Sensitive periods to train general motor abilities in children and adolescents: Do they exist? A critical appraisal.

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Abstract

Some long-term athlete development (LTAD) models have proposed generic sensitive periods or ‘windows of opportunity’ during childhood and adolescence that are optimal for training general motor abilities such as strength or speed. However, it remains unclear whether these periods exist. This review will therefore critically appraise the rationale behind generic sensitive periods. We discuss several issues with generic sensitive periods and argue that general motor abilities and the associated sensitive periods do not exist. The identified issues with generic sensitive periods questions their validity and we therefore suggest that they should not be used to train youth athletes.

Keywords: Trainability; Long-term athletic development; Training emphasize periods; Youth training; Resistance training; Latent variables.

1. Introduction

Children and adolescents experience numerous physical changes as a result of growth and maturation during the development towards adulthood, with the timing and tempo of these processes being individualized. For example, the respiratory, skeletal and central nervous system mature, hormonal concentrations are altered and the muscle-tendon unit experiences morphological, metabolic and mechanical changes (2, 4, 28, 35, 36, 48, 50, 63). Several athlete development models have been proposed that the non-linear development of several sub-systems and the resulting accelerated increases in measures of strength, speed and endurance result in sensitive periods (also referred to as 'windows of opportunity', 'periods of accelerated adaptation', 'training emphasis periods' or 'optimum periods') during which focused physical training is particularly effective towards improving physical characteristics in children and adolescents. (e.g., 5, 65).

The best known athlete development model in which sensitive periods were proposed is the long-term athlete development (LTAD) model by Balyi and colleagues (5) from 2005, which has been updated in 2013 in a book (6) and 2014 in a resource paper (14). In this model, the authors simplified the physical attributes of sports into five general motor abilities of suppleness (flexibility), speed, skills, stamina (endurance) and strength and proposed sensitive periods based on biological and chronological age for boys and girls (Figure 1). The ages 7-9 years and 13-16 years were for example proposed as sensitive periods to train speed in boys, while a sensitive period to train aerobic capacity was proposed prior to peak height velocity (PHV, the phase in which growth is fastest). It is assumed that training of speed or aerobic capacity outside these sensitive periods results in adaptations that are smaller in magnitude and therefore has a reduced effect on performance. In this context, it is important to emphasize the difference between sensitive and critical periods in that training outside of a critical period possibly has no effect (of practical or clinical significance) on the trained ability, whereas training outside a sensitive period has a reduced effect (27). This distinction is important as LTAD models often refer to sensitive periods, while some practitioners have interpreted these as critical periods.

2. Evidence for sensitive periods

The sensitive periods in the LTAD model are based on athlete development plans for specific sports developed in Canada, on the practical experience of coaches and empirically tested athlete development models from the former

Eastern Bloc countries (5, 6). However, empirical observations are influenced by subjective bias and lack scientific validity (20). Scientific evidence for the sensitive periods is however not provided in the first model from 2005 (5) and the evidence provided in the updated model (6, 14)as well as other LTAD models that feature sensitive periods (65) is primarily based on the idea that an accelerated growth and maturation related development of a physical attribute (e.g., weight lifted during squatting) or derived general motor ability (e.g., muscular strength) also leads to a greater sensitivity to training.

Previous reviews on sensitive periods and trainability have stated that there is currently insufficient evidence to support the belief that an individual will never reach his or her genetically determined maximum athletic capability or a specific proficiency level during adulthood if a general motor ability is not specifically trained during a hypothetical sensitive period (4, 19, 20). Nevertheless, in their review on the physiological evidence for the sensitive periods in the LTAD model, Ford and colleagues (20) concluded that more research is required to determine whether the sensitive periods proposed in the LTAD model truly exist as most evidence was based on cross-sectional studies and lower-quality intervention studies. Perhaps partly due to the absence of higher-quality evidence, the conclusions from previous reviews to not rely on sensitive periods were ignored in the recent update (6, 14) of the LTAD model as well as in several other athlete development models by (inter)national governing bodies and sports federations as they still incorporated generic sensitive periods. For example, although the 2017 LTAD USA baseball model does not include sensitive periods (60), the 2012 Canadian rowing (56), 2016 Dutch tennis (57) and many other sports federations and athlete development models (65) still use generic sensitive periods in their LTAD models. Given the widespread adoption of generic sensitive periods and the lack of strong evidence for or against sensitive periods in previous reviews, a re-evaluation of the sensitive periods is required. The aim of the current review is therefore to provide an updated evaluation of the generic sensitive periods as proposed in LTAD models. To this purpose, we will critically appraise the rationale behind sensitive periods using recently published studies. This will provide stronger evidence and additional insights on the validity of generic sensitive periods and such information can be helpful for future research on youth training, for practitioners working with youth athletes, and for developers of athlete development models.

