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ORIGINAL ARTICLE

The effect of resisted sprint training on maximum sprint kinetics and kinematics in youth

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Abstract
Resisted sled towing is a popular and efficient training method to improve sprint performance in adults, however, has not been utilised in youth populations. The purpose therefore was to investigate the effect of resisted sled towing training on the kinematics and kinetics of maximal sprint velocity in youth of different maturation status. Pre- and post-intervention 30 metre sprint performance of 32 children, 18 pre-peak height velocity (PHV) and 14 mid-/post-PHV, were tested on a non-motorised treadmill. The 6-week intervention consisted of ~12 sessions for pre-PHV and 14 for mid-/post-PHV of resisted sled towing training with each sessions comprised of 8–10 sprints covering 15–30 metres with a load of 2.5, 5, 7.5 or 10% body mass. Pre-PHV participants did not improve sprint performance, while the mid-/post-PHV participants had significant ($P < 0.05$) reductions (percent change, effect size) in sprint time (−5.76, −0.74), relative leg stiffness (−45.0, −2.16) and relative vertical stiffness (−17.4, −0.76) and a significant increase in average velocity (5.99, 0.76), average step rate (5.65, 0.53), average power (6.36, 0.31), peak horizontal force (9.70, 0.72), average relative vertical forces (3.45, 1.70) and vertical displacement (14.6, 1.46). It seems that sled towing may be a more suitable training method in mid-/post-PHV athletes to improve 30 metre sprint performance.

Keywords: *Sled towing, maturation, peak height velocity, running, mechanics*

Introduction

Sprinting is an essential component of performance in many sports, including football (Mendez-Villanueva, Buchheit, Simpson, Peltola, & Bourdon, 2011), rugby (Deutsch, Maw, Jenkins, & Reaburn, 1998) and cricket (Petersen, Portus, & Dawson, 2009). Accordingly, coaches and sport scientists are often interested in engaging individuals from an early age with training methods which may elicit improvements in speed (Oliver, Lloyd, & Rumpf, 2013). While several sprint training methods have been used in youth populations (Rumpf, Cronin, Oliver, & Hughes, 2012), resisted training methods are unexplored in youth populations, despite their popularity in adults (Harrison & Bourke, 2009; Lockie, Murphy, Schultz, Knight, & Janse de Jonge, 2012; Spinks, Murphy, Spinks, & Lockie, 2007). A total of six resisted training methods have been used in the training of adults: wearing weighted vests or belts (Clark, Stearne, Walts, & Miller, 2010), adding weight to distal limb segments (Smirnov, 1978), pulling a parachute (Alcaraz, Palao, Elvira, & Linthorne, 2008), running uphill (Paradisis & Cooke, 2006), resisted treadmill sprinting (Ross et al., 2009) and towing weights (Harrison & Bourke, 2009, Lockie et al., 2012; Spinks et al., 2007). In particular, the latter resisted training method is of interest to these researchers, as its efficacy has not been tested with youth populations (Rumpf et al., 2012).

With regard to speed development in youth, it may be that young athletes, particularly in mid- and/ or post-pubescent state benefit more (compared to

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pre-pubescent) from resisted type sprinting. For example, it has been shown that maturation, more particularly the rise of hormone levels (testosterone and growth hormones; Malina, Eisenmann, Cumming, Ribeiro, & Aroso, 2004) associated with puberty (Forbes et al., 2009) around peak height velocity (PHV), affected strength (Forbes et al., 2009) and power (Armstrong, Welsman, & Chia, 2001). Especially the later alters ground reaction forces, therefore increased stride length (Weyand, Sternlight, Bellizzi, & Wright, 2000) and ultimately increase running speed. Therefore, the age at which PHV occurs, typically between the chronological age from 12 to 15 years (Balyi & Way, 2005) and the onset of puberty (Malina, Bouchard, & Bar-Or, 2004), may be significant in the development of sprint performance. The interaction of structured training and growth may represent a time where training is thought to be most efficient (Viru et al., 1999); this has been termed "window of accelerated adaptation to training" or "window of trainability" (Balyi & Way, 2005), and it was reported that a training focus on strengthening to enhance power output and consequently running speed is suitable during this period of development (Oliver et al., 2013). A recent meta-analysis of resistance training in children and adolescents across a variety of age and maturation groups (Behringer, Vom Heede, Yue, & Mester, 2010) suggested more pronounced strength gains in late maturation populations. However, pre-pubescents also benefited from resistance training and therefore it would be plausible for pre-pubescent participants to gain benefits in sprint performance from resisted training as well.

