Citation:
Eisenmann, J and Hettler, J and Till, K (2024) The Development of Fast, Fit, and Fatigue Resistant Youth Field and Court Sport Athletes: A Narrative Review. Pediatric Exercise Science. pp. 1-13. ISSN 0899-8493 DOI: https://doi.org/10.1123/pes.2024-0015

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Document Version:
Article (Accepted Version)

The development of fast, fit and fatigue resistant youth field and court sport athletes: a narrative review

Running head: Locomotor profile of youth athletes

ABSTRACT

Humans are fascinated by the bipedal locomotor capacities at both ends of the athletic spectrum - sprinting speed and endurance. Some of the more popular field (e.g., soccer, rugby, lacrosse) and court (e.g., basketball, tennis, netball) sports utilize mixed energy systems requiring an interplay of both maximal sprinting speed (MSS) and maximal aerobic speed (MAS) to meet the high-intensity running demands of varying frequency, duration, intensity and recovery. Recently, these locomotor capacities have been considered in combination to produce what is called the anaerobic speed reserve (ASR) as part of the locomotor profile concept (MSS, MAS, ASR). The purpose of this narrative review is to 1) provide an overview of the locomotor profile concept, 2) review the assessment methods for estimating MSS, MAS and ASR, 3) examine the age- sex- and maturity-associated variations in MSS, MAS, and ASR, 4) examine the trainability of MSS, MAS and ASR in youth athletes and 5) conclude with the practical applications using principles of long-term athlete development for training the locomotor profile in youth field and court sport athletes. Based on the available data in young male athletes, MSS, MAS and ASR generally increase with age and across maturity groups and are trainable. Overall, decisions on training need to consider the sport demands, current fitness and maturity status and targeted training adaptation sought.

INTRODUCTION

Humans are fascinated by the bipedal locomotor capacities at both ends of the athletic spectrum. On one end of the spectrum is the speed displayed in the 100 m sprint, where we have witnessed a time of 9.58 sec set by Usain Bolt in the 2009 Berlin World Championship (63). This and other all-out, short distance efforts ($\leq$100m) rely on near-maximal or maximal neuromuscular force outputs at rapid skeletal muscle contraction velocities fueled predominantly by anaerobic metabolism to produce maximal sprinting speed (MSS), which in the world record 100 m performance was 12.32 $m \cdot s^{-1}$. On the other end of the locomotor spectrum is endurance represented by the 42.195 km marathon where there has recently been an attempt to break the 2-hour mark (i.e., "Breaking 2" marathon project) equating to a sustained running speed of 5.86 $m \cdot s^{-1}$ (33). The prolonged effort of the marathon and other endurance events relies on the cardiorespiratory system and oxidative capacities of skeletal muscle to sustain a significant portion of the maximal aerobic speed (MAS).

Aside from these hallmark speed and endurance events, other sports (non-swimming and non-cycling) that depend on bipedal locomotion, particularly field (e.g., soccer, rugby, lacrosse) and court (e.g., basketball, tennis, netball) sports, utilize mixed energy systems requiring an interplay of both MSS and MAS capabilities to meet the high-intensity (i.e. ≥80% of MAS to 100% of MSS) running demands of varying frequency, duration, intensity and recovery. For example, in U13-U16 youth soccer the total distance covered during match play can average 6,500-8,300 m including multiple sprint efforts (>19 km/hr) totaling between 186-384 m (14). In junior basketball, players covered distances of ~7,400 m including 55 sprint efforts (>24 km/hr) totaling 763 m (1). These studies present examples of the significant differences in the contribution of running demands across and within field and court sports.

Worldwide, millions of youth participate in field and court sports, including many with the aspirations and potential to succeed at the national and international level. In turn, there has long been an interest in the development of young athletes with the hopes of producing international level competitors (66).

Historically, Eastern bloc nations systematically selected and trained potential athletes using principles and frameworks that have now become popularized as long-term athlete development (LTAD) models (5). These models provide a range of recommendations for the development of physical qualities (e.g., strength, speed, endurance) across childhood and adolescence.

The age-, sex-, and maturity-related variation and trainability of both aerobic and anaerobic capacity (including sprinting performance) have been addressed independently in the pediatric exercise science literature (3,29,48,64). Most often, maximal oxygen consumption (VO_2max), the hallmark expression of aerobic capacity, is reported, whereas several indicators of anaerobic capacity, including sprint performance, have been utilized given that there is no "gold standard" criterion measure of anaerobic fitness. This lends support for using the MSS as the ceiling for absolute speed ability along with considering the speed range between MSS and MAS as a continuum of anaerobic capacity. Only recently have these locomotor capacities been considered in combination to produce what is called the anaerobic speed reserve (ASR) as part of a broader locomotor profile (MSS, MAS and ASR) (59), which is becoming popular among practitioners. However, to date, there is limited consideration in the peer-reviewed literature for the development and trainability of the locomotor profile within youth athletes. Therefore, the purpose of this narrative review is to 1) provide an overview of the locomotor profile concept, 2) review the assessment methods for estimating MSS, MAS and ASR, 3) examine the age-, sex-, and maturity-associated variations in MSS, MAS, and ASR, 4) examine the trainability of MSS, MAS and ASR in youth athletes and 5) conclude with the practical applications using principles of long-term athlete development for training the locomotor profile in field and court sport youth athletes.