3. Methods

A narrative synthesis rather than a systematic review approach was used as only few studies have investigated the effects of an intervention where groups of different (biological) ages performed training while using a control group to partition out the effects of training and maturation (e.g., 34, 41, 49, 55). A systematic review on this topic would therefore be premature. Further, the aim of this paper was to provide a critical appraisal of the rationale behind generic sensitive periods as proposed in athlete development models rather than providing a comprehensive overview of all studies on this topic to date. Nevertheless, the search process was performed as systematically as possible by searching electronic databases of Google Scholar and PubMed for relevant literature using combinations of keywords and Booleans that included (youth OR children OR adolescents OR pediatric OR young) AND (sensitive periods OR windows of opportunity OR training emphasize periods OR optimum periods OR periods of accelerated adaptation OR critical periods) AND (resistance OR strength OR weight OR sprint OR speed OR endurance OR stamina OR flexibility OR suppleness OR plyometric) AND (training OR intervention). *No limits were applied to date of publication or article types. Hand searching* for (to be published) articles in databases and *reference lists and forward citation searching of included studies was also used to identify additional relevant articles.*

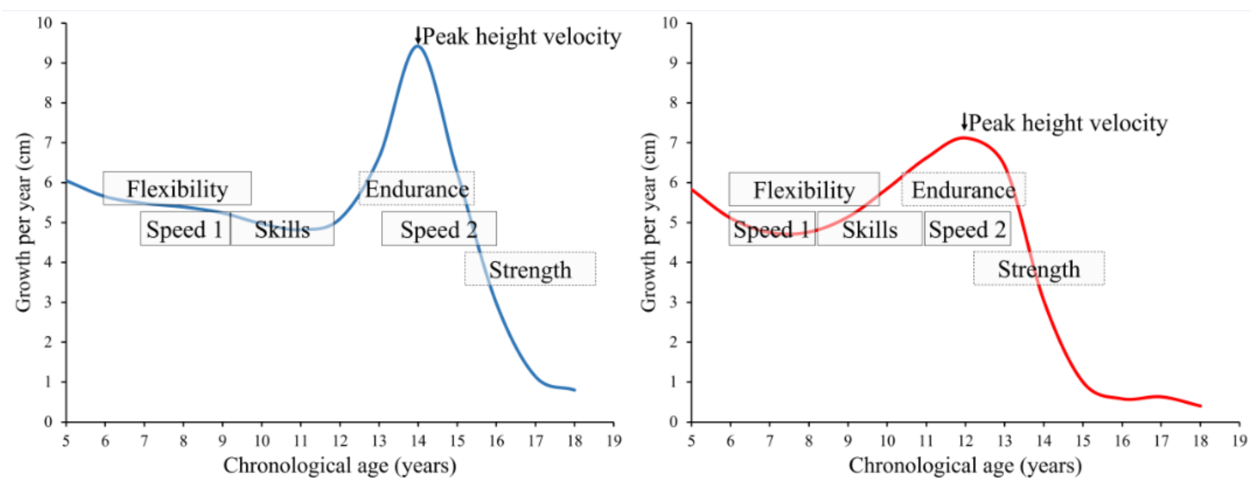

Figure 1. Sensitive periods to train general motor abilities in boys (left) and girls (right) according to the LTAD model. The solid lined boxes represent chronological age dependent periods, whereas the dotted lined boxes represent biological age dependent periods. Growth curves are based on data from Dutch children and adolescents reported by Gerver and de Bruin (22).

