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Hypertrophic muscle changes and sprint performance enhancement during a sprint-based training macrocycle in national-level sprinters

SERGI NUELL¹, VÍCTOR ILLERA-DOMÍNGUEZ¹, GERARD CARMONA²,³, XAVIER ALOMAR⁴, JOSEP MARIA PADULLÉS¹, MARIO LLORET¹, JOAN AURELI CADEFAU¹,⁵

¹Institut Nacional d’Educació Física de Catalunya (INEFC), Universitat de Barcelona (UB), Barcelona, Spain.
²Sports Sciences Department, FC Barcelona, Barcelona, Spain.
³Tecnocampus, Escola Superior de Ciències de la Salut, Universitat Pompeu Fabra, Mataró, Spain.
⁴Creu Blanca, Barcelona, Spain.
⁵Departament de Biomedicina, Universitat de Barcelona (UB)

Running head: Hypertrophic and performance changes in sprinters

Corresponding author:
Joan Aureli Cadefau Surroca
Institut Nacional d’Educació Física de Catalunya (INEFC), Barcelona, Spain
E-mail: jcadefau@gencat.cat
Phone: (+34) 679 774 327
Fax: (+34) 934 263 617
Abstract

This study aimed to analyse changes in sprint performance, muscle volumes (MVs) and sprint mechanical parameters (SMPs) in national-level sprinters performing a 5-month indoor sprint-based training macrocycle (SBTM). Twelve well-trained sprinters were tested on three different occasions throughout the SBTM. Testing procedures included: sprint performance over 10m, 40m, 80m, 150m, and 300m; MRI of thighs, to compute MVs of quadriceps, hamstrings and adductors; and a 40m sprint using a radar gun to assess SMPs such as theoretical maximal horizontal force, theoretical maximal horizontal velocity ($V_0$), maximal power and index of force application ($D_{RF}$). Improvements in sprint performance of between 4% and 7% (ES = 0.46-1.11, $P < 0.01$) were accompanied by increments in: quadriceps of 6% (ES = 0.41, $P < 0.01$), hamstrings of 10% (ES = 0.62, $P < 0.01$), adductors of 12% (ES = 0.87, $P < 0.01$), $V_0$ of 5% (ES = 0.40, $P < 0.01$) and $D_{RF}$ of 7% (ES = 0.91, $P < 0.01$). In conclusion, during the SBTM after the off-season, moderate hypertrophic changes occur in sprinters. Moreover, the greater increase in hamstrings and adductors, compared with quadriceps, might be related to the prominent role of these muscle groups in sprinting. Furthermore, the SBTM was likely effective at developing sprint performance in sprinters, thereby endorsing the idea that sprint-specific training is crucial for highly trained individuals. Finally, our results support the notion that $V_0$ or the “velocity-oriented” force–velocity profile is determinant of performance in sprinters.

Keywords: Sprint performance, Muscle volume, Sprint mechanical parameters, Magnetic resonance imaging, Sprinter training.
Introduction

Sprint ability is a key factor in many sports and hence the focus of many training programmes. Although many factors influence sprint performance, it has recently been shown that the propulsive forces produced during sprinting are the strongest predictor of acceleration and sprint performance (Brughelli et al., 2011; Morin et al., 2011; Rabita et al., 2015). Moreover, the ability to orientate the ground reaction force (GRF) vector forward is also the differential factor between recreational and top-level sprinters (Morin et al., 2011). The overall mechanical capability to produce horizontal forces is estimated by the inverse linear force–velocity and power–velocity relationships. These relationships characterise the mechanical limits of the entire neuromuscular system and are well explained by the theoretical maximal force at null velocity ($F_0$) and the theoretical maximal velocity the system can develop when force is equal to zero ($V_0$), together with the associated maximal power output ($P_{max}$) (Samozino et al., 2016).

