a large proportion of gymnastics training already involves plyometric exercise, prescribing an alternative training stimulus that focuses on different regions of the force-velocity curve may be more beneficial such as, strength training (high force), or weightlifting derivatives (high force-moderate velocities). Cumulatively, existing research would suggest that integrating resistance training with gymnastic-specific strength programs may indeed provide an additional training stimulus to enhance performance and reduce injury risk in young gymnasts. While studies have demonstrated the benefits of resistance training for adult gymnasts (32), the effects of a long-term resistance training intervention in pre-pubertal and adolescent gymnasts is yet to be explored.

Speed Development

The natural development of speed throughout childhood and adolescence is thought to follow a non-linear process (66), with fluctuating improvements in sprint performance occurring in pre-adolescent and adolescent periods (112). Researchers have indicated that the trainability of sprint speed is optimal when the prescription matches the natural adaptive processes that occur during maturation, a phenomenon referred to as "synergistic adaptation" (64). For example, when aiming to increase sprint speed in pre-pubertal populations, utilizing plyometrics to elicit neurally-mediated adaptations during this stage of maturation is a favorable form of training (24, 64). For post-pubertal males experiencing other maturity-related changes, such as natural increases in muscle mass and changes in circulating androgens, (66, 109) combined resistance training and plyometrics may be the most optimal training stimulus to improve sprinting velocity (64). It is important to note that coaches should pre-screen athletes individually prior to implementing plyometrics to ensure good technical competency is present during landing tasks (57). This is particularly important for gymnasts if the exercises chosen are not performed on sprung surfaces that the gymnasts are accustomed to. However, as previously stated, gymnasts experience a large amount of plyometric based training within their sport and therefore, strength and conditioning coaches must carefully consider the prescription of such training. Controlling the volume (number of foot contacts) and intensity (via exercise choice) is critical for appropriate periodization of gymnasts' training.

While integrated neuromuscular programs inclusive of resistance training and plyometrics increase speed (albeit indirectly at times) in young athletes (22, 36, 41, 61, 64, 94), specific speed training may provide additional adaptations in running speed for young gymnasts. The vault run-up approach in gymnastics is up to 25 m, thus technical coaching should focus primarily on developing relevant acceleration mechanics and horizontal force production, as opposed to those associated with maximal running velocity. A recent meta-analysis concluded that prescription of speed training for youth should occur twice a week and comprise of up to 16 sprints of approximately 20 m, with a work-to-rest ratio of 1:25 (79). Furthermore, the underlying ability to run fast towards the take-off board and vaulting table relies on both the gymnast's accelerative capacity and the ability to visually control and regulate the approach (10, 12). Gymnasts that achieve high speeds when running but slow down as they approach the vault will limit their performance (10, 12). Therefore, coaches should aim to develop running speed throughout the vaulting or tumbling sequence in young gymnasts to optimise the transfer of this ability to vaulting performance. To facilitate this transfer, researchers have recommended that coaches' implement targeting activities early on with young gymnasts, such as practising simple vaults from different approach distances (10).

Flexibility and mobility training strategies

It is common practise for gymnastics coaches to utilize the proposed sensitive period prior to puberty (98) for developing optimal levels of flexibility in gymnasts. Following the onset of the pubescent growth spurt, researchers have shown that range of motion plateaus or declines, particularly in males (27). Thus, due to the scoring criteria involved in gymnastics which rewards extreme ranges of motion, coaches should emphasize flexibility training throughout childhood and adolensese to maximize whole body range of motion. However, as a caveat to this, it must be recognized that appropriate levels of muscular strength are required to safeguard the young gymnast when using potentially extreme ranges of motion. Thus, strength and conditioning provision of gymnasts should be directed towards balancing the development of large ranges of motion around joints with appropriate strength and neuromuscular stability to reduce injury risk and enhance skill acquisition potential.

Coaches should be aware that there are a number of training modalities available to develop optimal levels of flexibility and mobility in young artistic gymnasts. For static stretches, durations of 10 to 30 seconds, three times per exercise appear optimal, as longer durations may result in greater gains but a potential weakening of connective tissue (67, 98). Gymnasts often stretch on a daily basis, as frequency is an important principle of training for maintaining and improving flexibility, and of importance, there are no studies in children that have shown adverse effects to this approach (98). For gymnasts with a greater training age, ballistic stretching can be an effective method to increase ranges of motion, providing they are performed under control (98). Proprioceptive neuromuscular facilitation (PNF) stretching can result in large improvements in range of motion in youth populations (96, 114). While many gymnastics coaches utilize this technique, caution is necessary so that stretching does not exceed the gymnasts' limits and cause injury (98). This highlights the need for appropriate prescription and supervision when choosing methods to develop range of motion in young gymnasts.

Recently, vibration training has been shown to be very effective in enhancing flexibility and range of motion in young gymnasts (72, 100, 101), with acute improvements of up to 400% and chronic adaptations of up to 100% reported (101). Greater benefits from vibration-training may occur in the gymnast's less flexible leg due to the greater potential for improvement in range of motion available (72). While the mechanisms underpinning these large improvements in flexibly from vibration-training are currently unknown, proposed theories include reduced pain (72, 100), inhibited activation of antagonist muscles (17) and increased blood flow resulting in increased tissue temperature (98).

SUMMARY

Strength and conditioning coaches working with young gymnasts must provide an effective training stimulus that is different from what they experience during their sport-specific gymnastics training. Due to the demands of the sport, strength, speed, power, flexibility/mobility, and anaerobic power appear to be the key determinants of artistic gymnastics performance; all of which strength and conditioning can improve with appropriate training prescription. When looking to develop these physical capacities in young gymnasts a number of training strategies can be adopted; however, technical competency must be prioritised at all times. Importantly, when designing training programs, coaches should be aware of the influence of growth and maturation can have on the trainability of physical abilities.

FIGURE LEGENDS

Figure 1. The physical demands of artistic gymnastics

Figure 2. Training strategies for the development of physical characteristic in young artistic gymnasts

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