The Locomotor Profile Concept

An athlete's MSS and MAS underpin their locomotor profile but further insight can be gleaned from the ASR, which is the speed range determined as the difference between MSS and the velocity at VO_2max (vVO_2max) determined in the laboratory or MAS in the field (ASR=MSS–MAS) (Figure 1, top panel).

Although MSS is often viewed as a key determinant in field and court sports, it represents a single, one-off effort; whereas most field and court sports require multiple, intermittent high-speed efforts across a range of speeds between MSS and MAS that rely upon neuromuscular / mechanical input for MSS and aerobic / metabolic capacity for MAS. Furthermore, MSS and MAS reflect performance measures or the actual speed(s) which play out on the field or court and thus are practically relevant unlike ratio scaled aerobic (e.g., VO_2max; $ml \cdot kg^{-1} \cdot min^{-1}$) and anaerobic (e.g., $W \cdot kg^{-1}$) measures. Although the ASR concept has recently been popularized by Buchheit and Laursen (12) for interval training and Sandforth et al (58) for describing elite 800-m subtypes, it should be noted that the concept has been used by athletics coaches for decades (50). In fact, the term 'speed reserve' was first defined in 1959 to explain the difference between the average speed per 100 m of a race event and the athlete's best 100 m time among middle-distance (800 m-1500 m) runners (50).

Within groups of athletes who train or compete alongside each other, it is commonly observed that there is some heterogeneity in the locomotor profile (Figure 1a). The locomotor profile provides insight into the limits of aerobic and neuromuscular/anaerobic ability, and importantly, the tolerance to efforts in the ASR range which in turn has implications for both training and performance that are discussed in the subsequent sections. Even among athletes participating in sports with a relatively low contribution of aerobic efforts, an adequate level of aerobic fitness (and MAS) is important to support recovery and repeated sprint ability (46). To represent an athlete's ability along the spectrum of neuromuscular/anaerobic capacities to aerobic capacity with a single variable, the Speed Reserve Ratio (SRR) can be calculated by dividing MAS by MSS (SRR=MSS/MAS) (Figure 1, bottom panel) (58).

<<INSERT FIGURE 1>>

Based on the SRR, an athlete can be classified into one of three locomotor profiles: speed, hybrid, or endurance (59)(Table 1). In the initial study exploring the application of SRR to the profiling of elite 800 m runners, Sandford et al (58) identified three subgroups: SRR >1.58 = 400-800 m specialist (speed), 1.48 – 1.57 = 800 m specialist and 1.36-1.47 = 800-1,500 m specialists (endurance). However, the cutoff points used were sample-specific and are likely to vary by athletic group and/or sport (i.e., population dependent). Although few published studies have reported data on the SRR, practitioners applying this concept to the profiling and training of athletes have reported using a combination of subjective methods based on the coach and athlete to establish profiles or groupings (e.g., coach observations). In another study that furthered the application of this concept by also considering the game type of junior tennis players, the following cutpoints were derived: SRR >1.89 = Serve and Volleyer; 1.78-1.89 = All-Court Player; 1.66-1.77 = Aggressive Baseliner; and <1.66 = Counter Attacker) (51). Clearly, more research is warranted to determine and recommend cutpoints for locomotor profile categories across sports and by position given the varying demands of such sports.

<<INSERT TABLE 1>>

ASSESSMENT OF MSS AND MAS

Since the locomotor profiling of youth athletes and the prescription of high-intensity training may be based on ASR, reliable and valid testing of MAS and MSS needs to be considered. In youth field and court sport athletes, testing sprint and/or endurance is a well-established practice to determine baseline values and to monitor changes associated with growth, maturation and training. Although some practitioners may test one or the other of these locomotor abilities, it is recommended that both be measured to allow for the calculation of the ASR and SRR. This section provides an overview of several methods commonly utilized to assess MSS and MAS in youth athletes.

Assessment of MSS. Peak running velocity or MSS can be obtained using a speed radar gun, a microtechnology unit or can be estimated from the fastest split-time using laser timing gates (30). Perhaps the most common approach is the timed distance sprinting test, where the aim is for the athlete to cover a given distance in the fastest time possible. This can begin from various starting positions (i.e., standing or 2-point stance or 3-point stance with one hand on the ground) and generally covers a distance between 30-50 m. If the distance is too short (e.g., 20 m), the MSS may not be captured. It is also possible to use a timed 10 yard (9.1 m) sprint from a moving start (i.e., “flying 10”), which has become a popular speed training method.

In the timed distance test, timing gates should be placed at 5-10 m increments. For example, a standard protocol with timing gates every 10 m for 30 or 40 m can also produce a speed-distance curve as shown in Figure 2. Aside from determining the fastest split-time that represents the MSS, the sprint phases can also be visually represented as another source of information about the athlete’s locomotor profile. The first phase of sprinting is referred to as acceleration followed by the transition phase which leads into maximal velocity, and depending on the distance, the speed maintenance or speed endurance phase (31).

