ABSTRACT

Speed is a key aspect of Youth Physical Development programs and commonly assessed during talent identification testing protocols, yet little is understood about the factors that underpin the natural development of maximal speed throughout childhood and adolescence. This article reviews the anthropometric, kinematic, kinetic and asymmetry variables that contribute to sprint performance, while examining the impact that growth and maturation may have upon all facets of maximal sprint performance in boys. Clear guidance is provided on the practical applications for the strength and conditioning coach that should help in design of effective speed development programs for male youth.

KEY WORDS

Velocity; Kinetic; Kinematic; Stiffness; Asymmetry; Maturation
INTRODUCTION

Sprinting is considered a fundamental movement that underpins successful sports participation (27,36,46). Sprint speed is also recognized as a key component of Youth Physical Development programs (26), and is common performance assessment in strength and conditioning programs and talent identification batteries (36). The development of speed in boys throughout childhood and adolescence has previously been considered (40), however the authors noted that little was understood about the factors that underpin natural developments in maximal sprint performance in youth. Given recent developments in the pediatric literature pertaining to the development of maximal sprint performance (22,32–34,45,51,52), this review aims to examine key variables that facilitate the development of maximal sprint speed in boys throughout childhood and adolescence.

DEVELOPMENT OF MAXIMAL SPRINT SPEED IN BOYS

In boys, maximal sprint speed is known to develop in a non-linear fashion throughout childhood and adolescence (28), with the suggestion of a pre-adolescent spurt (5-9 years old) and adolescent spurt (12-14 years old) in performance for boys (58). While these spurts in sprint performance are based upon chronological age, a maturational effect for the development of sprint speed has also been proposed (33,52). Peak height velocity (PHV) is often used as an indication of maturity and is defined as the maximum rate of growth in stature during the adolescent spurt (28). Peak improvements in sprint speed have been reported to occur between 8-18 months prior to the period of PHV (58,63). Conversely, it has been reported that peak changes in sprint speed
may occur in time with the period of PHV (43,56); however decrements in speed may be noted in the 12 months prior to PHV (43), thus reinforcing the non-linear nature of speed development. Recent cross-sectional data have suggested that maximal sprint speed does not change between groups of boys who were between 1-3 years pre-PHV, but significant increases in speed are observed between circa- and post-PHV groups (33).

Researchers have suggested that when monitored over a two year period boys who advance from 13-15 years old (~circa-PHV) improve sprint performance up to twice as much as those who advance from 15-17 years old (~post-PHV) (11), while boys who experience the period of PHV produce significantly greater increases in maximal sprint speed (10.4 vs. 5.6%) compared to boys who remain pre-PHV (45). Collectively these observations confirm the presence of a maturational effect upon the development of speed (32,33,52); however in order to facilitate appropriate training prescription for the development of maximal sprint speed in youth, it is important for practitioners to understand the kinematic and kinetic underpinnings of these observations and the manner in which natural growth and development may influence the development of these characteristics.

ANTHROPOMETRY AND MAXIMAL SPRINT PERFORMANCE

Throughout childhood and adolescence boys experience non-linear growth patterns for almost all anthropometric characteristics (28). The period of PHV is characterized by rapid increases in stature, however it is important to note that the greatest increases in leg length are observed in the early phases of the adolescent growth spurt, with more rapid increases in trunk length and
overall standing height observed in the latter portions of the growth spurt (28).

Very few studies have investigated the role of anthropometric variables upon sprint performance in youth. In a large sample of boys aged 11-15 years old (n = 355), negative relationships between body mass and maximal speed as well as step length have been reported; while increased body mass was related to elongated ground contact time (33). Furthermore, when examined in maturity groups, mass exerted a negative influence on speed, step length, step frequency, contact time and flight time in pre-pubertal boys, as well as a negative influence upon speed and step length in post-pubertal boys (32). It is important to note that standing height exerted a positive influence on speed and step length in pre-pubertal boys, while leg length exerted a positive influence on step length in post-pubertal boys (32). Furthermore, very strong relationships have been reported between leg length and contact length (distance travelled by the center of mass during ground contact) (22), which may highlight one of the key mechanisms for improved step length with increasing leg length.

