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Physiological Aspects of Early Specialized Athletic Training in Children

Thomas W. Rowland

Performance in all forms of motor activity related to sport performance improves progressively during the course of the childhood years as a consequence of normal growth and development. Whether (a) sport training can accelerate and ultimately enhance this biological development and (b) the existence of certain ages when training might prove to be more effective in improving performance, particularly early in childhood, remains uncertain. Physiological adaptations to endurance training in prepubertal children (improvements in maximal oxygen uptake) are dampened compared with adults, but enhancements of strength following resistance training are equally effective at all ages. The extent that intensive training regimens characteristic of early sport specialization in children can trigger physiological and performance adaptations may therefore depend on the form of exercise involved. Clearly, additional research is needed to enhance the understanding of the physiological responses to intensive sport training in prepubertal individuals.

Keywords: youth sports, aerobic fitness, biological development, muscle strength

The biological complex of systems that contribute to athletic performance in children can be modulated by two factors. First, repetition of the performance (read, *training*) improves function. By placing stress on the complex system, each of its separate components is enhanced in response, resulting in an augmentation of overall system performance. This *plasticity* of system function, presumably reflecting an evolutionary-based natural selection value, is highly physiologically-specific. Cross-country runners get better by distance running and weightlifters improve strength by lifting weights. Second, the process of normal biological maturation, that two-decade period from birth to the late teen years, is characterized by the development of motor performance in all its aspects—strength, endurance, speed, coordination, and so forth. Such improvement is a reflection of both quantitative (growth) as well as qualitative (functional) changes occurring in the maturation process.

This special issue of *Kinesiology Review* is dedicated to examining the wisdom (or lack of) in the juxtaposition of these two processes. What happens to this complex adaptive system of athletic performance when one superimposes early sport training regimens on the process of normal growth and development? Are the effects on sport performance additive and beneficial or are they injurious to long-term success and enjoyment in athletics? Which approach is "better": early specialized sport training during childhood, beginning as young as 5 years of age; or a multilateral involvement with many sports, delaying more specialized, intensive athletic training until the advent of adolescence?

Advocates of the former approach argue that acceleration of the normal process of increased fitness by early training results in an early peak of performance which is necessary for elite performance in some sports (e.g., gymnastics, figure skating) (Baker, 2003; Ericsson, Nandagopal, & Roring, 2009). Those advocating delayed specialized training are concerned that such early training places undue stress—physical, psychological, and sociological—on growing children, with early "burnout" and risk of injuries which are counterproductive to long-term involvement and performance in sport (Bompa, 2000).

The controversy—at times highly emotionally laden—between the supporters of each approach has encompassed a wide variety of medical, psychological, developmental, philosophical, and even legal issues. This article will be consciously restricted to a consideration of the physiological aspects that have bearing on the early sport specialization question. Specifically, the issue to be addressed here is the following: *Are there unique aspects of the physiological responses to athletic training which have bearing on its timing—early or delayed—during the growing years?* This article will consider the domains of aerobic fitness, muscle strength fitness, and short-burst (anaerobic) fitness in assessing differential responses to training in postpubertal and prepubertal individuals. This information can then be placed into context based on the other articles in this issue.

Rowland is with the Department of Pediatrics, Baystate Medical Center, Springfield, MA.

Physiological Contributions to Early Sport Training

Physiologic functional capacities have traditionally been considered closely linked to athletic performance. Some of these processes directly affect muscular function (muscle force production defines strength and performance in wrestlers), while others act indirectly as homeostatic responses that support high levels of athletic performance (cardiovascular adaptations which contribute to thermoregulation during exercise). In adults, each of these physiological mechanisms can be significantly improved through function-specific physical training (Wilmore & Costill, 1994); as well, each is steadily enhanced in the process of normal growth and development during childhood (Rowland, 2005).

In this article key questions are considered: (a) Do the same links of physiology and sport performance observed in adults exist in growing children? (b) Is the plasticity of physiologic function in response to training of similar magnitude in the two populations? (c) Are there particular periods during the growing years when physical training is expected to be most efficacious in improving performance? The reader is forewarned that clear-cut answers to these questions are not currently at hand. Indeed, considerable challenges exist in attempting to draw conclusions from the current fund of knowledge for a number of reasons:

- Little evidence-based information is available regarding the unique physiological responses to physical training in child athletes. Most studies surrounding this issue are simply descriptive cross-sectional investigations that profile characteristics of young athletes, providing no insight regarding training responses. Particularly lacking are longitudinal studies that track physiological adaptations to sport training in young athletes compared with a nontraining group of children.
- Success among specific sports is defined by different sets of physiological determinants. Performance in wrestling is largely a matter of explosive muscle strength. Distance runners rely on aerobic metabolic fitness. Performance in cycling and rowing is a combination of the two. Skill development in tennis and baseball, on the other hand, are largely linked to improvements in neuromuscular adaptations.
- Large interindividual variability can be expected in responses to physical training in both children and adults. This unpredictability of magnitude of change in a given physiologic marker with training in a particular individual appears to be principally genetically-based.
- Definitions of training are often vague. The nature of any training program for youth regarding factors such as intensity and duration, coaching skill, and social context vary widely, and this dissimilarity of training structure can be assumed to play a significant role in outcome measures of early sport specialization.

