Effects of Running Velocity on Running Kinetics and Kinematics

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Abstract

Brughelli, M, Cronin, J, and Chaouachi, A. Effects of running velocity on running kinetics and kinematics. *J Strength Cond Res* 25(4): 933–939, 2011—Sixteen semiprofessional Australian football players performed running bouts at incremental velocities of 40, 60, 80, and 100% of their maximum velocity on a Woodway nonmotorized force treadmill. As running velocity increased from 40 to 60%, peak vertical and peak horizontal forces increased by 14.3% (effect size [ES] = 1.0) and 34.4% (ES = 4.2), respectively. The changes in peak vertical and peak horizontal forces from 60 to 80% were 1.0% (ES = 0.05) and 21.0% (ES = 2.9), respectively. Finally, the changes in peak vertical and peak horizontal forces from 80% to maximum were 2.0% (ES = 0.1) and 24.3% (ES = 3.4). In addition, both stride frequency and stride length significantly increased with each incremental velocity ($p < 0.05$). Conversely, contact times and the vertical displacement of the center of mass significantly decreased with increased running velocity ($p < 0.05$). A significant positive correlation was found between horizontal force and maximum running velocity ($r = 0.47$). For the kinematic variables, only stride length was found to have a significant positive correlation with maximum running velocity ($r = 0.66$). It would seem that increasing maximal sprint velocity may be more dependent on horizontal force production as opposed to vertical force production.

Key Words sprinting, vertical force, horizontal force, stiffness, stride length

Introduction

Of interest to many strength and conditioning practitioners, coaches, and athletes is the best training practice for the improvement of running sprint speed. One approach that may provide useful information in terms of exercise selection, assessment, and program design is to investigate the contribution of incremental running velocities on peak vertical and peak horizontal force production. It has been well established that peak vertical (F_v) and peak horizontal forces (F_h) increase (50–100% and >200%) with increasing running velocities from slow to moderate values (i.e., 1.5–6.5 $m \cdot s^{-1}$) (20,21). However, little is known about how F_v and F_h are affected by greater running velocities (>6.5 m).

Three recent studies have directly investigated the effects of running velocity above 6.5 $m \cdot s^{-1}$ on F_v. These studies reported that F_v and relative F_v ($RF_v = F_v$ divided by body mass) remained constant after running velocities increased above 6.0–7.0 $m \cdot s^{-1}$ or 70% maximum running velocity (V_{max}) in endurance runners and sprinters (13,14,22). Furthermore, the correlational studies that have investigated the relationship between maximum running velocity and F_v have reported nonsignificant correlations (19,23). These findings suggest that peak vertical forces (i.e., F_v or RF_v) do not have a major influence on increasing running velocity (13,18,21). Conversely, Weyand et al. (27) indirectly studied the relationship between RF_v and running velocity by comparing the relative vertical force produced by faster runners in comparison to slower runners. According to their linear regression, the fastest runners (11.1 $m \cdot s^{-1}$) produced 26% greater RF_v than the slowest runner (6.2 $m \cdot s^{-1}$). As stated by Weyand et al. (27), the 26% difference was less than expected as they hypothesized that greater vertical ground forces enable runners to reach greater maximum velocities. With such contradictions in the literature, it is important to improve our understanding of how running velocity affects vertical force production in athletic populations. Furthermore, very little is known about how increasing running velocity affects horizontal force production in athletic populations. Nummela et al. (22) reported that RF_h increased in a linear fashion from 5 $m \cdot s^{-1}$ to maximum running velocity in endurance runners. Kuitunen et al. (13) reported that F_h significantly increased (i.e., both breaking and propulsive forces) with running velocity from 70 to 100% maximum velocity in 10 male sprinters. Nummela et al. (22) also reported a significant correlation between maximum running velocity and RF_h ($r = 0.66$), but not vertical forces.

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All of the studies previously cited have used endurance or running athletes. It is conceivable that field sport athletes, who perform a mixture of training methods including explosive training (including maximum velocity running) and endurance training, would exhibit different force profiles over a range of velocities. A better understanding of the relationship between running velocity and force production would enable greater insight into best practice for exercise selection, assessment, and program design of field-based sports. With this in mind, the first purpose of this article was to investigate the effects of running velocity (up to maximum) on a variety of kinematic and kinetic variables in Australian Rules football players. The second purpose of this article was to investigate the relationships between maximum running velocity and various mechanical variables.