Applications for the strength and conditioning coach

Collectively, these results suggest practitioners should devote their attention to offsetting the negative influences of mass seen as a consequence of natural growth and maturation. While increases in muscle mass should be an expected positive consequence of maturation, increases in fat mass would have a negative influence upon force production. Resistance training may be the most effective means by which to overcome the negative influence of mass by enhancing force production capabilities while also eliciting favorable
changes in body composition to maximize relative maximal force (7). Meylan and colleagues (37) reported that vertical strength and power helped to explain differences in sprint time in boys of advancing maturation, with strength and power explaining the majority of differences between boys who were pre- and mid-PHV. In line with Youth Physical Development models, these observations may serve to highlight the importance of early introduction into resistance training for boys wishing to enhance their maximal speed (26). It is important to note that the somatic variables discussed here were only able to explain a small proportion of the total variance in the kinematic characteristics of maximal speed (11–57%) (32), leaving a large proportion of unexplained variance to be accounted for by other factors. In boys of advancing maturation, the majority of variance in sprint performance may be accounted for by the combination of anthropometric variables, strength and power (37), further reinforcing the importance of these characteristics in youth sprint performance. Recent longitudinal data indicate that changes in anthropometric variables over a 21-month period were not related to, nor acted as significant predictors of, changes in maximal sprint speed over the same period (45), which may further highlight the importance of non-anthropometric variables upon maximal sprint performance in youth.

For practitioners working with youth athletes it is imperative that changes in these variables as a consequence of natural growth and maturation are regularly monitored and are factored in when designing training for youth athletes. It is suggested that changes in anthropometric variables (standing height, sitting height, leg length, mass) are monitored regularly (approximately every 3 months) (19) for each individual youth athlete so that coaches can
detect periods of rapid growth and maturation and be mindful of the consequences of these for maximal sprint speed and other aspects of physical performance.

KINEMATICS OF MAXIMAL SPRINT PERFORMANCE

Fundamentally, speed can be determined by the product of step length and step frequency, with the theoretical aim to concurrently enhance both characteristics in order to enhance sprint performance. Conversely, a negative interaction between step length and step frequency has been proposed in adults (12), and it has been further suggested that elite adult sprinters may be reliant upon one of a combination of these characteristics in order to elicit their best 100 m sprint performance (54). Clearly the interactions between step length and step frequency are not as well defined as the equation for speed may suggest, especially in pediatric populations. Furthermore, additional factors such as growth and maturation throughout childhood and adolescence serve only to increase the complexity of the development of sprint speed in youth.

Step length has been reported to increase throughout childhood and adolescence (33,55), with the suggestion that these changes may be proportional to changes in leg length (55). It has been proposed that increases in contact time and concomitant decrements in step frequency may occur in the pre-pubertal years, resulting in unchanged maximal sprint speed during this period (33). Conversely, the majority of youth literature actually suggests that step frequency appears to remain unchanged throughout childhood (55) and between boys of advancing maturity (32,45,52). Furthermore, it has been
consistently reported that no significant differences in flight time have been observed with advancing maturation (32,33,52). These observations serve to highlight the importance of focusing upon the period of ground contact to elicit improvements in step frequency that do not occur naturally as a result of growth and maturation.

It is important to note that the study by Rumpf and colleagues (52) utilized a non-motorized treadmill. It is know that the inherent resistance in a non-motorized treadmill reduces the maximal speed obtained compared to overground sprinting (16,38). Consequently, the kinetic and kinematic parameters of sprint performance may also differ between a non-motorized treadmill and overground sprinting. For instance, a comparison of studies suggests that maximal speed, step length and step frequency are ~27-60% lower and contact time is ~48-80% longer in boys sprinting on a non-motorized treadmill versus overground conditions (32,33,52). On this basis, practitioners should be mindful of interpreting data from non-motorized treadmills in youth, as they may not truly reflect the kinematics and kinetics associated with maximal sprint performance.

Currently there is a paucity of longitudinal data pertaining to the kinematic changes in sprint performance in youth. Recent data collected over a 21-month period has shown small decrements in step frequency (-2.4%) and small increases in contact time (2.3%) during the period prior to PHV; however, for boys moving from pre-PHV to post-PHV, small increases in step frequency (2.7%) and decreases in contact time (-3.6%) were observed (45). Furthermore, consistent increases in step length were seen in boys who remained pre-PHV and boys moving from pre-PHV to post-PHV (7.8% and 8.0%, respectively)
Importantly, changes in step frequency and contact time were below the threshold of measurement error for these variables (CV = 4.3% and 4.9%, respectively) (34). These data highlight that the reliability of the optical measurement system used in this study is not sufficient to attribute the longitudinal changes in step frequency and contact time to actual performance changes over-and-above the error of the data collection process. Conversely, the reliability reported for step length (CV = 3.9%) (34) is considerably lower than the observed longitudinal change in performance, and therefore practitioners can be more confident that real changes in performance are being observed over-and-above the system error. On this basis, step frequency and contact time in male youth may be viewed as relatively consistent before and around the period of PHV, while consistent increases in step length may be observed for boys who are pre-PHV and those who have experienced the period of PHV.