Aerobic Fitness

Performance in endurance sports events draws on energy provided by aerobic (oxygen-dependent) metabolism within the skeletal muscle. In turn, the effectiveness of this metabolic machinery is contingent on a supply of oxygen accessible to the exercising muscle (maximal oxygen uptake, or VO_{2max}) (Weibel, 1984). Absolute values of VO_{2max} rise progressively during the childhood and early adolescent years. An analysis of cross-sectional studies indicated that between ages 6 and 15, mean VO_{2max} increases from approximately 1.0 $L \cdot min^{-1}$ in all children to 2.0 $L \cdot min^{-1}$ in females and 2.8 $L \cdot min^{-1}$ in males (Krahenbuhl, Skinner, & Kohrt, 1985). This rise in aerobic fitness reflects the combined growth of the elements of the oxygen delivery chain (heart, lungs, blood volume) as well as the mass of metabolically-active tissue during exercise (i.e., skeletal muscle). That quantitative (size) rather than qualitative (functional) influences are responsible for the development of VO_{2max} during childhood is supported by the early study of McMiken (1976). He found that in 50 untrained males aged 7–13 years, age, height, and mass together accounted for 89% of the variance in VO_{2max}. Beunen et al. (2002) concluded that while changes in peak VO_2 are largely explained by body mass, level of habitual physical activity and biological maturity status also contribute independently to the growth of aerobic power during childhood.

During the course of childhood, performance in endurance events steadily improves as well. The average one-mile run times reported for 12,000 children indicated that between the ages of 5 and 13 values fell from 13:46 to 7:27 in males and from 15:00 to 10:00 in females (American Alliance for Health, Physical Education, Recreation and Dance, 1980). Interestingly, however, this improvement is not a consequence of increases in physiological aerobic fitness, as VO_{2max} expressed relative to body weight remains unchanged over the same period in males and declines slightly in females (Krahenbuhl et al., 1985). While a number of factors may be involved, the principal determinant of the augmented endurance performance during normal growth and development is increase in body size, resulting in progressively increasing stride length and diminished stride frequency to achieve a particular run distance. Metabolic demand is linked to stride frequency (Schmidt-Nielsen, 1984). When oxygen requirements for endurance exercise are related to stride length or stride frequency, age differences in oxygen demand for a particular endurance task are eliminated (Maliszewski & Freedson, 1996; Rowland et al., 1997). Superimposed on this normal development of physiological aerobic fitness, the impact of early endurance training can be assessed.

Training Effects on Aerobic Fitness

A period of endurance exercise training is expected to trigger an increase in VO_{2max} with concomitant improvements in endurance performance. The mechanisms underpinning this response involve (a) an increase in muscle aerobic metabolic capacity associated with (b) an expansion of the cardiovascular system involving a rise in blood volume and size of the left ventricle, which are responsible for augmenting maximal stroke volume and, consequently, maximal cardiac output. Current information outlined below indicates that both of these influences are observed to be less in prepubertal compared with postpubertal individuals.

Increases with training of +30–300% in aerobic enzyme activity in the skeletal muscles has been described in adults (Holloszy & Coyle, 1984). Hoppeler, Howald, and Conley (1985) reported a 40% increase in mitochondrial density in the vastus lateralis muscle of 11 adults following 6 weeks of cycle training. In the only pediatric study, Eriksson, Gollnick, and Saltin (1973) found a rise of +30% in succinate dehydrogenate (an aerobic enzyme) in vastus lateralis muscle biopsies in five 11- to 13-year-old males after a 6-week training period.

A considerable body of evidence suggests that the magnitude of the response of VO_{2max} to a period of structured endurance training is dampened in prepubertal children compared with mature individuals. In a group of previously sedentary young adults, a 3-month program of endurance exercise of sufficient duration (over 20 min) and frequency (three times a week) for 3 months at an intensity equivalent to 60–90% maximal heart rate can be expected to trigger a rise in VO_{2max} of approximately 25–30% (Hartley, 1992). Two observations here are important. First, the magnitude of response in VO_{2max} following such training regimens is generally observed to be inversely related to the initial pretraining value (Saltin, Hartley, Kilbom, & Astrand, 1969). That is, with training, VO_{2max} will usually increase substantially in a low-fit, previously sedentary adult, while little change is expected in a highly-fit distance runner. Second, in any group of adults a wide interindividual variability is observed in the extent of rise in VO_{2max} with endurance training. For example, Lortie et al. (1984) described a rise in VO_{2max} in previously sedentary individuals ranging from 5–88% in response to a 20-week training program. Interindividual variability among the general population in both VO_{2max} and the magnitude of improvement in aerobic physiologic fitness with endurance training are considered to be influenced by significant—and probably separate—genetic determinants.