Generally, sprint performance is tested by measuring the time over a given distance (Rumpf, Cronin, Oliver, & Hughes, 2011). As sprint performance is strongly associated with the average and peak velocity over the given distance and sprinting velocity can be calculated as step length multiplied with step frequency (Hunter, Marshall, & McNair, 2004), researchers have investigated the kinematics of sprinting as well (Coh, Milanovic, & Kampmiller, 2001; Copaver, Hertogh, & Hue, 2012). However, in order to gain a true appreciation of the underlying mechanisms it is paramount to investigate the forces (kinetics) responsible for the kinematic changes (Hunter, Marshall, & McNair, 2005). Researchers (Mann, 1981; Morin, Samozino, & Edouard, 2011; Morin, Samozino, Bonnefoy, Edouard, & Belli, 2010; Morin et al., 2012) have investigated the importance of these variables in cross-sectional studies and have identified the effect of training on the kinetic variables as a field of interest (Hunter et al., 2005). However, this area of research has primarily been conducted in adults, has predominantly described kinematic changes and has not investigated kinematic and kinetic changes in youth after a resisted sled towing intervention. Therefore we aimed to determine the efficacy of resisted sled training on the kinematics and kinetics of maximum sprint performance in male youth of different maturation status.

Materials and methods

Subjects

A total of 32 participants volunteered to participate in the study, with 14 subjects categorised as pre-PHV and the remaining 18 categorised as mid-/post-PHV. All participants were physically active and trained a minimum of two times per week in their sport. The participants and their parents or legal guardians were informed about the study and gave written consent to participate. The investigation was approved by the Institutional Ethics Committee of the AUT University.

Design

This study examined the effect of resisted sprint training on maximum sprint kinetics and kinematics in youth. Thirty-two participants (14 in pre-PHV and 18 in mid-/post-PHV state) participated in 6 weeks of resisted sled towing training with 2–3 sessions per week and a total of 16 sessions. Sprint performance was measured over 30 metres on a non-motorised treadmill, which is able to measure kinetic and kinematic variables such as horizontal and vertical force, power, step length and frequency, etc. All variables of interest were obtained from the fastest four consecutive steps. Data and statistical analyses were performed with regard to pre- and post-training intervention.

Data collection

A non-motorised force treadmill was used to measure variables of interest during a 30 metre sprint. The participants wore a harness around their waist, which was connected to a non-elastic tether. The tether was connected to a horizontal load cell (Model BS-500 Class III, Transcell Technology Inc., Buffalo Grove, USA), which measured horizontal force. The height of the load cell was adjusted accordingly to the subject's height, so that the tether was horizontal during testing. Vertical force was measured by four individual vertical load cells that were mounted under the running surface. The system was calibrated using a range of known weights. Vertical and horizontal force were collected at a sampling rate of 200 Hz with a cut-off frequency of 4 Hz. Treadmill belt velocity was monitored by two optical speed photomicrosensors, collected by a tachometer XPV7 PCB (Fitness Technology, Adelaide, Australia), and analysed with the Pacer Performance software (Fitness Technology, Australia).

Anthropometric measurements were taken before the familiarisation session on the non-motorised treadmill. The height (cm), sitting height (cm) and mass (kg) were measured. To calculate the maturity status of participants, a maturity index (i.e. timing of maturation) was calculated using the equation of Mirwald, Baxter-Jones, Bailey, and Beunen (2002): maturity offset = −9.236 + (0.0002708 × leg length × sitting height) + (−0.001663 × age × leg length) + (0.007216 × age × sitting height) + (0.02292 × weight by height ratio). This assessment is a non-invasive and practical method of predicting years from PHV as a measure of maturity offset using anthropometric variables with a standard error of estimate for PHV of 0.49 years for boys (Mirwald et al., 2002).

Participants then received a familiarisation session on the non-motorised treadmill (Woodway, Germany), which consisted of standing, walking and running at a self-selected speed. The familiarisation were also taken as a warm-up phase (~10 minutes) if the participants felt safe and were able to perform runs without using their hands to hold on to the frame of the treadmill. If the participants were unable to run freely, the data collection was postponed. Otherwise, a series of warm-up sprints on the treadmill (i.e. 3 × 5 seconds) preceded the initial data collection.