Whole-group analyses of boys between 11-16 years old as well as separate pre- and post-PHV groups, have revealed stronger relationships between speed and step length, compared to step frequency (33,34). Furthermore, multiple regression analyses have suggested that boys who are pre-PHV may be more reliant upon step frequency (~58% total explained variance of maximal speed) to elicit maximal sprint speed, whereas boys who are post-PHV may be more step-length reliant (~54% total explained variance of maximal speed) (32), highlighting the differential impact of maturation upon sprint performance. The shift in reliance from step frequency towards step length may also in part be explained by the increases in muscle mass (39,56) and resultant strength (31,47) and power (1,24) during the period of PHV.
Applications for the strength and conditioning coach

Practitioners should be aware of the expected increases in step length and limited changes, or potentially slight decrements, in step frequency as a result of advancing age and maturation. Recent evidence has suggested that plyometric training may be the most effective approach to elicit improvements in sprint performance in pre-pubertal boys (21,53). Practitioners should refer to previously published guidelines related to the prescription of plyometric training in youth populations to ensure the safe and effective implementation of this training modality (2,23). The use of plyometric training in pre-pubertal boys would seem to target positive adaptations in musculotendinous stiffness and neurological factors such as neural firing rates, preactivation and the stretch reflex, which are known to be naturally developing at this time (9,15,17,25,41). Furthermore, the step frequency reliance seen during the pre-pubertal period may also be accounted for by the natural developments in neural characteristics and sensitivity to training of a high neural stimulus. It has also been observed that post-pubertal boys may be more step length reliant, and therefore it could be suggested that combined strength and plyometric training may be the most effective training approach to enhance sprint performance in post-pubertal boys (21,53). It would seem that this approach effectively harnesses the continued enhancement of neural characteristics (42), while also targeting enhancements in force generating capability alongside the natural developments in muscle cross-sectional area (39,56) and pennation angle (3) that are also observed throughout adolescence. Furthermore the significant increases in testosterone in the PHV
period (58) create an enhanced anabolic environment that may be the
foundation of the observed increases in strength (31,47) and power (1,24) at
this time. The approach to training physiological qualities that are known to be
developing through natural growth and maturation has been termed “synergistic
adaptations” (7), and should be a key consideration when designing Youth
Physical Development programs.

**KINETICS OF MAXIMAL SPRINT PERFORMANCE**

Research on the kinetic determinants of maximal sprint performance
in youth is somewhat sparse; however data from non-motorized treadmills
suggests that maximal force and power may be important predictors of sprint
performance in pre-, mid- and post-pubertal boys (37,52), with the ability to both
produce (concentric) and absorb (eccentric) horizontal power viewed as key
determinants (48). Furthermore, in a small sample (n=11) of post-pubertal boys
(∼16 years) vertical stiffness during bilateral hopping was strongly related to
maximal overground sprint speed, and horizontal power on a non-motorized
sprint treadmill (4). Recent cross-sectional (22) and longitudinal data (45)
obtained during overground sprinting have also suggested that relative vertical
stiffness, relative maximal force and relative leg stiffness are important
determinants of maximal sprint speed in youth, collectively accounting for
between 79% - 98% of the total explained variance.

Based upon adult literature, it is perhaps not surprising to find that
the application of force relative to body mass (relative force production) (61) is
an important determinant of sprint performance in youth; however it is
interesting to note that in both cross-sectional and longitudinal analyses of
boys, relative force production may not naturally increase, and may even decline, between and within groups of advancing maturation (22,45). Furthermore, relative maximal force has a very strong relationship with step length and flight length (distance travelled by the center of mass from toe-off to touchdown), further highlighting the importance of developing relative force production capabilities in youth (22). Of note, absolute maximal force during sprinting increases with advancing maturation (22,48,52), and therefore it seems that concomitant increases in mass also observed with advancing growth and maturation (28) may preclude increases in relative force producing capabilities. Interestingly, research on a non-motorized treadmill has suggested that horizontal force and power may be the best predictors of maximal sprint velocity in pre- and post-PHV boys ($r^2 = 0.98-0.99$), while vertical force more important for boys who are mid-PHV to overcome increases in mass (52).