Most of the many studies which have examined aerobic responses to endurance training in healthy, nonathletic prepubescent children in the same experimental model have demonstrated increases of VO_{2max} in the range of 5–10%. Very few have found a rise > 15%, and in several such investigations no statistically-significant improvement in VO_{2max} has been observed at all. Table 1 outlines a sample of such reports. Two meta-analyses have been performed on this body of data. In 1993, Payne and Morrow reviewed 23 studies and found an overall increase in VO_{2max} with training of 5% (Payne & Morrow, 1993). Seven years later, a review (Baquet, Van Praagh, & Berthoin, 2003) of 22 training studies with children selected for optimal research design concluded that aerobic training leads to an average improvement in VO_{2max} of 5–6%. Most recently, a review by Armstrong and Barker (2011) indicated that nine of 14 published training studies in children up to 11 years of age had revealed a significant increase, with an average increase in VO_{2max} of 6.7%. These findings have indicated a consistent picture of aerobic training plasticity in children

Table 1 Representative Studies Assessing VO_{2max} Changes Following a Period of Structured Endurance Exercise Training in Nonathletic Prepubertal Children

Study	N	Age (Years)	Sex	Duration (Weeks)	$\%VO_{2max}$ Increase
Gilliam & Freedson (1980)	11	7–9	M,F	12	NS
Lussier & Buskirk (1977)	16	8–12	M,F	12	7
McManus et al. (1997)	12	9	F	8	7.8
Rowland & Boyajian (1995)	37	10–12	M,F	12	6.7
Welsman et al. (1997)	17	10	F	8	NS
Williford et al. (1996)	12	12	M	15	10.3
Rowland et al. (1996)	31	10–12	M,F	13	5.4
Shore & Shephard (1998)	15	10	M,F	12	NS
Tolfrey et al. (1998)	12	10	M	12	NS
Tolfrey et al. (1998)	14	10	F	12	7.9
Williams et al. (2000)	13	10	M	8	NS
Ignico & Mahon (1995)	18	8–12	M,F	10	NS
Eliakim et al. (2001)	20	9	F	5	9.5
Yoshizawa et al. (1997)	8	4–6	F	72	18.9
Mobert et al. (1997)	12	13	M	28	12.2

NS = no statistically significant change.

which is, on average, no more than one-third of that expected in young adults.

Most studies have indicated similar responses to training in young males and young females (Payne & Morrow, 1993; Rowland & Boyajian, 1995). In those investigations revealing a greater response in prepubertal females, the sex difference has been explained by lower initial pretraining values in the females (Mandigout, Lecoq, Courteix, Guenon, & Obert, 2001; Tolfrey, Campbell, & Batterham, 1998). In the review by Armstrong and Barker (2011), a modest inverse relationship was observed between pretraining peak VO_2 and percent change with training.

On examining the findings in Table 1 there is no obvious relationship between duration of training and magnitude of VO_{2max} response. Still, it may be important to note that the three longest programs (15, 28, and 72 weeks) effected the greatest aerobic training response (+10, +12, and +19%, respectively). The longest study, by Yoshizawa, Honda, Nakamura, Itoh, and Watanabe (1997), triggered an 18.9% rise in VO_{2max} in eight young females aged 4–6 who trained by performing a 915-m run 6 days a week over a 6-month period, mimicking the magnitude of increases described in adults.

Considerable interindividual variability in aerobic plasticity with training of children has been observed. Rowland and Boyajian (1995) described changes in VO_{2max} for adolescents aged 11–13 years after a 12-week training program; one-third demonstrated an increase of less than 3%, while the greatest response was +21%.

There is no reason, a priori, to expect that the degree of plasticity of VO_{2max} with endurance training should be inferior in children compared with adults. Also, while a good number of suggestions have been offered to account for this observation, no truly satisfactory explanation has been forthcoming. Some ideas can be considered. For example, a number of the early training studies in children suffered from methodological weaknesses (lack of non-training controls, no documentation of training intensity, and others) (Rowland, 1985). Perhaps children do not engage themselves in training programs as effectively as adults, necessitating a higher training intensity in prepubertal subjects. Or, perhaps children are more physically active than adults in their daily lives, thereby effectively "self-training" and leaving less room for improvement in structured exercise programs.

Early on, Katch (1983, p. 242) proposed a physiological basis for the dampened response of VO_{2max} to endurance training in children:

> There is one critical time period in a child's life (termed the 'trigger point') which coincides with puberty in most children, but may occur earlier in some, below which the effects of physical conditioning will be minimal, or will not occur at al. … This trigger phenomenon is the result of modulating effects of hormones that initiate puberty and influence functional development and subsequent organic adaptations. In this context, the effects that the androgens and growth hormone have in the development of functional capacity, metabolism, and muscular development are especially important.

Mirwald, Bailey, Cameron, and Rasmuseen (1981) conducted a longitudinal study of change in VO_{2max} in 14 active and 11 inactive males aged 7–17 years, supporting the concept of a critical period during adolescence for augmenting aerobic responses to training. They found that before the adolescent growth spurt, no significant differences were observed in VO_{2max} between the two groups, but following this point, VO_{2max} rose faster in the active males.

It would be expected that the suggestion that hormonal changes at adolescence could serve as a critical point of enhancing aerobic plasticity could be resolved in a straightforward manner with a study directly comparing responses to a period of endurance training in pre- and postpubertal subjects. Unfortunately, such investigations are, in fact, challenging to perform given the serious difficulties of equating training stimulus and pretraining fitness levels in different groups of subjects. Indeed, few investigators have taken on the task and, perhaps predictably, have observed conflicting outcomes. Kobayashi et al. (1978) trained seven males from the ages of 9–10 until they were 15–16 years old. Average VO_{2max} per kg rose little until the age of peak height velocity at puberty, when values rose from 47.0 to 56.9 $ml \cdot kg^{-1} \cdot min^{-1}$. Unfortunately, a control group of nontraining children was not included in this study. On the other hand, the investigation by Weber, Kartodihardjo, and Klissouras (1976) revealed equal improvements in VO_{2max} after a 10-week period of exercise training (running, stepping, cycling) in 10-, 13-, and 16-year-old males.