4. Critical appraisal of generic sensitive periods

4.1 General motor abilities

LTAD models frequently simplify/divide the physical aspects of sports into five general motor abilities: flexibility, speed, coordination (sometimes referred to as skills), endurance and strength. This subdivision is made by measuring physical attributes such as the weight lifted during squatting and using these to estimate underlying general motor abilities such as strength. In psychology, such an approach is known as a latent variable modelling (23). Sensitive periods are subsequently proposed to exist for these general motor abilities or latent variables (Figure 1). Although this reductionism is helpful to reduce the complexity of sports to five manageable constructs it (incorrectly) implies that there are distinct motor abilities that can independently be trained and each have separate sensitive periods. Such simplification for example implies that maximum running velocity (speed) can be improved independently of coordination or strength. It further implies that the sub-systems that mature and are involved in coordination are (largely) different than the sub-systems involved in speed or strength, resulting in separate sensitive periods for these general motor abilities. Several studies have however shown low to moderate correlations between measures thought to reflect the same general motor ability. Ellison, Kearney, Sparks, Murphy and Marchant (17) for instance observed a low percentage of shared variance among four tests that are all thought to reflect eye-hand coordination. Similarly, low correlations have also been observed between handgrip strength and knee muscle strength in healthy adults (66), and between two measures that are both thought to reflect eccentric hamstring strength (62, 64)-. Finally, different magnitudes of improvement has also been observed in isometric, isokinetic and isoinertial test conditions following a training program even though all measures are thought to reflect the general motor ability strength -(13). These findings collectively suggest that there are no general motor abilities, but rather that each motor skill is a result of a complex integration of abilities that are partly task specific. It can therefore also be questioned whether sensitive periods for general motor abilities exist, or whether they should be specific to each motor skill.

In most LTAD models it is however unclear to which motor skills the sensitive periods in the model refer. For example, it is unclear whether speed in the models refers to a sensitive period to improve maximum sprinting velocity (lower body speed) or also to other measures frequently conceptualized as measures of the general motor ability speed such as maximum swimming (lower and upper body speed), cycling, skating and throwing velocity or even acceleration and change of direction performance. The sensitive periods may however differ between these skills as a result of their different integration of specific abilities. Indeed, in a study by Radnor, Lloyd and Oliver (49), resistance training resulted in a significant increase in acceleration in post PHV boys, while there was no significant increase in maximum sprint velocity. Similarly, squat jumps and reactive strength index are frequently conceptualized as measures of muscular power, but although squat jump performance showed a significant increase following resistance training in post PHV boys, reactive strength index showed no significant increase (49). Similar conflicting findings have been reported by other studies in youth athletes (34). Finally, age and maturation related changes in strength have been reported to be both muscle group and muscle action specific (15). Peak gains in isometric strength of the elbow flexors can for example occur at a different time point during growth and maturation compared to eccentric strength gains in the hamstrings. Collectively, these findings suggest that sensitive periods for general motor abilities as proposed in LTAD models need to be specific for each motor skill, for each muscle group and for each muscle action, or at least for groups of highly similar motor skills (Figure 2).

4.2 Training method to improve the general motor ability

A second issue is related to the lack of information about the training method(s) that should be used during the proposed sensitive periods. In the LTAD model resource papers (5, 14) it is for example unclear whether (sprinting) speed during the proposed sensitive periods should be trained using specific sprint training, plyometric training or resistance training, while their effectiveness likely differs. The effectiveness of the method will determine whether larger adaptations can be induced during the sensitive period. A review by Rumpf, Cronin, Pinder, Oliver and Hughes (58) for example found plyometric training to be most effective at improving sprinting speed in children, while a combination of plyometric, resistance and sprint training was most effective in adolescents. More recent studies report similar findings (34, 49). Interestingly, a study among youth soccer players found that sprint training was slightly less effective at improving sprint and change of direction performance during PHV (i.e., the period that coincides with one of the two sensitive period to train speed in the LTAD model) compared with pre PHV (39). In the resource papers it is also unclear which method(s) should be used to train endurance during the proposed sensitive period, although the LTAD book suggests to use long slow aerobic intervals and fartlek training to improve aerobic capacity when growth accelerates during puberty and aerobic power training when growth decelerates for most late specialization sports (6). It has been suggested that the stress induced by low-intensity training is small compared to the stress induced by the high natural activity of children, thereby making low-intensity programs less effective (11). Furthermore, physiological mechanisms such as a greater reliance on aerobic metabolism in children result in less fatigue and a faster recovery following bouts of exercise compared to untrained adult individuals (52). It has therefore been suggested that children need to exercise at a higher intensity (>85% of their maximum heart rate) and with shorter breaks to elicit the same adaptations as adolescents and adults (1, 7). In support of this, Armstrong and Barker (1) found in their review that the increase in VO_2max was approximately equal in children <11 years and > 11 years (7.7% vs. 8.6%, respectively) when they only included studies that applied a training stimulus which resulted in an increased VO_2max.