Vertical power has been shown to have a large impact upon sprint performance in boys, especially those classified as pre- or mid-PHV (37). On a non-motorized treadmill large increases in horizontal power have been reported between boys of advancing maturation, whilst relative horizontal power may increase in pre- and mid-PHV boys yet decline in the post-pubertal period (52). Furthermore, eccentric and concentric power development have been reported as the strongest predictors of sprint speed male youth (48,52). Power absorption (eccentric power) and power production (concentric power) are indicative of storage and utilization of elastic energy and therefore indicators of the strength shortening cycle (SSC) function. Importantly, greater power production during shorter eccentric and concentric periods is observed with
advancing maturation (48), highlighting the improved SSC function with advancing age and maturation (25,28).

A small number of studies have also investigated the role of vertical stiffness in youth sprint performance (4,10,22,45,48,55). Vertical stiffness may be of particular relevance to sprint performance as it reflects the ability to tolerate and overcome gravitational forces. Greater vertical stiffness is reflective of reduced vertical displacement of the center of mass, which in turn would allow for shorter ground contact times and increased step frequency. In youth populations it is especially important to ensure anthropometric variations are accounted for by normalizing stiffness to both leg length and body weight (30) to produce a relative measure. Maturity is suggested to have an influence upon relative vertical stiffness on a non-motorized treadmill, with increases (~17-30%) observed between boys of advancing maturation (48). Conversely, cross-sectional data from vertical hopping and overground sprinting suggest relative vertical stiffness does not change between 11-16 years old (22,24), although longitudinal data suggests there may be some small increases in relative vertical stiffness around the growth spurt (45). During overground sprint performance, increases in step frequency and decreases in contact time have been related to higher levels of relative vertical stiffness in boys (22). These observations may help to explain the role that relative vertical stiffness may have during maximal sprinting and further highlights the potential importance of developing relative vertical stiffness characteristics for sprint performance in youth.

Leg stiffness is different to vertical stiffness as it accounts for the magnitude of leg compression during ground contact rather than center of mass.
displacement. Whilst these variables are identical in vertical motion such as jumping, they differ during horizontal motion such as sprinting (29). Maximal leg compression and relative leg stiffness have been shown to be contributors to multiple regression models for enhanced sprint performance in cross-sectional (22) and longitudinal studies (45) of boys. The mechanisms driving the contribution of these variables appear to be associated with the concept of contact length (distance travelled by the center of mass during the period of ground contact) (60). An almost perfect negative relationship has been reported between maximal leg compression and contact length, while very large positive relationships exist between leg length and contact length (22). These observations highlight that those boys with higher levels of leg compression and longer leg lengths may also elicit greater contact lengths that would consequently benefit overall step length. While the argument for longer limbs enhancing step length may seem intuitive, increasing leg compression (decreasing leg stiffness) at the same time as enhancing vertical leg stiffness, as discussed earlier, does not seem plausible. Interestingly, an explanation for this may be offered by examining the limb angle at touch down, and the resultant leg sweep during ground contact. It has been suggested that leg stiffness decreases with a more horizontal orientation of the leg at touchdown (greater limb angle from the vertical) (30). It is therefore theoretically possible to maintain levels of vertical stiffness, whilst increasing leg compression with more horizontal lower limb angle at touchdown to elicit enhanced contact length and step length.

It is important to point out that relative vertical and leg stiffness are different qualities to relative muscle-tendon stiffness measured around the joint.
In isolated contractions muscle-tendon stiffness increases with age (9,17,59) but no study has directly measured relative musculotendinous stiffness in youths while sprinting. If the large increases in relative muscle-tendon stiffness that are observed with advancing age contribute to speed development, this might be through facilitating increases in step length rather than step frequency, as the latter does not increase with age while the former does. It is important to note that no study has measured all these variables concurrently in a youth population to confirm these assertions, nor have previous studies in this field accounted for maturation in their analyses and therefore further research is required to establish the value of these contentions.