<<INSERT FIGURE 2>>

The distances at which the sprint phases occur is important in accurately capturing the MSS, and can vary by age. This has been shown in a study of U12-U18 male soccer players, where there were significant differences across age groups and considerable inter-individual differences when MSS was reached during a 40 m sprint (15)(Figure 3). In general, most (~80%) U12 players attained MSS between 20-30 m and this decreased across age groups with ~40% of U18 players attaining MSS between 20-30 m. In contrast, few (~10%) U12 players attained MSS between 30-40 m, which increased across age groups with ~60% of U18 players attaining MSS at 30-40 m. Interestingly, ~10% of U12 and U13 players attained MSS between 10-20 m along with some (~2-3%) U14 and U15 players. The reason why younger athletes will typically achieve MSS earlier than their older peers is that there is a significant relationship between the age-related changes in various lower body strength and power measures such as countermovement jump, reactive strength index, and isometric mid-thigh pull force production and sprint speed (21).

<<INSERT FIGURE 3>>

As recommended above, the distance between timing gates is also an important consideration. Zabaloy et al (69) assessed the validity of 5 m and 10 m split times to estimate MSS against a radar gun during the maximum velocity phase of a 30 m sprint. Although correlations between radar gun, 5 m split time, and 10 m split time determined MSS were strong ($r > 0.93$), pairwise comparison in MSS determined from radar gun (7.85 $\pm$ 0.58 $m\cdot s^{-1}$) were significantly different from 10 m split (7.77 $\pm$ 0.53 $m\cdot s^{-1}$) but not 5 m split (7.89 $\pm$ 0.56 $m\cdot s^{-1}$). Thus, it is recommended that timing gates are set at 5 m increments, if possible, for more accurate estimations of MSS. Depending on the number of timing gates available, it is also important to consider the distance(s) where MSS is most likely to occur in the athletes being tested.

Although timing gates are commonly used in sprint testing, they only provide an average velocity over the given segment (e.g., 20-30 m or 25-30 m). To assess instantaneous velocity, radar guns can be used to provide a constant measure across the entire distance and a more accurate MSS (30). Additionally, some commercially available radar guns will also provide a speed-distance curve to highlight various sprint phases as shown above.

Given the increased use of microtechnology (e.g., GPS) to monitor training load in some youth sports organizations (57), there is the potential to obtain MSS from such technology. A recent review article concluded that MSS values obtained through GPS systems may be considered valid and reliable only when collected under more controlled conditions (e.g., linear sprint tasks, progressive acceleration, and static starts) (68). However, the authors concluded that it is not advisable to use GPS systems for tracking prospective changes in MSS. Another consideration, besides the practical feasibility, is that the use of

GPS during training and competition provides the most ecologically valid assessment of peak speeds as it is not reliant on a maximal performance coming on a particular testing date but rather captures a more longitudinal assessment of an athlete's ability.

Besides the quality of the testing equipment, several other factors need to be considered to obtain reliable and accurate MSS data. The training and recovery status of the athlete should be noted. Prior to testing, a proper dynamic warm-up that culminates with maximal or near maximal sprinting is recommended. Depending on where the testing is conducted (which should be consistent), the environmental conditions (temperature, humidity, wind speed and direction, precipitation) may affect test performance and should be noted, particularly when tests are administered outside where weather is variable. Finally, the surface (natural grass, turf, court, etc.) is an important consideration (30).

Assessment of MAS. The assessment of endurance or aerobic fitness has a long history in pediatric exercise science and youth fitness testing. Most research studies report VO_2max values often expressed as $ml\cdot kg^{-1}\cdot min^{-1}$ rather than $\dot{v}VO_2$max or MAS (e.g. 3,17,39). However, VO_2max values are not practical in prescribing training in many instances. In addition, although laboratory assessment of VO_2max provides the most accurate assessment of MAS (10), this is not feasible or practical when assessing large groups of athletes, especially youths. Thus, field tests that obtain MAS are often employed in the practical setting.

The original research that investigated the determination of MAS using field-based tests were based on the Universite de Montreal Track Test (37) and the 20 m multistage shuttle test (38). In the past several decades, other field tests including distance runs (i.e., 1-mile run), time trials (i.e., 6 or 12 min run), or incremental continuous field tests such as the Yo-Yo Intermittent Recovery (35), 45-15 (18), Carminatti's test (65) and the 30-15 intermittent fitness test (13) have become commonplace. For a description of these tests, please refer to the related articles referenced above.

In the general youth population, the reliability and validity of field tests such as the 1.6 km run and 20-m multistage shuttle test are, for the most part, high ($r = 0.85$) (22). However, the reliability of distance runs in younger children (<10 yrs) is lower ($r=0.40-0.60$) probably because of cognitive and psychological factors related to motivation and pacing factors. Among youth athletes, there is generally a moderate-to-high correlation between MAS determined by field tests and treadmill test (2,18,65). Although these studies used correlation as the reliability and validity statistic, it should be noted that this is not best practice and other statistics (i.e. typical error, Bland-Altman, etc.) should be considered.

Similar to sprinting tests, several of the same factors need to be considered when conducting field tests to determine MAS. In particular, environmental conditions (e.g. heat and humidity) may impact endurance performance moreso. Although no published study has examined performance on an MAS test specifically, Rowland et al. (55) showed a decrease in endurance performance capacity (i.e. steady-load cycling to exhaustion at ~63% $\dot{V}O_2$max) in prepubertal boys (11.7 +/- 0.4 yrs old) from ~19.7°C and 60% relative humidity (41 ± 6 min) to 31.1° C and 54% relative humidity (29 ± 6 min). In addition, the hydration and nutritional status of the athlete are also important factors for endurance tests.