By what biological mechanism might plasticity of VO_{2max} with training be diminished in children compared with mature individuals? As noted previously, increases in VO_{2max} in response to endurance training are mediated principally by two factors. First, increases in aerobic metabolic capacity of skeletal muscle occur as a consequence of augmented enzymatic activity and increases in cellular mitochondrial population. Since the volume of skeletal muscle changes little with endurance training, this rise in muscular metabolic capacity is evidenced by an increase in tissue mitochondrial density (Andersen & Henriksson, 1977). Second, expansion occurs in the cardiovascular system, with enlargement of the left ventricle and an increase in maximal stroke volume. The popular notion holds that left ventricular stretch during the repeated volume overload of training bouts causes increases in diastolic dimension (Shapiro, 1997). However, this is unlikely since the left ventricle is not observed to enlarge during acute bouts of exercise (Rowland & Blume, 2000). Instead, left ventricular enlargement is enhanced from endurance training principally by increases in plasma volume as well as the augmented diastolic filling from the resting bradycardia that occurs as a response of increased parasympathetic tone (Perrault & Turcotte, 1993).

Potential explanations for dampened aerobic trainability in children can be logically sought within these two factors. Plasma volume typically rises by 5–10% in endurance training studies of adults (Convertino, Brock, Keil, Bernauer, & Greenleaf, 1990). Since plasma protein concentration remains stable during such training responses, it has been suggested that increases in protein content of the blood is a primary mechanism for augmentation of plasma volume during exercise training (Convertino, 1994).

Information regarding changes in plasma volume in children with endurance training is limited to the single study of Eriksson and Koch (1973). These authors found an average 12% increase in estimated blood volume in nine males aged 11–13 years following a 4-month training period which resulted in a mean rise in VO_{2max} of 16.8%. Whether prepubertal subjects might respond to endurance training by producing less serum protein—and thus demonstrating a reduced rise in plasma volume compared with adults—is not known. Similarly, maturational influences on responses of hormones that affect plasma volume (aldosterone, vasopressin, atrial natriuretic peptide) to a period of endurance training have not been investigated.

Some evidence exists from animal studies to suspect that the increased action of reproductive hormones at puberty might affect magnitude of plasma volume changes with training. For example, testosterone administered to mice increases blood volume and estrogen decreases the transcapillary escape of serum proteins (Broulik, Kochakian, & Dubovsky, 1973; Stachenfeld, Taylor, & Keefe, 2003). While these data are far from sufficient to conclude that similar mechanisms could be operant in adolescents, they at least offer some support to Katch's (1983) original idea that pubertal hormonal events might accentuate aerobic training plasticity.

Previously sedentary adults typically demonstrate a 10–15% decrease in resting heart rate following a period of endurance training (Wilmore & Costill, 1994). Findings have been similar in reports of training programs in nonathletic children (Eriksson & Koch, 1973; Obert et al. 2003). This observation indicates that no maturational differences exist in training-induced augmentation of parasympathetic tone. By extension, such autonomic responses do not contribute to child–adult differences in stroke volume responses to endurance training.

Information regarding the responses of metabolic capacity of skeletal muscle to training in children, which requires biopsy data, is understandably limited. The single report on such is that previously noted by Eriksson, Gollnick, and Saltin (1973), who found a 30% rise in the aerobic enzyme succinate dehydrogenase with training in males aged 11–13 years.

In summary, the bulk of research evidence indicates that physiologic plasticity to endurance training (increases in VO_{2max}) is less in nonathletic children than adults. Whether this difference is defined by a threshold period (i.e., puberty) or a matter of increase in body size is uncertain. Specifically, the "trigger hypothesis" of Katch (1983), implicating a critical role of hormonal alterations at the time of puberty in defining aerobic trainability, is supported by some evidence but not others, and its physiologic foundation remains uncertain. As Armstrong and Barker (2011, p. 76) have concluded, "The existence of a maturational threshold below which children are not trainable remains to be proven." A question of equal importance, which will be addressed below, is whether such restriction of physiologic response to endurance training in children implies a similarly dampened response of endurance performance.

VO_{2max} Responses to Training in Child Athletes

Up to this point, the discussion has focused on aerobic responses to training in nonathletic prepubertal youth. It can be noted that the training studies described above in these children were of relative short term (few were > 12 weeks), and the duration, frequency, and intensity of training did not resemble that which might be expected in the training regimen of a 10-year-old distance runner. Training data in young endurance athletes might be expected to provide better insights into the utility of aerobic trainability of youth involved in early endurance sport specialization.