Overall, these studies suggest that certain motor skills or derived general motor abilities may only be extra sensitive to certain training methods and not to all methods that can potentially be used to train the motor skill or derived general motor ability. This is in line with findings in animal studies where neural circuits are only sensitive to selected experiences (27). Information on the training method that should be used is usually not provided in the models, which implies that there is a sensitive period for the general motor ability irrespective of the training method employed. Since studies have shown that the effectiveness of training can differ between training methods, this further questions the validity of the proposed generic sensitive periods.

4.3 Characteristics of the training method during the sensitive periods

Athlete development models also provide few guidelines on the characteristics of the training method, even though this may also influence the effectiveness of training (29, 43). It is for instance unclear whether one extra training session per week is sufficient, or whether specific training should be included during or after the warm-up for every training session during the sensitive period. Indeed, a meta-analysis among female youth athletes found program variables such as the number of weekly sessions and session duration to influence the effectiveness of plyometric training on jump height (38). Similar findings have been reported by other meta-analyses and reviews on strength (29, 44), balance (21), endurance (1, 7), agility (3) and speed (40) training. Further, Rodriguez-Rosell, Franco-Marquez, Mora-Custodio and Gonzalez-Badillo (54) found that combined plyometric and resistance training was most effective in under-13 (~ pre PHV) boys and became less effective with an increase in chronological age, while Lloyd, Radnor, De Ste Croix, Cronin and Oliver (34) concluded that combined training was more effective post PHV compared to pre

PHV. Although these conflicting findings could be related to differences in biological age between the studies, they may also reflect differences in the characteristics of the training program such as the load, number of reps, sets and duration of the rest period. Similarly, a study among female gymnasts aged 8-10 (i.e., the ages within the sensitive period proposed for flexibility training) found that the effectiveness of a static stretching protocol differed depending on the duration of the stretch (90 s continuous vs 3x30 s intermittent) (16). As a final example, a combination of small-sided games and high-intensity interval training has been shown to be more effective at improving physical performance parameters such as VO_2peak in team sports players aged 13 compared to small sided games alone (25).

Taken together, these findings suggest that the characteristics of the training method may influence the effectiveness of training during potential sensitive periods, potentially making training less effective when a method with less favorable training characteristics is used. Athlete development models do however not provide sufficient information on the characteristics of training during the sensitive period, again implying that there is a sensitive period irrespective of the characteristics of the method. Although we acknowledge that models cannot always provide detailed information on the characteristics of a training method, the findings of the studies summarized here suggest that such information is of importance for effectively inducing training adaptations and improving sports performance during hypothetical sensitive periods. Further, young individuals have been reported to be particularly susceptible to injuries before and during the growth spurt (61) and careful prescription of a training program (i.e., training mode and characteristics) is especially important during these periods to prevent injuries that may limit future potential. The findings of recent research can offer some guidelines on a training program that may be used to effectively improve performance, while likely minimizing injury risk during this period (46, 47). The complexities of training/match load management in the growing and maturing child to promote training adaptations and subsequent athletic performance, combined with the susceptibility to acute and chronic injuries are often not taken into account in LTAD models that promote sensitive periods.

4.4 The effect of prior training experience and individual differences

The models (5, 65) do also not clarify whether the sensitive periods and their content differs between individuals with varying experience levels and different training backgrounds, even though it is widely acknowledged that athletes with less experience in a structured training program and lower technical proficiency should generally perform less advanced exercises than technically proficient athletes who may be younger (30). This may affect the possibility to utilize the potential sensitive period. For instance, a 17-year old athlete who has no prior resistance training experience will likely first perform low weight resistance exercises before continuing with heavier weight exercises, hereby potentially not allowing him to (optimally) capitalize on the proposed sensitive period for resistance training. Indeed, evidence from animal studies also shows that prior experience will affect how certain neural circuits respond to future experience (27), suggesting that (lack of) prior training experience also determines whether sensitive periods exist.