Variation in ASR parameters based on MSS and MAS testing. In a study of 10 adolescent female rugby players (45) the ASR was computed across nine different methods based on MSS from 20 m, 30 m and 40 m sprint tests and 3 aerobic parameters (vVO_2max, MAS, vIFT) (Table 2). Although the ASR calculations for 30 m and 40 m were similar for each expression of MAS, the 20 m metric was lower. Values including the vIFT were consistently higher. Overall, there were slight differences across the nine methods which demonstrates large variability (range 1.84 $m \cdot s^{-1}$ to 2.29 $m \cdot s^{-1}$) in the calculation of ASR based upon the methods used. Therefore, future research should aim to establish the most effective methods to measure MSS and MAS to then calculate ASR for effective use in practice.

<<INSERT TABLE 2 *Variation in ASR parameters based on MSS and MAS testing* >>

AGE- SEX- AND MATURITY-ASSOCIATED VARIATION OF MSS, MAS AND ASR

Given the long-standing history of sprinting and endurance in youth fitness testing batteries, there is a range of available research in the general population of youth. Similar to most physical performance outputs in youth, both sprinting and endurance performance differ between sexes and are impacted by normal growth and maturation. Figure 4 shows the age- and sex-associated variation in the 50th percentile of endurance (1 mile run) and sprinting (50 yd) performance in U.S. youth aged 6-17 yrs from the 1985 National Study of Youth Fitness (53). Although nearly 40 yrs ago, these data were chosen because they represent the general age- and sex-related trends for both sprinting and endurance variables across the entire age range of childhood and adolescence. In general, both sprinting and endurance performance improves with age in boys and girls during childhood and early adolescence, and sex differences are relatively small but consistent. Among girls, sprinting and endurance performance generally reaches a plateau at about 13-14 yrs, while increases in performance continue through late adolescence in boys. More recent data of Australian youth also show these well-known age- and sex-related differences as Catley & Tomkinson (19) presented the percentiles for the 1 mile run of 9-17 yr olds and 50 m sprint of 9-15 yr olds (Figure 4). For the 1-mile run, the 50th percentile at 9 and 15 yrs of age was 522 s (MAS=3.1 $m \cdot s^{-1}$) and 430 s (MAS=3.7 $m \cdot s^{-1}$) in boys. For girls, 50th percentile was 609 s (MAS=2.6 $m \cdot s^{-1}$) and 570 s (MAS=2.8 $m \cdot s^{-1}$). For 50 m sprint time the 50th percentile for boys was 9.1 s (MSS=5.5 $m \cdot s^{-1}$) to 7.7 s (6.5 $m \cdot s^{-1}$) and for girls was 10.0 s (MSS= 5 $m \cdot s^{-1}$) and 8.6 s (5.8 $m \cdot s^{-1}$). It is important to note that the MSS shown here were calculated based on the given sprinting distance only (e.g., 50 m/9.1 sec = 5.5 $m \cdot s^{-1}$) and thus are not a true indication, and more specifically an underestimation, of MSS given the acceleration and speed maintenance phases thus representing the average sprinting speed across the given distance. This is due to many speed tests in the general population not including split times as used in testing settings of young athletes as described above. Nonetheless, it provides insight into the age-related changes in sprinting ability and the locomotor profile of the general population of youth.

<<INSERT FIGURE 4>>

A range of studies presenting the speed and/or endurance capabilities of young athletes have demonstrated improvements with age and maturity as shown in the general population. As in adults, only recently have studies begun to calculate and report the ASR of youth athletes given the emergence of the concept as mentioned above (23,54, 60, 61). As shown in Table 3, MSS and MAS generally increase with age, and there appears to be an increase in ASR with age as well (23,54,61). This is also evident across maturity groups (Figure 5) as Rowan et al (54) and Selmi et al. (60) have demonstrated significant differences in MSS, MAS and ASR between youth soccer players grouped as pre-, circa-, and post-peak height velocity. However, it is important to point out that these results indicate differences by maturity status are also confounded by chronological age (e.g., a 13 yr old circa-peak height velocity is not the same as a 14 yr old post-peak height velocity boy). Ideally, the impact of maturity would be examined within a chronological age group or by statistically controlling for chronological age (7). It should be noted that only published data on males are available; thus, future research should include female athletes.

<<INSERT TABLE 3>>

<<INSERT FIGURE 5>>

The age- (and maturity) related differences in ASR represent the disproportionate increase in MSS relative to the age-related changes in MAS. This observation is in line with previous data on the age- and maturity-related changes in anaerobic and aerobic capacity in youth often represented as peak power output from the Wingate test and VO_2max, respectively (4). The changes in anaerobic capacity and sprinting ability are largely due to a number of factors including maturity and body composition changes (i.e., muscle mass), and neuromuscular determinants including muscle size, fibre composition, anaerobic enzyme concentration, and connective tissue / tendon changes (64).