As indicated in Table 2, typical VO_{2max} values reported in the literature for elite-level prepubertal endurance runners of 60–65 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ are about 30% greater than the average nonathletic prepubertal male (~50 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$) but significantly less than those found in highly-trained postpubertal runners (65–75 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$). The former observation suggests significant aerobic trainability of prepubertal distance runners, while the latter could be interpreted as indicating that a "ceiling" of aerobic trainability exists before the age of puberty, consistent with the findings in nonathletic children reviewed above. Still, such conclusions may be premature. Higher values in the older athletes, for example, could simply be a matter of their longer duration and/or higher intensity of training. Additionally, a selection factor could be operant—those with greater fitness might be expected to continue in the sport.

Importantly, the question that looms over all such data is whether the high VO_{2max} values in young runners compared with nontraining youth are an expression of training effect or genetic predisposition. That is, an alternative and equally reasonable explanation for the group differences besides differential trainability is the likelihood that the child who possesses a high level of hereditary-based aerobic fitness will be expected to be drawn to, and succeed in, endurance sports. There is no means of deciphering the difference between these two

Table 2 Representative Mean Values of Maximal Oxygen Uptake in Studies of Highly-Trained Male Endurance Runners

Study	N	Age	VO_{2max} (ml·kg^{-1}·min^{-1})
Prepubertal			
Van Huss et al. (1988)	20	9–15	65.9
Daniels & Oldridge (1971)	14	10–15	59.5
Mayers & Gutin (1979)	8	8–11	56.6
Sundberg & Elovainio (1982)	12	12	59.3
Lehmann et al. (1981)	8	12	60.3
Postpubertal			
Kobayashi et al. (1978)	4	17	73.9
Dill & Adams (1971)	6	17	72.0
Cunningham (1990)	12	16	74.6
Sundberg & Elovainio (1982)	12	16	66.4

possibilities in such cross-sectional data. In adults, the extent of fall in aerobic fitness with detraining studies has suggested that approximately half of the elevation in VO_{2max} in athletes can be accounted for by each effect (Wilmore & Costill, 1994). No such studies have been performed in child athletes.

Several studies have reported VO_{2max} values obtained in prepubertal child endurance athletes in the course of their training, with conflicting findings. Some have indicated no significant increases in VO_{2max}. Van Huss et al. (1988) showed that VO_{2max} per kg did not vary significantly over time in elite distance runners studied longitudinally between ages 10 and 13, and in a cross-sectional analysis of 42 runners ages 9–14, no effect on VO_{2max} per kg was observed by age. Daniels and Oldridge (1971) reported no significant change in VO_{2max} per kg from an initial mean of 59.5 ml·kg^{-1}·min^{-1} after 22 months of run training in males aged 10–15 years. In the longitudinal study of young athletes by Baxter-Jones, Goldstein, and Helms (1993), no changes in mean values of VO_{2max} per kg were observed in male or female swimmers between the ages of 11 and 13 years. The four prepubertal runners described by Hakkinen, Mero, and Kauhanen (1989) did not demonstrate any significant change in VO_{2max} after one year of training.

On the other hand, Sperlich et al. (2010) described a rise of +10% in VO_{2max} per kg after 5 weeks of high intensity swim training in 26 athletes 9–11 years of age. Measuring VO_{2max} by arm ergometry on a swim bench, Obert, Courteix, Lecoq, and Guenon (1996) found an increase from a mean of 26.2 to 33.8 ml·kg^{-1}·min^{-1} after 10 months of training in five 9-year-old swimmers. Brown, Harrower, and Deeter (1972) reported an 18% increase in VO_{2max} in five female runners after 6 weeks of training. Paterson, McLellan, Stella, and Cunningham (1987) measured VO_{2max} yearly in 18 males between the ages of 11 and 15 who were involved in ice hockey, basketball, football, and track and field competitive teams. From a high initial mean value of 60.8 ml·kg^{-1}·min^{-1}, values rose approximately 2 ml·kg^{-1}·min^{-1} per year, reaching an increase of +11.8% by the end of the study. It is difficult to know how to interpret these data. Besides the conflicting findings, these athletes were generally well-trained before the beginning of the study period and already exhibited high initial values of VO_{2max}. Consequently, only minimal increases might be expected in such highly-trained youth. Again, whether the elevated prestudy VO_{2max} values reflect genetic predisposition or early training effect cannot be determined from these reports.

The critical questions of whether early training might simply *accelerate* normal development of aerobic fitness—either physiological or performance—or serve to elevate an individual's ultimate fitness ceiling are not known. As emphasized by McNarry and Jones (2014), "it remains to be determined if commencing intensive training during pre-puberty is associated with any greater benefit during adulthood than commencing intensive training at a later maturity stage" (p. S65).

Effect of Endurance Training in Prepubertal Children on Performance

A dampened ability to improve VO_{2max} with endurance training does not necessarily imply a diminished capacity to augment performance on distance events. While aerobic capacity is considered a key factor in such performance, other determinants may be operant as well. In fact, Mahon, Del Corral, Howe, Duncan, and Ray (1996) reported that performance by 10-year-old males on vertical jump (i.e., a measure of explosive power), 55-m sprint time, and VO_{2max} correlated similarly to performance on a

3-km run (r = .67, .59, and .61, respectively). Endurance performance might be dissociated from VO_{2max}, too, in sports such as swimming, in which motor technique is critical to performance.