The mean of three runs of a 30 metre distance from a standing split start was used for data collection. The participants recovered completely after each trial with at least 4 minutes between each run to ensure phosphocreatine recovery (Dawson et al., 1997). The effect of training was evaluated by comparing the results administered prior to (Week 1) and after (Week 7) the 6-week training intervention.

Training programme

The training intervention consisted of 6 weeks of resisted sled towing training with 2–3 sessions per week and a total of 16 sessions during the competitive/in-season of the athletes. The first 5 minutes of every training session were used for a standardised warm-up, which consisted of jogging, running, dynamic stretches of the leg muscles and warm-up accelerations runs. Custom made sleds with a total weight of 300 grams in conjunction with harnesses from SPEEDY sled equipment (Sport Pawlik, Unterkirnach, Germany) and weightlifting plates of different loads were used during training. Eight to ten sprints over distances from 15 to 30 metres with a load of 2.5, 5, 7.5 or 10% body mass (BM) were performed in each session. The effect of these loads on sprint mechanics and performance were determined during piloting, and were deemed the best loads to progressively overload the youth athlete over the 6 weeks of training. The difference in percent BM load applied on the sled and the true calculated load from the participants' BM was below 50 grams. The daily training volume (calculated by number of sprints per distance × distance × load) was altered after each session by increasing the total distance covered for each session. The progression in the training programme can be observed in Table I.

Table I. Training programme

			Number of sprints with percent BM load				
Session	Number of sprints per session	Total distance (m) per session	2.5%	5%	7.5%	10%	Total load per session
1	8	140	4	4			525
2	8	160	5	3			525
3	8	160	4	4			650
4	8	180	4	4			650
5	8	180	2	6			775
6	8	200	4	3	1		775
7	8	200	2	5	1		900
8	8	220	4	3	1		900
9	10	220	3	4	3		1025
10	10	240	4	4	2		1025
11	10	240	4	3	2	1	1150
12	10	260	5	3	1	1	1150
13	10	260	3	4	3		1275
14	10	280	3	6	1		1275
15	10	280	4	2	4		1400
16	10	300	4	3	3		1425

Data analysis

The majority of variables (sprint time, average velocity, average step rate, average and peak power, average and peak horizontal force, average and peak vertical force, average work) were collected and analysed using Pacer Performance software (Fitness Technology, Joondalup, WA, Australia). Dimensionless leg stiffness and dimensionless vertical stiffness were analysed with a custom designed Matlab (MathWorks, Inc., Natick, MA, USA) programme. Dimensionless vertical stiffness was calculated from the maximum ground reaction forces during contact divided by the vertical displacement of the centre of mass as described by McMahon and Cheng (1990). Vertical displacement was determined by double integration of the vertical acceleration (Cavagna, Franzetti, Heglund, & Willems, 1988) in the eccentric phase. Vertical acceleration was obtained from the peak vertical force divided by BM after subtracting gravitational acceleration (Cavagna et al., 1988). Dimensionless leg stiffness was calculated as the maximum vertical force (F_{max}) divided by the peak displacement (Δ) of the initial leg length (L; Morin, Dalleau, Kyrolainen, Jeannin & Belli, 2005), calculated from standing height minus sitting height:

$$k_{leg} = F_{max} \times \Delta L^{-1}$$

The peak displacement of the initial leg length was calculated as:

$$\Delta L = L - \sqrt{L^2 - \left(\frac{vt_c}{2}\right)^2} + \Delta y_c$$

where v = running velocity (in metre per second), t_c = contact time (in seconds) and Δy_c = the vertical displacement (in metres) of the centre of mass when it reached its lowest point during mid-stance. Dimensionless leg stiffness and vertical stiffness were derived from further multiplying the two stiffness measures with the initial leg length and then dividing the product by the participants' respective BM multiplied by gravitational acceleration of 9.81 (McMahon & Cheng, 1990). Relative average and peak vertical force were calculated using the BM of the participants.

Step length, step frequency and power were calculated the variables were defined as follows:

Step length:	difference in distance from consecutive alternating feet
Step frequency:	1/contact time + aerial time of a step
Power:	horizontal force × velocity
Work:	horizontal force × distance
Contact time:	time from initial foot touchdown until toe-off
Flight time:	time outside contact time

Statistical analysis

Means and standard deviation for all dependent variables of interest were used as measures of centrality and spread of data. Percent changes from pre- to post-training were calculated for every dependent variable [(1-post-/pre-score) × 100]. Paired-sample *t*-test were used to determine if the percent change in the dependent variables of interest differed significantly from pre- to post-testing for each maturation groups. Effect sizes (ES) were also calculated for each dependent variable and discussed based on the interpretation of negative/positive effects sizes according to Hopkins (2009). The ES of < −0.20, ≤ −0.20 > −0.60, ≤ −0.60 > −1.20, ≤ −1.20 > −2.00, ≤ −2.00 > −4.00 were categorised as trivial, small, moderate, large and very large, respectively. An analysis of covariance (ANCOVA) was used to detect differences in the percent change of dependent variables between groups by removing the variance of a certain predictor variable (adherence to training), which was thought influential on the outcome variables of interest. An alpha level of $P < 0.05$ was chosen as the criterion for significance for all tests.