Applications for the strength and conditioning coach

Relative maximal force is a determinant of maximal speed but practitioners should not rely on growth and maturation improving this quality into the second decade of life, instead the use of resistance training is strongly recommended. Research has shown improvements in force production are associated with enhanced sprint performance in youth (5,37), especially when combined resistance training methodologies are employed (7,13,18,50,53). Furthermore, regression modeling has suggested that 10% improvements in force production in boys would result in 1.6 – 4.2% increase in sprint performance (22,37), highlighting the positive impact that may be achieved through modest improvements in strength in youth athletes. Interestingly, a recent six-week training study utilizing resisted sled towing elicited no improvement in maximal sprint performance in the pre-PHV boys whilst the combined mid- and post-PHV group demonstrated enhanced sprint velocity,
step length, step frequency, leg and vertical stiffness, horizontal and vertical force and power (50). Whilst the sled resistance in each group were relative to body mass (2.5-10%), previous research has suggested that the same relative load can reduced the sprint speed of pre-PHV boys by as much as 50% compared to post-PHV (49). These data highlight the benefits of resisted sled towing for mid- and post-pubertal boys but also highlight the importance of determining resisted loads appropriate to different stages of maturation.

Power development is also an important determinant of maximal sprint speed in youth (37), and although natural developments in power expression and SSC function may be seen with advancing maturation, these characteristics should still be developed during training. Combined horizontal and vertical plyometrics have been shown to elicit the greatest enhancement in sprint performance in 11 year old soccer players (~pre-PHV) over a 6-week training period (44), and therefore may be deemed a suitable stimulus to enhance power development during sprint performance in boys. Furthermore, regression modeling has suggested a 10% improvement in power during jumping may elicit a 2% improvement in sprint performance in youth (37), again highlighting the nature of the positive impact that strength and conditioning coaches can have on sprint performance in youth.

The importance of optimizing vertical displacement and development of relative maximal force to elicit enhancements in relative vertical stiffness has been outlined. Improvements in relative vertical stiffness have been shown in 12 and 15 year old boys (~pre- and post-PHV) boys after just 4 weeks of plyometric training (20), and therefore this may be deemed an appropriate strategy for developing maximal sprint speed in youth. Furthermore
the increase in relative vertical stiffness reported in this training study (~8%) (20) would result in ~1.3% increase in maximal sprint speed based upon regression modeling (22), further reinforcing the positive impact of this approach to training youth.

It is interesting to note that while enhanced vertical stiffness is associated with enhanced speed this may not be the case for leg stiffness, which represents a separate quality. Recommendations related to leg stiffness and leg compression are difficult, as it appears that decreases in both variables are observed with natural growth and maturation, which in turn have been linked to enhanced sprint performance via increases in contact length. It is plausible that technical training may be able to influence leg compression and leg stiffness although this claim remains speculative and further research is required before practical recommendations can be generated.

ASYMMETRY AND MAXIMAL SPRINT PERFORMANCE

The literature examining the concept of asymmetry in youth is somewhat sparse, and only two studies have examined asymmetry in boys during sprint performance. Rumpf and colleagues (51) examined kinetic asymmetry during sprinting on a non-motorized treadmill with results indicating an average of 17% asymmetry for force, power and work in a non-injured youth population, with significant difference between maturation groups only evident for work. It is important to note that limb dominance was not assessed in this study (51) and asymmetry calculations were based upon the ratio of asymmetry between legs. This observation may be important given the assertion that during locomotion one leg may act as a "propulsive" leg (greater positive work)
while the other may actual as a “stick” leg (greater stiffness) (6), resulting in the
masking or inflation of individual asymmetry due to limb dominance during
group comparisons. More recently, asymmetry of kinematic and kinetic
variables has been assessed during overground running in a large cohort of
non-injured boys (n = 344) (35). The results of this study reported the
magnitude of asymmetry across all variables ranged from 2.3-12.6%, and that,
predominantly, the magnitude of asymmetry was not different during age and
maturity group comparisons (35). Furthermore, the same study revealed that
there were no strong relationships between the magnitude of asymmetry in any
kinematic or kinetic variable and maximal sprint performance (35).