A meta-analysis on strength and power training to improve measures of power, strength and speed in youth athletes showed that adaptations were generally larger for untrained than for trained individuals (10). In adults, it has been shown that the optimum dose and intensity of training depends on training experience (53). This may be similar in youth athletes, which suggests that better trained youth athletes may need to use higher intensities and/or larger volumes to induce optimal adaptations during hypothetical sensitive periods. Other studies among adults have also found associations between genetic factors and training adaptation (12, 45). Youth athletes may similarly be more or less responsive to a particular training method depending on their genetic predisposition, which further limits the generalizability of the generic sensitive periods. The findings of several recent studies indeed suggest that there is a range of individual responses to different training modalities in youth athletes (37, 49, 51), potentially due to different prior training experience or genetic predisposition. Collectively, these findings suggest that the most appropriate training modality during the hypothetical sensitive period may differ between individuals depending on the previous training experience and genetic predisposition.

4.5 Consequences of no specific training during the sensitive period

Finally, the models (5, 65) provide no information on the consequences of no specific training on the general motor ability during the proposed sensitive period. It is unclear whether this means that the individual is more prone to injuries, reaches the maximum performance at a later age or whether the maximum performance level as determined by the genetic predisposition is not subsequently achievable (4, 19). It is important to note here that it is questionable to what extend it is possible to not specifically train a general motor ability when individuals regularly participate in sports. For example, soccer involves sprinting, which could be regarded as specific speed training. Additionally, soccer also involves repeated sprinting, which could be regarded as high-intensity interval (endurance) training. Indeed, small sides games have been reported to improve measures of endurance such as VO_2max, measures of speed such as 20 m sprint performance and measures of muscular power such as vertical jump height (18, 24, 51). Similarly, resistance (strength) training has been reported to lead to improved measures of endurance performance such as running economy (8) and measures of speed (59) and change of direction performance (26).

5. Practical applications

Collectively, these findings indicate that each motor skill and derived general motor ability can be trained by many different methods, and each training method is potentially most effective during differing stages of development, although more research that controls for biological maturation is required to confirm this. The effectiveness of a training method also depends on the characteristics of the training (and competition) such as the amount of resistance, sets and repetitions, the duration of intervals and rest periods and the total load of activities undertaken at school, other sports and regional and international teams. Finally, the effectiveness of training differs between similar biological aged individuals based on their previous training experience and genetic predisposition. These findings therefore question the validity of generic sensitive periods as proposed in many athlete development models and have important consequences for youth trainers, researchers working in the field of pediatric exercise science and developers of athletic development models.

For youth trainers these findings indicate that they should no longer rely on generic sensitive periods as proposed on LTAD models, but rather train all physical attributes during all stages of development, as also suggested by other researchers (1, 4, 19, 31). However, these findings do not mean that some training methods cannot be prioritized or reduced at certain periods (e.g., prioritizing motor coordination training when motor coordination is impaired during PHV in an attempt to reduce injuries). Further, the LTAD model states that the model will continuously be updated as new information becomes available and also continues to use the sensitive periods until their existence has been disproven (6). We believe that the critical appraisal of sensitive periods in the current review and previous reviews has provided sufficient information to seriously question the validity of generic sensitive periods and discontinue their use in LTAD models. Although we acknowledge that the LTAD model by Balyi and colleagues (6) has had many positive influences on sports practice such as creating awareness on the risks of early specialization, awareness on biological rather than chronological age and a focus on long-term success rather than short-term success, the lack of validation of the sensitive periods has been reported as a barrier to implement the model by coaches (9). Removing this questionable aspect from updated LTAD model as well as other athlete development models (e.g., 65) may therefore lead to a better implementation. Indeed, several publications have discussed other ways of structuring training in youth athletes, without relying on sensitive periods, and the guidelines offered in these papers can instead be used to structure youth training (30-33, 42). Nevertheless, it is important to note that better quality studies are still required on this topic. These studies should include intervention groups of different (biological) ages while using a control group to partition out the effects of training and maturation. When each group utilizes a different training method and is assessed on multiple motor skills, it will be possible to provide insight into the existence of generic sensitive periods or task and training method specific sensitive periods. A major challenge with such studies will be to ensure a large enough sample size and control the confounding factors such as prior experience.