Methods

Experimental Approach to the Problem

This study was performed during the preseason of the Western Australian Football League. The athletes ran over a nonmotorized force treadmill with embedded vertical load cells and were tethered to a horizontal load cell. A randomized crossover design was used to assess various kinetic and kinematic variables during running over a range of velocities (i.e., 40, 60, 80, and 100% of maximum running velocity) in semiprofessional athletes. Secondarily, the relationship between various kinetic and kinematic variables in regards to maximum running velocity was investigated using Pearson product–moment correlations. The variables of interest included vertical force, relative vertical force, horizontal force, relative horizontal force, contact times, stride length, stride frequency, and center of mass (CM) displacement.

Subjects

Sixteen semiprofessional Australian Rules football players participated in this research (age 23.3 ± 2.1 years; height 184.8 ± 12.4 cm; and weight 84.1 ± 7.4 kg). The players were recruited from the West Australia Football League. All subjects provided written, informed consent within the guidelines of Edith Cowan University. The subjects had at least 2 years experience with resistance training, endurance training, and performed maximum effort sprints on a regular basis.

Equipment

All running bouts were performed on a nonmotorized force treadmill (Woodway 3.0, Eugene, OR, USA). The present treadmill design was a modified version of the original system designed by Lakomy (14) and Lakomy (15). The subjects wore a harness around their waists, which was connected to a nonelastic tether. The tether was connected to a horizontal load cell, which measured horizontal force, with a "Y" jointed steel wire. The horizontal load cell was attached to a metal vertical strut with a sliding gauge, which locked into place to avoid any movement during testing. The sliding gauge allowed the horizontal load cell to be adjusted vertically in accordance with the subject's height, so that the tether was horizontal to the load cell during the running bouts. The load cell was calibrated before and after each testing session using a range of known weights hanging from the load cell. The first weight was at the lower end of the range (i.e., 10 kg), and the second weight was toward the top end (i.e., 30 kg) of the expected forces to be measured. Two different force inputs were required so that a line could be fitted, the slope of which was the calibration factor and the y-intercept was the zero offset. Force was calibrated into Newtons (N) by multiplying the mass of the calibration object by 9.81 $m \cdot s^{-1} \cdot s^{-1}$ (i.e., the acceleration due to gravity).

Treadmill-belt velocity was monitored by 2 optical speed photomicrosensors, which were mounted on the rear shaft of the treadmill belt. The distance measurement did not require calibration because it was measured from the photomicrosensors when the treadmill drums turned. The distance

Table 1. Running velocity, running kinetic, and kinematics.*

Variable	40%	60%	80%	100%
Vertical force (N)	1,681.6 ± 226.0	1,922.7 ± 235.0†‡	1,942.3 ± 278.9†‡	1,983.7 ± 271.9†‡
Horizontal force (N)	178.6 ± 14.3	240.1 ± 17.1†‡	290.2 ± 22.0†‡§	360.9 ± 27.9†‡§‖
CM displacement (cm)	5.51 ± 0.78	5.46 ± 1.11	4.18 ± 0.38†‡§	2.83 ± 0.41†‡§‖
Contact times (ms)	301.78 ± 22.67	280.45 ± 18.56†‡	248.29 ± 21.78†‡§	209.67 ± 19.67†‡§‖
Stride length (m)	1.70 ± 0.62	2.12 ± 0.54†‡	2.57 ± 0.64†‡§	3.27 ± 0.65†‡§‖
Stride frequency (Ss^{-1})	0.80 ± 0.05	1.15 ± 0.03†‡	1.45 ± 0.03†‡§	1.67 ± 0.02†‡§‖

*R. = relative; N = Newtons; kg = kilograms; m = meters; ms = milliseconds; S = stride; s = seconds; W = Watts; cm = centimeters.
†$p < 0.05$.
‡Significantly different from 40%.
§Significantly different from 60%.
‖Significantly different from 80%.