Applications for the strength and conditioning coach

Existing data might suggest that the concept of asymmetry is of no
concern for those working in youth populations. However, if asymmetry is
monitored throughout childhood and adolescence, any changes in the
magnitude of asymmetry may present “red flags” for practitioners to investigate
further, as changes may not be expected as part of normal growth and
development (35). At present there is little evidence to inform the exact
magnitude of change or threshold of asymmetry that may represent an injury
risk in youth, and therefore more longitudinal research in this field is required to
enable practitioners to make more informed decisions. Interestingly, the
concept of “adolescent awkwardness” (24,43) that has previous been used to
explain decrements in performance around the time of the growth spurt may
not supported by the asymmetry data presented in the present review; however
it is important to note that further research is required to formalize the links
between asymmetry and the concept of adolescent awkwardness, as this issue has not been fully explored.

Monitoring of asymmetry was previously the preserve of biomechanics laboratories with expensive force-plate or optical measurement systems, however a new generation of app-based software is facilitating coaches to collect this information in the field. While issues still exist surrounding the validity and reliability of some systems (8), the advent of new smartphone-based technologies, such as Runmatic and MySprint, certainly represents a positive move to enhance coaching knowledge in the training environment and facilitate easier and more regular monitoring of sprint performance.

**PRACTICAL APPLICATIONS**

Strength and conditioning practitioners working with youth athletes wishing to enhance their maximal sprint performance should be mindful of the growth and development that occurs with advancing age and maturation, and the predictors of sprint performance in youth that may highlight important training foci. From the available evidence, Table 1 provides an overview of the changes in key sprint performance variables with advancing maturation. This information is critical to help practitioners disentangle where gains in speed are as a result of effective programming of training, or due to the considerable influence of growth and maturation. Long-term systematic training in a youth soccer academy resulted in greater increases in speed compared to control (~9 vs. 4%) (62) over a 3 year period, while similar improvements (~19%) were observed for controls and academy players over a 6 year period (56). These
Figure 1 provides an overview of the key predictors of maximal sprint speed in youth, with suggested training stimuli and resultant influence on maximal sprint performance based upon the current literature. Relative, force, relative vertical stiffness as well as vertical and horizontal power appear to be key predictors of the determinants of sprint performance in youth, independent of advancing age and maturation, and therefore should be key training foci for all youth sprint athletes. Importantly, strength and conditioning practitioners should include primary sprint training as a key method for developing sprint performance (14,57); however there is a paucity of research in youth that actually investigates the impact of primary sprint training upon sprint performance in male youth (53) despite it being the most specific form of training for sprint performance. Furthermore, while it is important to understand that all physical parameters may be trainable at all stages of development (26), there may be opportunities to develop certain physical qualities at specific times to enhance the “synergistic adaptations” with naturally occurring developmental processes (7). On this basis, the training of pre-pubertal boys should focus upon the development of neuromuscular qualities through modalities such as plyometric training and traditional resistance training. Owing to the lack of circulating androgens in pre-pubertal boys, these training methods should facilitate enhancement in force production and stiffness via neurally mediated adaptations, and if combined with a clear focus on technical competency and primary speed training, should allow pre-pubertal boys to achieve a strong foundation of movement efficiency for sprint performance.
While strength and conditioning practitioners should expect greater enhancements in maximal sprint speed around the period of PHV, it is especially important that physical qualities associated with relative force production and relative vertical stiffness are addressed, as rapid changes in stature and mass observed around and immediately after the period of PHV could negatively impact these qualities. Post-pubertal boys should also focus on maximizing gains in relative vertical and horizontal force production and power due to the developmental increases in testosterone and muscle mass witnessed at this stage. It is therefore clear that while combined training methods may be recommended for all stages of development, the effectiveness of neural-focused training methods in the pre-pubertal period, and force-production training methods in the post-pubertal period (21), provide useful guidance for practitioners developing long term Youth Physical Development programs.

**TABLE AND FIGURE CAPTIONS**

**Table 1.** Changes in characteristics of maximal sprint performance with advancing maturation. **Key:** PHV = peak height velocity; ↑= trend towards increases; ↑↑= trend towards large increases; ↓= trend towards decreases; ≈ = approximately equal or no change.

**Figure 1.** Predictors of maximal sprint performance in male youth with suggested training stimuli and projected performance outcomes.
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Predictor of sprint performance

- Relative vertical & horizontal force

Suggested training stimuli

- Resistance training & combined methods
- Plyometric & resistance training
- Multidirectional plyometric & resistance training

Performance Outcome

- Step length & relative vertical stiffness
- Step frequency
- Contact time
- Step length
- Contact time
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