Understanding the extent that endurance training can or cannot influence performance during childhood is highly problematic. A number of studies have indicated performance improvements following training in prepubertal subjects, but the extent that such changes reflect a true training effect is unclear for at least two reasons. First, performance on repeated trials of an endurance task is influenced by test familiarization and motivation, quite apart from true physiologic or neuromuscular training adaptation. For example, Watkins and Moore (1996) found a 3–5% improvement in one-mile run times between trial 1 and trial 2 in 272 healthy females aged 12–15 years. Similarly, Lambrick, Rowlands, Rowland, and Eston (2013) reported a significant difference in performance after a single repetition of an 800-m run in children aged 9–11 years. Second, it is often difficult to distinguish increases in performance following a period of training with the expected normal improvements of normal growth and development over the same time span. For example, in the report by Daniels and Oldridge (1971) noted above, while VO_{2max} remained stable, performance over 13 months of training improved by 32 s in the mile and 63 s over two miles. This observation has been taken as evidence that endurance performance can be improved in youth by training without alterations in VO_{2max}. However, the magnitude of performance improvement in these runners was similar to that described over one year during normal growth and development of children (American Alliance for Health, Physical Education, Recreation and Dance, 1980). This issue is particularly problematic in evaluating improvements in performance in sports such as swimming and cycling, for which no normal curves of changes during childhood are available.

Consequent to these issues, the degree that performance in distance running, swimming, and cycling can be attributed to training effects in children is currently unknown. Even more to the point of this discussion, the extent that any improvement in performance with endurance training in childhood can be related to the magnitude of those of mature athletes, or whether there are certain periods of growth and development when such responses might be maximized, is unclear.

Risks of Early Intensive Aerobic Training

There exists no evidence that intensive aerobic training in the prepubertal years carries any risks to aerobic physiological systems. Echocardiographic studies in child athletes have revealed no untoward changes in response to chronic training (Rost, 1987) or following acute endurance events (Roberts & Nicholson, 2010; Rowland, Goff, Popowski, & DeLuca, 1997). In what could be considered a natural experiment, reports of adverse cardiopulmonary outcomes have not been forthcoming despite substantial involvement of prepubertal youth in intensive endurance training programs.

Summary

Based on the information presented in this section, it is not unreasonable to suggest that the child placed in a program of early specialization in an endurance sport such as distance running might be expected to exhibit a reduced response of aerobic physiologic response (lower plasticity of VO_{2max}) than if such training is delayed until the pubertal period. It is not known whether this damped rise in VO_{2max} in response to endurance training in children compared with adults is accompanied by a similar limitation of improvement in endurance performance; however, considering the close link between the two, this would not seem unlikely.

Certain factors, however, may temper this conclusion. For example, the data presented above reflect group average values of aerobic responses to training. Considering the large interindividual variability in VO_{2max} plasticity with training, certain youth may, in fact, respond at an early age with a higher magnitude of response that mimics that of older individuals. In addition, improvements with training in endurance sports that integrate the importance of factors in addition to VO_{2max} might be evident at an early age (e.g., strength in cycling or rowing, stroke technique with swim training).

Muscular Strength and Explosive Power

Muscle strength—the capacity of skeletal muscle to generate force—contributes to the performance of most forms of sport competitions. Consequently, adult athletes in sports as divergent as wrestling, tennis, and swimming regularly incorporate resistance workouts into their training regimens to improve strength. The story underlying (a) the ability of resistance training to improve strength in children before the age of puberty and (b) the appropriateness of such training in prepubertal athletes has taken a 180-degree turn in the last several decades. Initially, gains in strength from resistance training, thought to require testosterone stimulation, were considered impossible before puberty (Vrijens, 1978). Moreover, strength training was claimed to carry the risk for potential damage to the immature musculoskeletal systems of young athletes. Subsequent studies, however, have now indicated these conclusions to be ill-founded (Faigenbaum et al., 2009; Ratel, 2011). Relative gains in strength from resistance training are currently considered to be independent of age and sex, and risks in supervised programs for young children are negligible. Consequently, strength training for prepubertal athletes is now routinely accepted as a safe and valuable means for improving sport performance, increasing physical fitness, and preventing injuries.

Normal Development of Muscle Strength During Childhood

Muscle strength, defined as the maximal force generated in a single contraction (1-RM), progressively increases during the course of the growing years. Between the ages of 5 and 11, for example, a doubling of hand grip strength is observed in both males and females (Blimkie, 1989). At puberty, strength gains accelerate in males in response to the anabolic effects of circulating testosterone. The ability to generate force over time, or acceleration, is reflected as *explosive power,* most commonly measured by performance on a vertical jump test. This capacity clearly plays a key role in many forms of athletics, especially in those events characterized by rapid change of direction (e.g., soccer, basketball). Developmental improvements in explosive power with age during childhood mirror those of single-contraction muscle strength.