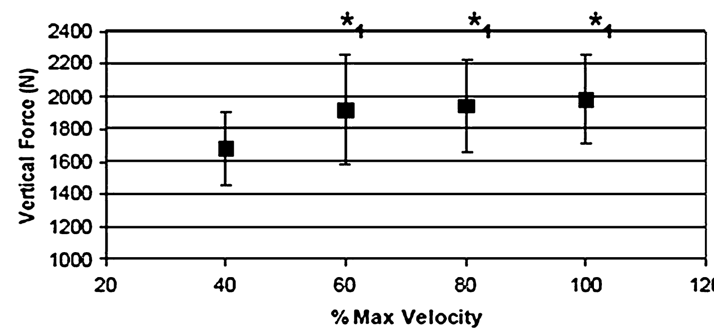

Figure 1. Effects of running velocity on vertical force production. $*p < 0.05$; *1 = significantly different from 40%.

moved for each pulse was known and did not change, and so, the conversion factor from pulses to distance in meters was coded directly into the Force 3.0 software (Innervations Solutions, Joondalup, Australia). Vertical force was measured by 4 individual vertical load cells that were mounted under the running surface. The vertical load cells were calibrated before and after each testing session by placing a range of known weights on the treadmill deck according to the manufacturer's instructions. The first weight was at the low end of the range (i.e., 60 kg), and the second weight was at the top end of the expected forces measured (i.e., 300 kg). Treadmill-belt velocity, distance, vertical force, and horizontal force were collected at a sampling rate of 200 Hz by the XPV7 PCB interface (Fitness Technology, Adelaide, Australia) and analyzed with Force 3.0 software. The data were exported to Microsoft Excel files, which were then analyzed with a custom-made Labview program.

The subjects in the present study performed maximum and submaximum running efforts on the nonmotorized treadmill, which has the advantage of quantifying various kinetic and kinematic variables over multiple steps. Previous research has reported that nonmotorized treadmills are reliable for both kinetic and kinematic variables (12,24,25), and valid in comparison to overground running (8,17). Chelly and Denis (8) reported that maximum running velocity was lower on a nonmotorized treadmill, but the correlation for velocity between maximum overground running and running on a nonmotorized treadmill was very high, that is, $r = 0.84$. Furthermore, McKenna and Riches (17) reported that running on a nonmotorized treadmill produced similar running kinematics in comparison to overground running.

Experimental Protocol

The subjects performed running bouts at 40, 60, 80, and 100% of their maximum velocity on the Woodway nonmotorized treadmill. The maximum velocity bouts were performed first to determine a baseline for the subsequent bouts. After the baseline was determined, the subjects ran at the submaximal velocities in a randomized order. The subjects were asked to build up to maximum velocity over a 4-second period and then to maintain maximum velocity for another 5 seconds. The subjects were given verbal encouragement during the 5-second period to maintain maximum running velocity. The mechanical variables were collected during the 5-second period. Long rest periods (>3 minutes) were provided to minimize the effects of fatigue. During the slower-moderate running bouts, subjects were asked to build up to 40, 60, or 80% of maximum velocity over a 4-second period and then maintain these velocities for 8–10 seconds while F_v and F_h were collected. To help maintain a constant velocity over the 8–10 seconds, a real-time profile of running velocity was projected on a screen in front of the subjects. For all running bouts, 10 steps were recorded for analysis.

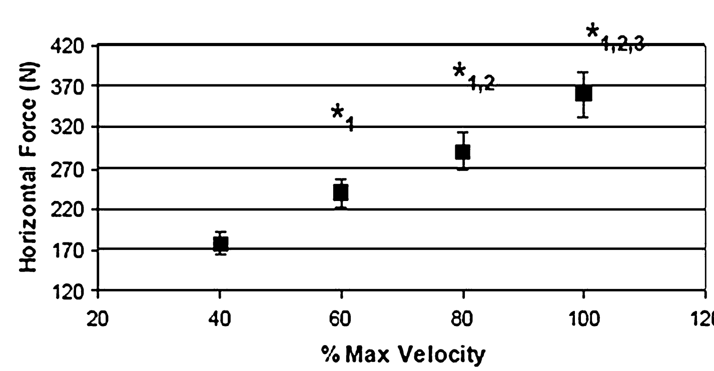

Figure 2. Effects of running velocity on horizontal force production. $*p < 0.05$; *1 = significantly different from 40%; *2 = significantly different from 60%; and *3 = significantly different from 80%.