TRAINABILITY OF MSS, MAS, and ASR

Although it is important to understand the natural development of physical qualities during childhood and adolescence as shown in the preceding section, the effects of training are typically of more interest to practitioners. However, teasing out the effects of normal growth and maturation from the training response in youth has been a long-standing dilemma of the pediatric exercise scientist (7). Besides age, growth and pubertal status, the adaptation to training of growing and maturing youth also depends on sex, genotype, nutrition, pre-training levels (current status), psychological factors, and training age.

In the context of the trainability of youth, it is important to mention that some scholars and practitioners aligned with earlier Eastern European LTAD models have popularized the notion of ‘critical’ or ‘sensitive’ periods of trainability or windows of trainability (5,67). Concurrently, this idea was coined the ‘trigger hypothesis’ and suggested that puberty or the adolescent growth spurt was a critical period to amplify physiological adaptations to exercise training (34). However, a lack of empirical evidence to support the original LTAD model (5), along with the lack of recognition of the natural development of physical traits during the adolescent growth spurt, has resulted in much debate surrounding its application (6,26,32). In turn, this led to the Youth Physical Development model (42) that provides a framework for the development of general athleticism (fundamental and sport skills, speed, agility, strength, power, mobility, and endurance) from childhood through adolescence, with an emphasis that all physical qualities are trainable at all ages.

Research has shown that specific sprint training (16,44), non-specific sprint training modalities such as resistance training (40) and plyometric training (8), and a combination of specific and non-specific modalities (40,56) contribute to the development of MSS. The meta-analysis conducted by Moran et al

(44)found a significant overall improvement in sprinting velocity (effect size, ES = 1.01) but the response was only positive for those classified as mid- and post-PHV. However, it is important to note that only two studies were included for the pre-PHV group. In a meta-analysis of five studies, Rumpf and colleagues (56) found that plyometric training was the most effective method for improving sprint times in pre-PHV participants and mid-PHV participants, and post-PHV youth benefited most from combined training methods. Other meta-analyses have also shown the impact of resistance training and plyometrics on sprinting. Lesinski et al. (40) found resistance training to have a small effect on linear sprint performance (standardized mean difference, SMD=0.58), while Behm et al (8) also reported an overall small effect of traditional resistance training (SMD = 0.48) and power training/plyometrics (SMD = 0.38) on sprint measures.

A more recent meta-analysis of sprint speed in the football codes (athletes of all age) showed resistance training, resisted sprint and combinations to be the most effective for developing MSS but no mode was more beneficial than another (47). A moderator analysis for age showed similar effects. Interestingly, sport only training and sprinting alone were insufficient training modes to develop MSS and therefore MSS training should include a resistance element to be effective. Practitioners should focus on long-term training interventions, which are not regularly reported in the literature, to enhance MSS. However, future research is needed to better understand the trainability of MSS of youth athletes.

Several excellent reviews and/or meta-analyses have been published on the trainability of aerobic fitness (3,17,39), but not MAS specifically, and sprinting speed (44,56), so the discussion here highlights only key points and major observations. VO_2max (also referred to as VO_2 peak; note it is beyond the scope of this paper to discuss the nuances of these terms) has shown a responsiveness to endurance or interval training throughout childhood and adolescence. In general, the average training-induced increase in relative VO_2max ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$) has been reported to be about 5-10% or 2-4 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ with a range in the mean training response from 1% to 29% (17,39,52). Obviously, frequency, intensity and duration of the training session and overall training program are important factors. Although previous results show a training-induced improvement in VO_2max (and an assumed increase in MAS), few studies are available that specifically examine the training effectiveness on MAS. In a 12-week study of relatively untrained 14-17 yr olds, it was found that subjects in the intense training group (i.e., consisting mainly of intermittent exercise at 90%-120% of MAS) improved their MAS by an average of 5.7% for males and 5.4% for females (9).

Training studies that simultaneously examine the effect on MAS and MSS (and ASR) are generally limited. In national-level junior soccer players (18.1 ± 0.9 yrs of age) Ortiz et al. (49) showed significantly greater improvements than the control group in flying 20m sprint and VO_2max following an 8-week supramaximal intermittent shuttle run training aimed at improving both MSS and MAS. The authors concluded that the training stimulus was effective in enhancing aerobic performance-related indices along with small improvements in MSS without impairing acceleration (49). In a study of U17 male soccer players (16.8 ± 0.4 yrs) exposed to small-sided games of 3v3 and 5v5 significant increases were observed for vIFT and 30 m sprint speed, while no significant differences were found for ASR (62). However, these were mean responses, which is common in research; yet there was considerable individual variation in ASR. This was alluded to by the authors and shown in their Fig 2 where 9 of 20 subjects show an improvement in ASR. In junior tennis players (51), individual pre- and post-training values were actually reported for the locomotor profile (Table 4). Prior to training, athletes were grouped into either an endurance-based high-intensity interval training (HIIT) group or sprint-based HIIT group based on game style and corresponding SRR (as described previously in this paper). In addition, athletes also completed on-court movement sessions focusing on acceleration and change-of-direction plus stand-alone sessions of resistance training and plyometrics two days per week. There were significant and meaningful improvements in ASR and SRR for all athletes.

<<INSERT TABLE 4>>

In summary, whilst evidence exists for the trainability of aerobic and sprint characteristics in youth athletes, research specific to the trainability of MAS, MSS and ASR is limited and therefore an area for future research. The following section provides practical considerations for such training studies.