Results

As can be observed from Table II, age, height, leg length, BM and maturation offset were significantly (all $P < .05$) different between the pre- and mid-/post-PHV group. Averaged values for all variables of interest from pre- and post-training, the percent changes and ES for both groups are reported in Table III. Statistically significant reductions in sprint time, leg and vertical stiffness ($P < .05$, percent change range = −5.76 to −45%, ES range −0.74 to −2.16) as well as increased average velocity, average step rate, average power, peak horizontal force, average relative vertical force and vertical displacement ($P < .05 – 0.041$, percent change range 3.45 to 14.6%, ES range 0.31 to 1.70) were observed in the mid-/post-PHV group post-intervention. However,

Table II. Participant characteristics (mean ± s) and training attendance for both groups

	PHV (n = 14)	Mid-/post-PHV (n = 18)
Age (years)	10.4 ± 0.8	15.2 ± 1.6
Maturation offset (years from PHV)	−3.16 ± 0.80	1.32 ± 0.95
Height (cm)	141 ± 7.93	173 ± 5.32
BM (kg)	38.2 ± 15.6	62.7 ± 11.0
Leg length (cm)	69.0 ± 4.1	82.9 ± 3.7
Adherence to training (no. of sessions)	11.6 ± 2.0	13.8 ± 1.6

All variables significantly ($P < .05$) different between groups.

Table III. Sprint performance kinematics and kinetics (mean ± s), percent change and ES for both groups in pre- and post-test

	PHV (n = 14)					Mid-/post-PHV (n = 18)				
	Pre-training	Post-training	Percent change	ES		Pre-training	Post-training	Percent change	ES	
Sprint time (s)	10.1 ± 0.96	10.0 ± 1.02	−0.99	−0.1	Trivial	6.95 ± 0.54	6.55 ± 0.44*	−5.76	−0.74	Moderate
Average velocity (m/s)	3.00 ± 0.30	3.04 ± 0.30	1.33	0.13	Trivial	4.34 ± 0.34	4.60 ± 0.32*	5.99	0.76	Moderate
Average step rate (#/s)	4.17 ± 0.58	4.24 ± 0.56	1.68	0.12	Trivial	4.25 ± 0.45	4.49 ± 0.29*	5.65	0.53	Small
Average step length (m)	0.79 ± 0.15	0.78 ± 0.17	−1.27	−0.05	Trivial	0.99 ± 0.15	0.96 ± 0.15	−3.03	−0.2	Small
Average power (W)	282 ± 69.6	280 ± 68.6	−0.71	−0.03	Trivial	660 ± 136	702 ± 134*	6.36	0.31	Small
Peak power (W)	1026 ± 176	964 ± 206	−6.04	−0.35	Small	2156 ± 360	2228 ± 420	3.34	0.2	Small
Average horizontal force (N)	94.7 ± 14.3	93.7 ± 13.9	−1.06	−0.07	Trivial	155 ± 19.5	158 ± 18.9	1.94	0.15	Trivial
Peak horizontal force (N)	324 ± 20.9	318 ± 40.8	−1.85	−0.28	Small	495 ± 66.6	543 ± 95.3*	9.70	0.72	Moderate
Average relative vertical force (N/kg)	10.2 ± 1.40	9.93 ± 0.16	−2.65	−0.19	Trivial	9.86 ± 0.20	10.2 ± 0.15*	3.45	1.7	Large
Peak relative vertical force (N/kg)	29.0 ± 7.49	28.7 ± 6.82	−1.03	−0.04	Trivial	30.6 ± 3.29	29.9 ± 3.23	−2.29	−0.21	Small
Average work (J)	73.4 ± 24.8	72.3 ± 25.4	−1.5	−0.04	Trivial	145 ± 25.3	143 ± 28.4	−1.38	−0.08	Trivial
Contact time (s)	0.24 ± 0.02	0.24 ± 0.02	0.23	−0.14	Trivial	0.17 ± 0.01	0.17 ± 0.01	3.03	0.26	Small
Flight time (s)	0.28 ± 0.03	0.29 ± 0.02	5.8	0.42	Small	0.30 ± 0.02	0.29 ± 0.01	−2.43	−0.3	Small
Vertical displacement (cm)	5.36 ± 2.87	5.37 ± 2.16	0.19	0.4	Small	5.70 ± 0.99	6.53 ± 1.72*	14.6	1.46	Large
Vertical stiffness	32.9 ± 13.7	33.2 ± 13.8	0.91	0.02	Trivial	40.2 ± 9.21	33.2 ± 6.75*	−17.4	−0.76	Moderate
Leg stiffness	3.90 ± 0.99	3.88 ± 0.90	0.51	0.03	Trivial	10.9 ± 2.27	6.00 ± 1.37*	−45.0	−2.16	Very large