Data Analyses

Peak horizontal and vertical forces and running velocity were derived directly from the nonmotorized force treadmill as described above. Relative peak vertical force (RF_v)

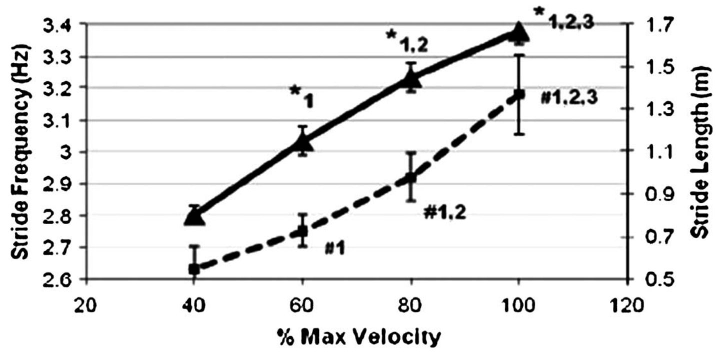

Figure 3. Effects of running velocity on stride length and stride frequency. *$p < 0.05$ for stride length; *1 = significantly different from 40% for stride length; *2 = significantly different from 60% for stride length; and *3 = significantly different from 80% for stride length. #$p < 0.05$ for stride frequency; #1 = significantly different from 40% for stride frequency; #2 = significantly different from 60% for stride frequency; and #3 = significantly different from 80% for stride frequency.

and relative peak horizontal force (RF_h) were calculated by dividing peak vertical and horizontal forces by body mass. Vertical displacement of the CM was determined by double integration of vertical acceleration over time, as described by Cavagna et al. (3). Vertical acceleration was obtained from the peak vertical force divided by body mass after subtracting gravitational acceleration (3). *Contact time* (Ct) was determined from the time (in seconds) the force applied to the treadmill exceeded 0 N and returned to 0 N. *Aerial time* (At) was determined from the time between the end of the ground contact period of one foot to the beginning of the ground contact period of the opposite foot. *Stride frequency* was determined from the following formula: 1/(Ct + At). *Stride length* was determined from the following formula: running velocity divided by stride frequency.

Table 2. Correlations with maximum running velocity.*

Variables	Pearson correlation (*r*)
R. vertical force ($N\cdot kg^{-1}$)	0.13
Vertical force (N)	0.24
R. horizontal force ($N\cdot kg^{-1}$)	0.28
Horizontal force (N)	0.47†
CM displacement (cm)	0.17
Contact times (ms)	0.13
Stride length (m)	0.66†
Stride frequency (Ss^{-1})	0.02

*R. = relative; N = Newtons; kg = kilograms; m = meters; ms = milliseconds; *S* = stride; s = seconds; W = Watts; cm = centimeters; CM = center of mass.
†$p < 0.05$.

Statistical Analyses

Means and *SD*s were used as measures of centrality and spread of data. A repeated-measure analysis of variance with Bonferroni post hoc tests were used to determine if significant differences existed between the mechanical variables at the 4 different velocities. An intercorrelation matrix (Pearson product–moment correlations) was used to compare the strength of relationships between the kinematic and kinetic measures and running velocity. Correlations were described as trivial (0.0–0.1), low (0.1–0.3), moderate (0.3–0.5), high (0.5–0.7), very high (0.7–0.9), and practically perfect (0.9–1.0). All percentage changes were calculated by the formula:

$$(\text{High value} - \text{Low value})/\text{Lowvalue} \times 100 = \text{Percentage change}(\%).$$

In addition, effect sizes (ESs) and coefficient of variations (CVs) were calculated with the following formula:

$$\text{ES} = (\text{High value} - \text{Low value})/(SD \text{ of High value}).$$

Effect sizes were described as trivia l(<0.2), small (<0.41), moderate (0.41–0.7), and large(>0.7) based on the description of effects by Cohen (9). The CV was calculated as the ratio of the *SD* to the mean value over the 10 steps. Statistical significance was set at 0.05.

Results

Firstly, the CVs of all variables over the 10 steps were less than 9.6%. As running velocity increased from 40 to 60% maximum velocity, F_v significantly increased from (14.3%; ES = 1.0). However, as running velocity increased from 60% to maximum, F_v remained relatively constant (see Table 1 and Figure 1). In contrast, F_h significantly increased with increments from 40 to 60% (34.4%; ES = 4.2), from 60 to 80% (21.0%; ES = 2.9), and from 80% to maximum (24.3%; ES = 3.2; see Figure 2). The total increase in F_h from the slowest running speed (i.e., 40% max) to maximum was 102.1% (ES = 9.3). At 40% maximum running velocity, F_h was 11.0% of F_v. As running velocity increased to maximum, F_h was 18.3% of F_v.