PRACTICAL APPLICATIONS AND CONSIDERATIONS FOR TRAINING

Given the inter-individual variability in the locomotor profile of field and court sport youth athletes, it is suggested that creating and utilizing a locomotor profile be considered when designing training programs. This approach can be used to calibrate and individualize an athlete's locomotor profile towards their strengths and/or weaknesses. With an understanding of the athlete and the sporting needs, the practitioner can assess if an athlete's locomotor profile matches the demands that they will be exposed to and better prioritize training prescriptions. In this section, we highlight a four-step process adapted from Sandford et al. (59) that will guide sport scientists and coaches in the development of fast, fit, and fatigue resistant youth athletes.

Step 1 - Assessment of MSS and MAS

Based on the available resources and potential contextual factors and restraints, practitioners must determine the most appropriate protocols for assessing MSS and MAS in their setting. First and foremost, data collection protocols should be standardized. Ultimately, the protocol needs to be feasible and should have high ecological validity and repeatability to monitor longitudinal changes in youth athletes. In addition, growth and maturity indicators should also be routinely measured to interpret changes in the locomotor profile (and other physical qualities) and also modify training, if needed.

Step 2 - Calculate the ASR and SRR and determine locomotor profile subgroups

Once MSS and MAS are determined, ASR (MSS - MAS) and SRR (MSS/MAS) can be easily calculated. From here, subgroups (speed-based, hybrid, and endurance-based; see Table 1) can be determined using tertiles from the training groups' data. However, subjective methods as previously mentioned should also be considered when making decisions. This may come into play if the data are skewed one way or the other. For example, some teams or training groups may naturally have a large percentage of speed-based or endurance-based profiles. In this case, using subjective methods and practical experience may inform the cutpoints. Using data from Figure 1, Athletes A and E would perhaps fall into the speed and endurance groups, respectively, with Athletes B-D being included in the hybrid group.

Step 3 - Determine the macro-training scheme for each profile

Once athletes are placed into subgroups, the training prescription that best suits each profile can be developed. For instance, endurance-based profiles will typically prefer, and respond better to, continuous training or longer intervals. Conversely, speed-based profiles can benefit more from varied paces and shorter intervals. Hybrid profiles would be suited for a blend of both. However, a well-rounded youth physical development program should include resistance training, plyometrics, locomotor profile-based conditioning, and mobility and recovery techniques. In many youth athlete programmes, endurance training has less emphasis (as suggested by Lloyd and Oliver YPD model) due to sport-specific training and competition providing an endurance stimulus with other training time being spent on other physical qualities. However, assessing and monitoring individuals allows athlete's needs to be considered for the most appropriate programme.

To optimize conditioning, coaches must determine if/when to push athletes outside of their profiled 'comfort zone' versus staying within their current profile. In addition, the off-season or pre-season training presents an opportunity to challenge speed-based profiles with continuous or longer interval training and, subsequently, an opportunity to challenge endurance-based profiles with varied paces or shorter intervals. During periods of training where sport-specific skill development is priority (i.e., in-season competitive cycle), it is advisable to keep the training scheme in line with the locomotor profile with the expectation that the desired adaptation will be more accurately targeted without compromising the sport practice through excessive fatigue or discomfort.

Step 4 - Prescribe training session details based on individual profile and desired response to training

Besides the individual athlete's locomotor profile and subgroup, each training session will need to consider and calibrate to the individual athlete's specific intensity, duration and mode of activity. In addition, the age (and training age) and maturity of the young athlete is also important to consider. It is also important to note that younger athletes can benefit greatly from exposure to a variety of training modes; however, diversifying the movement portfolio and training modalities has benefits for adolescent athletes as well. Variety in training can serve to develop (or refine) fundamental movement skills and reduce the risk of overuse injury and burnout (36,41).

As discussed in the section on trainability, multiple training modalities can be considered to enhance MSS. Sprint-specific training includes sprinting, resisted- (e.g., sled pulls and pushes, uphill) or assisted-sprinting (downhill, towed), and technical sprint training (e.g., running drills). Non-specific sprint training includes training modalities that do not include sprinting including resistance training and/or plyometric training. In practical settings, there is often a blend of these modalities within a session or across a microcycle. While the determinants of sprint performance are multifactorial and include genetics, body size, maturity, neuromuscular physiology and technical proficiency, a considerable amount of research has indicated strong correlations between resistance training or lower body muscular strength and sprint performance (8,21,27). More specifically, strength and power training, when combined with sprint training, may lead to the best results (31). The combination of strength/power training and sprint training may best be accounted for by employing resisted sprinting options such as hill sprints, sled sprints, or motorized resistance machines. These methods can be considered specific-strength exercises when completed with high levels of resistance and may assist with the transfer of neural improvements to increased sprint performance.

For the development of MAS, training methods include continuous, steady-state training below lactate threshold, high-intensity interval training, and game-based conditioning that involves movement (i.e. invasion games) and technical skills related to the sport or related activity (29). Regarding the latter modality (i.e. small-sided or invasion games), player numbers, field/court size, and rules/behaviors can be constrained or manipulated to achieve specific volumes and intensities aimed at aerobic adaptations while continuing to work on the development of sport skills (28). The variations are only limited by imagination and allow for keeping training fun and fresh to enhance motivation and avoid boredom. Small-sided games thus provide a great option as they have been shown to be as effective as conventional endurance training for increasing aerobic performance among male adolescent soccer players (43). This finding is important for a few reasons: 1) small-sided games can allow both endurance and sport skills training to be carried out simultaneously, thus providing a more efficient training stimulus, and 2) practical experience informs us that young athletes enjoy small-sided games more than conventional endurance training methods (long, slow continuous distance or intervals). The study also found that the training effect requires two sessions per week with $\geq$ 4 sets of 4 min of activity, interspersed with recovery periods of 3 min.