Any consideration of the effect of resistance training with early sport training needs to be taken in the context of the normal improvements in strength that occur in the course of childhood. Current information suggests, too, that the principal mechanisms responsible for enhanced strength by these two pathways are different. The principal determinant driving this rise in strength and explosive power during childhood is increase in muscle size. Muscle fiber hypertrophy as a consequence of protein accrual with age is typically reflected in a three-fold increase in fiber diameter between the time a child reaches his first birthday and when he enters adolescence. Still, statistical approaches have suggested that gain in muscle cross-sectional area cannot by itself entirely account for developmental improvements in muscle strength and explosive power (Rowland, 2005). Most particularly, neural mechanisms are suspected to be likely to contribute, such as increases in nerve conduction velocity, motoneuron firing rates, central command, and motor recruitment. Alternatively, changes in muscle fiber architecture (e.g., pennation angle) or increases in intrinsic muscle force could be involved.

Responses to Resistance Training in Children

A multitude of studies have indicated that young males and females of all ages respond to resistance training with relative strength gains equivalent to those experienced by adults. These investigations have been the subject of several reviews (Blimkie & Sale, 1998; Faigenbaum et al., 2009; Ratel, 2011) and meta-analyses (Falk & Tenenbaum, 1996; Payne, Morrow, Johnson, & Dalton, 1997). Malina (2006) reviewed 22 studies of strength training in youth, which mostly employed isotonic machines and free weights and lasted 8–12 weeks in duration. Subjects in these studies were as young as 5–6 years. Increases in tests of strength following resistance training typically approximated 20–30%, with equal improvements in males and females at all ages.

Interestingly, the great majority of these investigations describe significant gains in muscle strength with training in prepubertal subjects with little or no increase in muscle bulk, implying that the neurological factors described above play a key role in training outcomes. It appears, then, that the principal determinants of normal strength gains during childhood (muscle size) differ from those that trigger responses of increased strength that occur with resistance training (neurological) (Rowland, 2005).

Resistance Training and Performance in Young Athletes

Intuitively, gains in strength from resistance training in young athletes should be expected to enhance performance, particularly in sports such as football and wrestling. Documentation of this outcome has not been forthcoming, however, given the inability to tease out the effect of resistance training from the multitude of other anatomic, physiologic, psychological, and extrinsic variables that influence sport performance. As surrogate measures, however, certain fundamental performance outcomes which should relate to athletic success have been described following resistance training and training for explosive power (by plyometrics) by young athletes (Behringer, vom Heede, Matthews, & Mester, 2011). Most commonly, this has involved responses of such training to sprint time and performance on a vertical jump.

Behringer et al. (2011) reviewed outcomes in 34 resistance training studies in children and adolescents, one-third of whom were athletes. The greatest effect size occurred in throwing performance for training studies of sprint performance and jumping. The authors concluded that "structured training programs significantly improve running-, jumping-, and throwing-performance in children and adolescents," and that "it can be assumed that there is a positive transfer of resistance training effects to sport specific performance in young athletes" (Behringer et al., 2011, p. 193). Similar findings were reported in a review of 34 training studies limited to adolescent athletes aged 12–18 years (Harries, Lubans, & Callister, 2012). Eleven of 13 studies described statistically significant improvements in sprint performance, and 19 of 25 found a significant increase in vertical jump. Although some of these studies stated that sport performance had improved with training, "few were able to support their claims with an objective measure of sports performance" (Harries et al., 2012, p. 536).

Risks of Strength Training in Children

Among the training studies described earlier, injury rates have been essentially negligible. In 10 such reports, only three minor injuries (two shoulder strains and thigh pain from a falling bar) were described, all in males. The estimated injury rate was 0.05–0.176 per 100 participant hours (Malina, 2006). It should be noted that all these programs were conducted under close adult supervision with a high instructor-to-subject ratio. As Faigenbaum and Myer (2010) have noted, growth plate injuries have not been described in any prospective youth resistance training study that provided professional guidance and instruction. Injury rates during nonsupervised weight training in youth are not available, nor are there reports of the incidence of such injuries specifically in the training of young athletes. There exists some evidence, based on serum creatine kinase levels (a marker of muscle damage) and reports of muscle soreness, that children experience less muscle stress with strength training than do adults (Ratel, 2011).

Summary

Children of all ages, regardless of sex, are capable of responding to a period of resistance training with relative gains in strength equivalent to those of adults. Increases in muscle bulk from such programs, however, are not expected before the age of puberty. At least in supervised programs, resistance training is safe for young athletes. It should be expected that resistance training as part of a training regimen for prepubertal athletes should contribute to improvements in performance and resistance to injuries in sports in which strength plays a significant role.

Short-Burst (Anaerobic) Fitness

Whether performance improvements in short-burst activities can be achieved by children involved in early specialized sport training remains uncertain. Short-burst fitness incorporates those sport activities that depend on propelling the body at a maximal velocity over a number of seconds (e.g., sprint events in track and swimming) as well as those which involve the capacity to resist fatigue during repeated short sprint bursts (e.g., tennis, basketball). Physiology textbooks traditionally classify such activities as anaerobic, meaning that they rely on glycolytic rather than oxygen-dependent metabolic pathways for their energy supply. Growing evidence suggests, however, that performance in short-burst activities is limited by neuromuscular rather than metabolic factors (Goodall, Charlton, Howatson, & Thomas, 2015; Rowland, 2005). Muscle strength and endurance, explosive power, and neurological drive all appear to contribute to peak sprint performance as well as the ability to resist fatigue in repeated sprint activity.