*Significant ($P < .05$) different pre- vs. post-test.

no significant changes were observed in the pre-PHV within group pre-post comparison ($P < .05$, −6.04 to 1.68%, ES: −0.35 to 0.12) in any variable after the training intervention.

In terms of the between-group comparison, the percent changes from pre- to post-training were significantly different ($P < .05$, − 11.3 to 11.1%) for sprint time, average velocity, peak power, peak horizontal force, relative vertical force, flight time and leg stiffness when controlling for adherence to training (see Table IV). The overall average percent changes from pre- to post-training in those variables were 6.80% (±3.19) for the mid-/post-PHV group and 3.75% (±2.95) for the pre-PHV group.

Discussion

In this first study of resisted sled towing training in youth we found significant reduction in sprint times (−5.76%; ES = −0.74) and an increase in average velocity (5.99%; ES = 0.76) in the mid-/post-PHV group. The training was trivial and non-significant for the pre-PHV group (−0.99, 1.33%; ES = −0.10 and 0.13). Given the ES of the mid-/post-PHV participants (0.76, −0.74,) in this study and the reported improvements in performance parameters, such as average velocity (ES = 0.26 – 0.96) and sprint times (ES = −0.51), after training interventions with adults (Clark et al., 2010; Harrison & Bourke, 2009; Lockie et al., 2012; Spinks et al., 2007; Upton, 2011), it seems that the youth of this maturity status responded similar to if not better than adults when resisted sled towing was utilised as a training stimulus. Generally, the adults training studies (Clark et al., 2010; Harrison & Bourke, 2009; Lockie et al., 2012; Spinks et al., 2007; Upton, 2011) consisted of 4–8 weeks of training with a volume of 12–18 sessions utilising ~13% BM sled load or a load that resulted in 10% speed reduction in trained male field-sport players (Lockie et al., 2012), male semi-professional athletes (Harrison & Bourke, 2009; Spinks et al., 2007) and male (Clark et al., 2010) and female collegiate athletes (Upton, 2011).

As stated previously, changes in average velocity may be the product of changes in step length and/or step frequency. The mid-/post-PHV participants in this study significantly increased (5.65%) step rate with a non-significant reduction in step length (see Table III). Certainly, a greater reduction in step length as opposed to stride frequency with increasing load has been reported in cross-sectional studies (Cronin, Hansen, Kawamori, & McNair, 2008; Letzelter, Sauerwein, & Burger, 1995; Lockie, Murphy, & Spinks, 2003), indicating that step length is compromised to a greater extent by sled towing. It seems possible that after repeated application of this

Table IV. Percent change in sprint kinematics and kinetics after adjusting for adherence to training

Variable	Adjusted (mean ± s) percent change PHV	Adjusted (mean ± s) percent change Mid-/post-PHV	Covariate
Sprint time	−1.40 ± 1.16	−5.52 ± 1.00*	Adherence to training
Average velocity	1.55 ± 1.28	5.81 ± 1.10*	Adherence to training
Average step rate	7.04 ± 4.56	3.86 ± 3.93	Adherence to training
Average step length	−0.92 ± 5.26	−0.74 ± 4.53	Adherence to training
Average power	0.60 ± 2.33	6.06 ± 2.01	Adherence to training
Peak power	−8.69 ± 4.71	6.53 ± 4.06*	Adherence to training
Average horizontal force	−0.19 ± 1.73	1.58 ± 1.49	Adherence to training
Peak horizontal force	−3.04 ± 4.34	11.1 ± 3.74*	Adherence to training
Relative vertical force	−2.05 ± 1.90	3.81 ± 1.64*	Adherence to training
Average work	−1.52 ± 5.55	0.46 ± 4.78	Adherence to training
Contact time	0.43 ± 2.55	2.88 ± 2.20	Adherence to training
Flight time	7.22 ± 2.87	−3.54 ± 2.47*	Adherence to training
Vertical displacement	11.1 ± 8.13	13.7 ± 7.01	Adherence to training
Vertical stiffness	−2.13 ± 7.85	−10.8 ± 6.76	Adherence to training
Leg stiffness	2.31 ± 5.72	−11.3 ± 4.93*	Adherence to training