In a review of studies investigating training to enhance aerobic fitness of young athletes, Harrison and colleagues (29) recommended that moderate-intensity aerobic fitness training (e.g., 60-80% VO_2max) should be integrated into a range of sport-specific drills, activities and games during childhood (the sports sampling stage). During the specialisation stage, high-intensity small-sided games (e.g., 3-4 x 4 min games above 90% max HR) should be used, and a combination of small-sided games and high-intensity interval training in the investment stage (pursuit of proficiency in a chosen sport) is recommended.

An important aspect of individualizing the training session involves prescribing training intensity. Several options for prescribing training intensity exist based on physiological markers including %VO2max, % heart rate max, heart rate reserve, and the aerobic and anaerobic thresholds. Although these options have varying degrees of ecological validity, in many instances they are not as practical as prescribing intensity as %MAS. A common prescription in this manner entails programming bouts at an intensity of 120% MAS with a work:rest ratio of 1:1 (often 15 or 30 second efforts of rest and recovery). This type of protocol has been shown to have a positive effect on VO_2max when compared with other intensities and durations of %MAS (24) .

While using %MAS is relatively simple to implement, there is a significant shortcoming to this approach. This approach uses an aerobic measure to prescribe training that elicits a high anaerobic contribution without taking into consideration the athlete's ASR. For this reason, using %ASR to prescribe training intensities above MAS can help ensure the programming of a more precise stimulus by taking into account the relationship between an athlete's aerobic and anaerobic abilities. For example, let's illustrate this point using Athletes A and B from Figure 1 who have the same MAS (4.3 $m \cdot s^{-1}$) but different MSS and ASR. If a prescribed bout was 120% MAS, they would both be running at 5.2 $m \cdot s^{-1}$. In turn, this equates to 27% ASR in Athlete A and 35% in Athlete B. Indeed, research has shown that utilizing ASR to prescribe training intensity explained individual differences in continuous running time to exhaustion above MAS better than MAS itself (11). Further, the prescription of intensity using ASR compared to %MAS in a group of 16-18 yr old Australian Rules footballers provided a similar physiological demand by reducing the variability in interval running performance, potentially eliciting more accurate physiological adaptations in team settings (20). As stated by Sandford and colleagues (59, pg 2018) "what likely matters the most, irrespective of athlete profile or locomotor mode when exercising at intensities beyond MAS, is how much of the ASR is used, rather than the relative intensity in relation to MAS".

CONCLUSION, LIMITATIONS AND FUTURE RESEARCH

This paper has provided a review of the locomotor profile concept consisting of MSS, MAS, ASR and SSR in youth athletes. In addition, practical considerations for the implementation of assessing and training these parameters have been provided. It is important to consider the assessment of the underpinning measures of MSS and MAS as each method has its own strengths and weaknesses which can make interpreting the data challenging, both within research and practice. Based on the available data in young male athletes, MSS, MAS and ASR generally increase with age and across maturity groups (i.e., pre-, circa-, and post-PHV). The increase in ASR during adolescence is a result of the disproportionate increase in MSS relative to the changes in MAS, which are likely due to changes in body size and composition (i.e., muscle mass), metabolic physiology (i.e., muscle glycogen and anaerobic enzymes), and neuromuscular physiology. Although data is not available for young female athletes, based on values from the general population there is a clear pattern that boys outperform females for both MSS and MAS performance, and this becomes more pronounced during adolescence. Although teasing out normal growth and maturation is difficult, these parameters are trainable using a variety of modalities including continuous training, HIIT, small-sided games, repeated sprint and circuit training. Furthermore, resistance training and plyometrics should also be included in the training programs. Overall, decisions on training need to consider the sport demands, current fitness and maturity status and targeted training adaptation sought.

Given that research examining ASR and the locomotor profile in youth athletes is in its infancy, further research is required to understand the effect of age, sex (especially females), and maturity on ASR and the locomotor profile. Insights into reference values and locomotor profile cutpoints for different sports and positions is also encouraged. Few studies are available that consider the trainability of MSS, MAS and ASR and future research should consider both baseline level and the training load accumulated over a training period. The concurrent changes in growth- and maturation-driven morphological covariates should also be considered in training studies. Given the increased popularity of the locomotor profile among practitioners, it is hoped (and encouraged) that data will emerge and be made available from these "Living Labs" (25).

In conclusion, this paper has expanded upon a recent challenge of current conventions in pediatric exercise science that focused on the development of aerobic and anaerobic fitness (4) by shedding light onto the utilization of locomotor profile (MSS, MAS, and ASR). More specifically, the locomotor profile provides a practical way to monitor and prescribe training in a feasible manner. Whilst future research is required to understand this concept, the assessment and training of MSS, MAS, ASR and SRR can be integrated into the long-term athlete development programmes of youth athletes to enhance their performance and development.