6. Conclusion

This is the first study that has critically evaluated the rationale of the widely adopted generic sensitive periods for youth training. The identified theoretical issues with generic sensitive periods provide stronger evidence than previous criticisms and further questions their validity (Figure 2). Athlete development models and practitioners should therefore not rely on generic sensitive periods to train youth athletes.

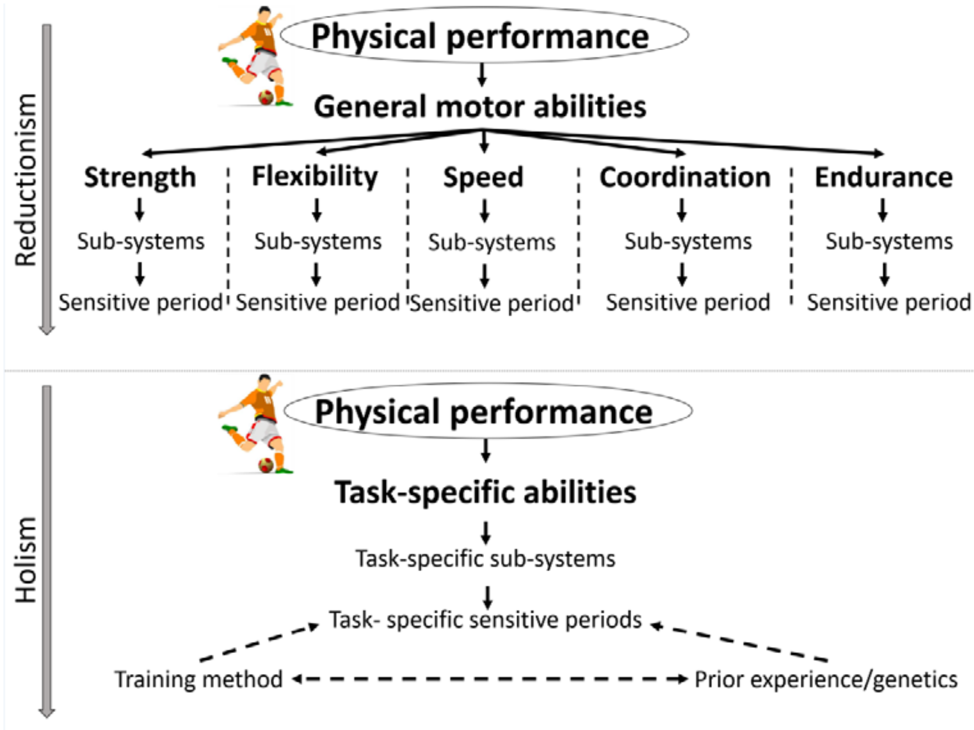

Figure 2. Reductionist approach with latent variables (top) and holistic approach based on network analysis (bottom) to sensitive periods. In the reductionist approach to sensitive periods used in many LTAD models, the physical attributes of sports (e.g., soccer) are simplified into five general motor abilities (latent variables): flexibility, speed, coordination, endurance and strength. Sensitive periods are proposed for each general motor ability. This implies that the sub-systems that mature and are involved in each general motor ability are different, resulting in separate sensitive periods for all general motor abilities (upper image). The first issue with sensitive periods for general motor abilities is that these can refer to many different motor skills. A sensitive period for speed can for example refer to a sensitive period to improve maximum sprinting speed, but also to improve change of direction performance or maximum swimming speed. However, the sensitive periods to train maximum speed for sprinting or swimming or change of direction performance may differ because these are partly distinct motor skills with different involved sub-systems that have sensitive periods at different times. If sensitive periods exist, they are therefore likely largely task-specific with each motor skill integrating a network of abilities and sub-systems, potentially resulting in task-specific sensitive periods (lower image). Whether a sub-system is sensitive to certain training methods however also depends on the exact training method used, and the prior experience and genetic predisposition as indicated by the dashed arrows.

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