Vertical CM displacement remained relatively constant as running velocity increased from 40 to 60%, but significantly decreased as velocity increased from 60 to 80% and from 80% to maximum (see Table 1). Contact times significantly decreased between each measured running velocity (see Table 1). Both stride length and stride frequency increased significantly with incremental running velocity (see Table 1 and Figure 3).

The correlations between the performance variables of interest and maximum running velocity can be observed in Table 2. A significant moderate correlation was found between F_h and maximum running velocity ($r = 0.47$). There were no significant correlations between maximum running velocity and any other kinetic variables (i.e., RF_v, RF_h, and F_v) For the kinematic variables, only stride length was found to have a significant high correlation with maximum running velocity ($r = 0.66$). There were no significant correlations found between maximum running velocity and any other kinematic variables (i.e., CM displacement, Ct, At, or stride frequency).

Discussion

This is the first study, to our knowledge, that has investigated the effects of running velocity (up to maximum) on F_v and F_h in well-trained athletes who routinely perform a mixture of training methods, including maximum effort sprints, power training, strength training, and endurance training. F_v increased significantly as running velocity increased from 40 to 60% of the subject's maximum velocity. These large effects are similar to previous studies that have reported that F_v increases as running velocity increased to 6.0 $m \cdot s^{-1}$, or approximately 65% of a runner's maximum running velocity (1,19,20). However, as the runners increased their velocity from 60 to 80%, and from 80% to maximum, F_v remained relatively constant. This was also similar to previous studies that have reported F_v remained relatively constant at 6.0 $m \cdot s^{-1}$, or approximately 65% of a runner's maximum velocity (13,14,19). The studies that have directly investigated the relationships between velocity and force production and have used crossover study designs (14,18–20,22), have also found that vertical forces increase with running velocity up to moderate values and remain relatively constant after 6.5 $m \cdot s^{-1}$ or 65% V_{max}. In 3 recent studies, the influence of running velocity (up to maximum velocities) on running mechanics has been investigated in endurance and sprint athletes (13,14,22). Each of the studies reported similar findings on the effects of running velocity on RF_v. Kyrolainen et al. (14) reported that RF_v increased only slightly (%–nonsignificant) as running velocity increased beyond 6.0 $m \cdot s^{-1}$. Nummela et al. (22) studied the effects of running at velocities from 4.5 $m \cdot s^{-1}$ to maximum over a 9-m force plate system in 25 male endurance runners. It was reported that RF_v remained relatively constant after the athletes attained a running velocity of 6.5 $m \cdot s^{-1}$. Kuitunen et al. (13) reported that vertical forces remained relatively constant from 70 to 100% V_{max} in 10 male sprinters. The findings of these studies in conjunction with the present findings support the argument that vertical force does not have a major influence on accelerating from ~65% to maximum running velocity.

The results and conclusions of Weyand and colleagues (26,27), however, were different to those found in the present study. These researchers compared the kinematics and kinetics of subjects with greater running velocities against those of lesser velocities on a high-speed motorized treadmill (27). Weyand et al. (27) proposed that with greater RF_v, a runner's vertical velocity (CM) would increase upon take-off, which would increase stride length and ultimately maximum running velocity. Thirty-three subjects with various maximum running velocities (range = 6.2–11.1 $m \cdot s^{-1}$) were used in this study. The average RF_v values were compared between subjects with a simple linear regression. It was reported that the RF_v increased by 1.26 times (or 26%) from the slowest runner to the fastest runner. Although this increase was lower than the authors had reportedly expected, they argued that (according to their regression) an increase in RF_v by one-tenth of one body weight would increase maximum running velocity by 1.0 $m \cdot s^{-1}$. However, it has been demonstrated repeatedly by Cavagna and colleagues (3–7) that an increase in RF_v leads to an asymmetrical rebound (i.e., the amount of time force exceeds body weight < amount of time force is less than body weight) during high-velocity running. As running speed increases, the asymmetry becomes greater, thus leading to a decrease in push-average power (i.e., the work done divided by the duration of positive work production), and a decrease in maximum running velocity. Thus, it is not very likely that maximum running velocity is limited by the ability to produce peak RF_v as proposed by Weyand et al. (26,27) and others (2). It also should be noted that the results of Weyand et al. (27) were based on variables calculated on a motorized treadmill, the kinematics of which have been reported to be different (i.e., invalid) to overground running (17). Other limitations of the research design by Weyand et al. (27) were using 2 separate populations to investigate the relationship between fast and slow runners and also the heterogeneity of these populations (i.e., range = 6.2–11.1 $m \cdot s^{-1}$) which no doubt would inflate any correlation coefficient.