*Significant ($P < .05$) difference between groups.

type of training, stride frequency supercompensates after unloading and is therefore the variable that better explains increases in average velocity.

Other notable adaptations to the sled towing stimulus in the mid-/post-PHV group was the increase in peak horizontal force, which no doubt influenced the peak power measure, as power was calculated as the product of horizontal force and velocity. The increases in horizontal force and power are most likely best explained by the force vectors relative to the ground implicit in sled towing as indicated by the increase in trunk lean (Cronin & Hansen, 2006; Lockie et al., 2003). Interestingly, a large increase (3.45%; ES = 1.70) in average relative vertical force from pre- to post-testing in the mid-/post-PHV participants was also observed. It would seem that the resultant force vector associated with sled towing was of sufficient magnitude in the horizontal and vertical directions to elicit multi-planar adaptation as evidenced in improved sprint times.

Finally, it seems that sled towing resulted in significant reductions in vertical (−17.4%) and leg stiffness (−45%) in the mid-/post-PHV group. Given that vertical force did not change significantly in either group, this seems to suggest that sled towing had an increased effect on the rise and fall of the centre of mass, i.e. vertical displacement. This was certainly the case, a significant increase in vertical displacement (15.3%, ES = 1.46) was noted in the mid-/post-PHV group from pre- to post-testing. A number of researchers have also reported increased ground contact times with increased sled loading (Cronin et al., 2008; Letzelter et al., 1995; Lockie et al., 2003). It maybe that these kinematic adaptations that result from increased sled loading when repeated over time, affect running kinematics and in turn variables such as stiffness.

Decreasing stiffness might be seen as a negative adaptation to resisted sled towing, as it supposedly would reduce the rate of force transmission between the legs and the ground and therefore acceleration and running speed (Arampatzis, Brüggemann, & Metzler, 1999; Bret, Rahmani, Dufour, Messonnier, & Lacour, 2002). Limited supporting evidence for such a contention can be observed from the work of Rumpf, Cronin, Oliver, and Hughes (2013) stated that stiffness measures increased significantly with increasing maturation and maximal velocity speed. However, as this study was cross-sectional one must be careful when making definitive conclusions as to the importance of stiffness to sprint performance.

The use of the non-motorised treadmill enabled a number of novel findings that allows some insight into some of the mechanistic adaptations to resisted sled towing. Unfortunately, none of the studies that have utilised this method of sprint training has provided information regarding the effects of resisted sled towing on other mechanistic variables and as a consequence the comparison of data from this study with other research, be it adult or youth, is problematic.

The adherence to training was different between the two groups, the mid-/post-PHV groups attending on average two more sessions than their younger counterparts. This disparity was controlled for by use of the ANCOVA, however, the results do illustrate some of the challenges working with athletes especially younger athletes who are dependent on parents for transport and are at the behest of schools in terms of extracurricular activities. As the pre-PHV group in our study did not positively (increase in sprint times) with the provided stimulus, it seems that resisted sled towing is not a suitable choice to improve sprint performance in this population. Interestingly, a recent analysis of sprint training method in youth (Rumpf et al., 2012) reported plyometric training forms as the preferred choice for pre-PHV athletes.

Conclusion

Resisted sled towing is a form of sprint training suitable to improve sprint performance in developing athletes who have attained mid-PHV maturity status. Training frequency of two times per week with total sprint distances of 140–300 metres will produce moderate sprint training effects in mid-/post-PHV athletes. This type of training increases velocity via increased step frequency, increased horizontal force and power production as well as decreased stiffness. Decreased stiffness however, might be viewed as disadvantageous in the long term in terms of fast force production. It might be that other resisted training methods such as adding a weighted vest might counteract the loss in stiffness by providing greater vertical eccentric overload as well as a more upright running posture. The ideal combinations and adaptations of such training methods are yet to be determined in both youth and adult populations.

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