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Figure 1. The locomotor profile of five youth athletes (Hettler and Eisenmann, unpublished data). Values in the top panel are MAS (blue), ASR (red) and MSS (value above). Values in the bottom panel show the speed reserve ratio (SRR=MSS/MAS) for the five athletes.

Figure 2. Speed-distance curves for a sample of junior tennis players, 13-17 yrs of age (Hettler and Eisenmann, unpublished data).

Figure 3. Fastest 10-m split time distribution as a function of age in young soccer players. Sample sizes per age category are: U12, n=59; U13, n=188; U14, n=173; U15, n=190; U16, n=142; U17, n=148; U18, n=67. Figure redrawn from Buchheit et al. 2011.

Figure 4 shows the age- and sex-associated variation in the 50th percentile of endurance and sprinting performance in the general population of U.S. youth age 6-17 yr (top panel) in the general population of Australian youth age 9-15 yr. U.S. data from Reiff et al. 1985 and Australian data from Cately and Tomkinson, 2013.

Figure 5. Maturity-associated variation in MSS, MAS and ASR among youth soccer players (Rowan et al 2019 and Selmi et al 2021).

Table 1. A general classification scheme for the locomotor profile. Adapted from Sandforth et al. (2019).

	Speed Profile	**Hybrid Profile**	**Endurance Profile**
MSS	High	Moderate	Low
MAS	Low	Moderate	High
ASR	Large	Moderate	Small
SRR	High	Moderate	Low

Table 2. Variation in ASR among adolescent female rugby players (n=10) based on MSS testing at different distances (20 m, 30 m and 40 m sprint) and different MAS tests (vVO_2max, MAS, vIFT). Data from Muller et al (45).

	20 m MSS	**30 m MSS**	**40 m MSS**
vVO2max	2.01 ± 0.59	2.20 ± 0.63	2.21 ± 0.60
MAS	1.84 ± 0.59	2.03 ± 0.52	2.04 ± 0.48
vIFT	2.09 ± 0.46	2.28 ± 0.51	2.29 ± 0.41

Table 3. Maximal sprint speed (MSS), maximal aerobic speed (MAS) and anaerobic speed reserve (ASR) in male youth athletes.

	MSS ($m \cdot s^{-1}$)	MAS ($m \cdot s^{-1}$)	ASR ($m \cdot s^{-1}$)
Silva et al. (2022) n = 124 soccer players			
14 yr	7.9 ± 0.5	4.8 ± 0.4	3.1 ± 0.6
15 yr	8.5 ± 0.8	5.1 ± 0.3	3.5 ± 0.8
16 yr	8.8 ± 0.8	5.1 ± 0.3	3.7 ± 0.8
17 yr	9.0 ± 0.6	5.2 ± 0.3	3.7 ± 0.6
18 yr	8.9 ± 0.5	5.4 ± 0.2	3.5 ± 0.6
Rowan et al. (2019) n = 47 soccer players			
U13	7.1 ± 0.3	4.1 ± 0.3	3.0*
U14	7.7 ± 0.3	4.1 ± 0.3	3.6
U15	8.0 ± 0.4	4.4 ± 0.3	3.6
U16	8.4 ± 0.4	4.6 ± 0.2	3.8
Darrall-Jones et al. (2016) n= 36 rugby union forwards			
U16s	7.6 ± 0.3	5.0 ± 0.4	3.7 ± 0.4
U18s	8.1 ± 0.4	5.1 ± 0.3	3.9 ± 0.4
Darrall-Jones et al. (2016) n = 32 rugby union backs			
U16s	8.2 ± 0.6	5.2 ± 0.3	4.0 ± 0.6
U18s	8.6 ± 0.4	5.4 ± 1.0	4.2 ± 0.4

Table 4. The locomotor profile of junior tennis players at baseline and following a training and conditioning block. Data from Parkes et al 2022.

		Pre-training (Sept 2021)				**Post-training (Dec 2021)**			
ATHLETE	**GAME STYLE**	**MAS** $(\text{m}\cdot\text{s}^{-1})$	**ASR** $(\text{m}\cdot\text{s}^{-1})$	**MSS** $(\text{m}\cdot\text{s}^{-1})$	**SRR**	**MAS** $(\text{m}\cdot\text{s}^{-1})$	**ASR** $(\text{m}\cdot\text{s}^{-1})$	**MSS** $(\text{m}\cdot\text{s}^{-1})$	**SRR**
Athlete A	Counter-Attacker	4.3	2.5	6.8	1.57	4.4	3.3	7.7	1.75
Athlete B	Aggressive Baseliner	5.0	2.3	7.3	1.46	4.7	3.7	8.4	1.79
Athlete C	Aggressive Baseliner	4.3	2.8	7.1	1.65	4.4	3.6	8.0	1.82
Athlete D	Aggressive Baseliner	4.3	2.8	7.1	1.66	4.3	4.1	8.4	1.95
Athlete E	Aggressive Baseliner	4.5	2.9	7.43	1.67	4.8	3.6	8.4	1.75
Athlete F	All-Court Player	4.5	2.9	7.43	1.67	4.8	3.6	8.4	1.75
Athlete G	All-Court Player	4.7	2.7	7.4	1.59	4.6	3.7	8.3	1.80