Mero et al. (18) reported that the resultant of F_v and F_h increased by 77% as their subjects (track sprinters) increased running velocity from 55% to maximum. However, because F_v and F_h were combined, it was impossible to determine the effects of running velocity on either F_v or F_h individually and therefore comparisons cannot be made with this study.

The present study found that peak horizontal force significantly increased with incremental running velocity (see Table 1 and Figure 2). Also, F_h significantly increased as running velocity increased from 40% to maximum. Previous studies have reported that RF_h increased from 2 to 4 times as running velocity increased from moderate to high or maximum values (20,22). Kyrolainen et al. (14) reported that F_h increased by more than 2.5 times in male ($n = 9$) and female ($n = 8$) distance runners, and Nummela et al. (22) reported that RF_h increased 2–4.5 times from 4.5 $m \cdot s^{-1}$ to maximum velocity. The authors concluded that maximum running velocity was more dependent on horizontal force production than vertical force production. Kuitunen et al. (13) reported that horizontal forces significantly increased with running velocity in male sprinters. In addition, Fukunaga et al. (10) reported that the horizontal component of work increased with running velocities greater than 6.0 $m \cdot s^{-1}$. It would seem that the results of the present study are similar to those in the bulk of the literature supporting the contention that increasing velocity from moderate to maximum sprint velocity is more dependent on horizontal than on vertical force production.

As expected, CM displacement significantly decreased with running velocity (see Table 1). To run faster, contact times need to be decreased to aid in repositioning the legs during running. As a result, CM displacement is decreased, and horizontal forces need to be increased. In agreement with previous studies, the present study found that stride length and stride frequency both significantly increased with each incremental running velocity, stride frequency increasing at a greater rate.

To gain a greater insight into the influence of running velocity on running mechanics, Pearson correlations were performed between maximum running velocity and various kinetic and kinematic variables (see Table 2). It was found that neither RF_v ($r = 0.13$) nor F_v ($r = 0.24$) significantly correlated with maximum running velocity. RF_h ($r = 0.28$) did not significantly correlate with maximum running velocity, but F_h did ($r = 0.47$).

There remains controversy in the literature in regards to improving maximum running velocity via stride frequency vs. stride length. It has been suggested that both stride length and stride frequency increase linearly with running velocity up until 7.0 $m \cdot s^{-1}$ (16,23). Above running velocities of 7.0 $m \cdot s^{-1}$, stride frequency is thought to increase at a higher rate than stride length. Thus, it has been argued that there is a limit to how much an individual can increase stride length and thus increasing stride frequency would be more important in improving maximum running velocity (11,16,23). In the present study, stride length significantly correlated with maximum running velocity ($r = 0.66$), but stride frequency did not ($r = 0.02$). It could be speculated that an increase in F_h could lead to an increase in stride length and ultimately in maximum running velocity. However, because there have been no studies that have manipulated stride length or stride frequency at maximum running velocity, only speculations can be made at the present time.

Practical Applications

Increasing velocity from 60 to 100% of maximum running velocity appears to be more dependent on horizontal force production as opposed to vertical force production. Future research should investigate the effects of various training interventions on increasing horizontal force production and stride length, and their effects on maximum running velocity. In addition, stride length may have more of an influence of maximum velocity running than was once thought. It may be that assessment procedures need to place greater emphasis on horizontal force production and also a battery of tests that allows diagnosis of an athlete's strengths and weaknesses in both the vertical and horizontal directions would be beneficial in individualizing programs. In terms of sprint specific strength and power development, exercises that concentrate on force production in the horizontal directions may well lead to greater speed development, given that most exercises in the weight training room accentuate force production in the vertical plane.

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