Since short-burst performance for sprints is influenced largely by anthropometric factors other than body weight (especially stride length and its corollary, stride frequency), it is probably best to examine such fitness in youth in terms of field performance (that is, actual sprint times). As expected, sprint performance on the track (typically studied as time for a 50-yard dash) steadily improves during the course of childhood. Improvements of approximately 25% are expected in males over a 10-year span, while average finish times and improvement with age are slower in females (American Alliance for Health, Physical Education, Recreation and Dance, 1980).

The determinants of this rise of sprint speed during growth are not clear. A number of potential factors have been implicated, including the development of muscle force production, velocity of muscle contractions, neural drive (peripheral and central), neuromuscular fatigue, elastic recoil, and segmental energy transfer (Rowland, 2005). Progressive improvements in sprint performance during childhood have been closely linked to body height, assumed to reflect stride length and consequently stride frequency. Since the "currency" of the neuromuscular demands of sprinting may be considered as per stride, it is possible that anthropomorphic changes accompanying growth, especially the fall in neuromuscular demands associated with diminishing stride frequency, may be the primary driving factor behind the improvements in sprint performance with age. As has been concluded, however, "information regarding the factors involved in the development of sprint performance in children is highly fragmentary and precludes any definite conclusions" (Rowland, 2005, p. 207).

One observation may be particularly relevant to sport performance in prepubertal subjects. Studies reveal that children appear to experience less decrements of performance following repeated cycling and running sprints than do adults (Hebestreit, Mimura, & Bar-Or, 1993; Ratel, Williams, Oliver, & Armstrong, 2006). This would suggest that prepubertal athletes would be more resistant to fatigue than young adults in sports which demand repeated sprint performance, such as tennis, rugby, and basketball (given, of course, an appropriate scaling of the size of the playing surface).

Trainability of Short-Burst Fitness in Youth

While evidence in adults clearly indicates the trainability of the multiple factors that contribute to short-burst fitness, information in prepubertal subjects is limited. Indeed, a survey of the available research literature regarding short-burst activity trainability in young athletes reveals a great deal of conflicting results. Enhancement in sprint run performance after a period of ~12 weeks of sprint training in prepubertal athletes and nonathletes has been described by several authors (Diallo, Doré, Hautier, Duché, & Van Praagh, 1999; Kotzamanidis, 2003; Venturelli, Bishop, & Pettene, 2008). However, others have failed to observe such improvements (Mosher, Rhodes, Wenger, & Filsinger, 1985; Prado, 1997). Sperlich et al. (2010) reported that a 5-week high-intensity training program in elite, highly-trained swimmers aged 9–11 years resulted in improved times in competition (10-m freestyle, 5-m breaststroke) but not in a test of 100-m sprint time. Johnson, Salzberg, and Stevenson (2011) reviewed seven studies which overall described a positive effect of plyometric training (jumping) in young children on running speed. However, these reports were judged to be of low quality.

Two periods during childhood have been suggested to represent periods of accelerated adaptation to short-burst activity training: (a) ages 5–9 years, based on considerations of neurological maturation and the observation that gains in sprint speed are greatest during early childhood; and (b) ages 12–15 years, in the circumpubertal period, at which time improvements in strength and power output are related to the surge of reproductive anabolic hormones. As noted by Rumpf, Cronin, Pinder, Oliver, and Hughes (2012), "sprint training that focuses on the muscular system to improve strength, therefore power output and consequently spring running speed, might be more appropriate at age 12–17 for male youth" (p. 181). These authors considered that suggestions of periods representing optimal "windows of trainability" are highly conjectural and not supported by experimental or observational evidence. Indeed "cross-sectional studies supporting this theory are scarce and results conflicting" (Rumpf et al., 2012, p. 182).

Summary

The plasticity of short-burst fitness in response to training in prepubertal participants is inadequately studied. Additionally, the conflicting results in the present literature precludes any conclusions regarding the magnitude of sprint performance training in this age group or any periods of time when such training might be optimal.

Conclusions

It is evident from the foregoing discussions that conclusions as to whether (a) prepubertal children can exhibit similar qualitative and quantitative physiological responses to physical training as mature individuals, and (b) whether there exists critical periods during the growing years when such training is optimized, are far from clear. However, the current body of experimental and observational research suggests the following:

- Physiological adaptations to endurance training may be blunted in young children. Consequently, early intense, highly-specialized training by young children for endurance events such as distance running may not be warranted.
- Relative improvements in muscle strength with resistance training equivalent to those achieved by adults are expected in all pediatric age groups and by both young females and males. Supervised training regimens to promote sport-specific strength for enhanced performance and injury prevention are appropriate at all ages in children.
- Scant research evidence suggests that strength, plyometric, and sprint training may be effective in improving performance on short-burst activities in prepubertal children. However, the available information is far too limited to draw firm conclusions.
- Prepubertal children are more resistant to fatigue on repeated sprint activities and may be particularly physiologically suited to perform well in athletic activities such as basketball, tennis, and soccer. It is reasonable to conclude that, from a physiological standpoint, early-specialized training may be appropriate for these sports.

The current scientific literature is clearly inadequate to base firm recommendations regarding the wisdom of early sport specialization for children from a physiological perspective. However, these data do suggest that the form of the sport involved might influence such recommendations.

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