Force production seems to be largely determined by muscle mass (Trezise et al., 2016). When comparing sprinters with an average population, the differences in muscularity are evident (Bex et al., 2017; Handsfield et al., 2017). However, it is known that changes in muscle shape induced by training are not uniform along the muscle (Ema et al., 2013). This fact evidences the limitations of a single cross-sectional area measurement, which might not be sufficient to gauge hypertrophic changes. In addition, joint torque and power generation capabilities are largely determined by muscle volume (MV) rather than cross-sectional area (Akagi et al., 2009; Fukunaga et al., 2001). Hence, it seems logical to believe that MV could play an important role in sprint performance. Some authors have worked on this hypothesis, finding strong relationships between different leg MVs and both maximal running speed and acceleration capacity (Chelly et
al., 2010; Tottori et al., 2017). In this regard, Perez-Gomez et al. (2008) analysed the role of the lean lower body mass in sprint performance and found that the total muscle mass of the legs is strongly correlated with sprint performance. In a recent study comparing two elite groups of sprinters and endurance athletes, Bex et al. (2017) found differences in MV, especially in the thighs, suggesting the relevance of upper leg muscle groups in sprint performance.

In a recent paper, Bezodis et al. (2018) analysed how training periodisation influences sprint performance in a group of elite sprinters, finding that the improvements in sprinting speed are, mainly, due to increases in step frequency. In contrast, findings from Nagahara et al. (2017) revealed that improvements in maximal velocity over a full winter season were due to increments in step length and vertical stiffness. However, the few literature studying the effects of periodised training seems focused on spatiotemporal variables. The studies analysing muscularity and sprint performance are cross-sectional, thus, it seems there is a lack of long-term investigation about hypertrophic and sprint performance changes in sprinters. Therefore, in this study, we analysed the effect of a 5-month sprint-based training macrocycle (SBTM) on sprint performance. Moreover, aside from the assessment of fitness in sprinters, a better understanding of which muscular and mechanical changes accompany potential sprint performance enhancements might be highly beneficial for the development and control of training plans. Therefore, the aim of the present study was to analyse changes in sprint performance, as well as in MV and sprint mechanical parameters (SMPs), in national-level sprinters during an SBTM.
Methods

Participants

Twelve well-trained adult sprinters (men=6; women=6) (age: 23.5 ± 4.1 years; body mass: 65.0 ± 12.3 kg; height: 172.1 ± 11.8 cm) volunteered to participate in the study. The gender, athletic event speciality and personal best times of the athletes are provided in Supplemental Content 1. The inclusion criteria were: (1) sprinters who compete in races over 100m to 400m at a national level; (2) preparing for the 2017 indoor season; and (3) free from lower limb soft tissue injuries for the previous 4 months. The exclusion criteria were: (1) medical problems contraindicated for experimental testing; and (2) not having completed at least 80% of the training sessions at the end of the study. Initially, fifteen athletes were recruited, although three of them were forced to withdraw from the study, due to injuries during the SBTM. All the participants gave written informed consent to participate in this study, which was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the Catalan Sports Council.

Design

The study was designed as an ecological (no interference with athlete training schedules) follow-up of an indoor SBTM (from September to February). During the training period, the athletes were tested on three different occasions: the week before starting the SBTM (PRE); exactly in the middle of the SBTM (IN); and at the end of the SBTM, two weeks before the Spanish National Indoor Championship, (POST). Therefore, two different periods of training with the same duration were differentially assessed by the tests: period 1, from PRE to IN (P1); and period 2, from IN to POST (P2). The 10m and 40m sprint tests, and the SMPs test were recorded during the same sprint. In all the sprint tests, the
athletes adopted the three-point start position, using their usual competitive spikes. All
the tests were performed in the same order, at the same time and under the same
conditions during PRE, IN and POST (Figure 1).

***Insert Figure 1 near here***

Sprint performance

To assess the whole spectrum of maximal anaerobic power distances for the sprinter, we
included: 10m, 40m, 80m, 150m and 300m tests. In fact, the training of all sprinters is
composed of different sprint distances, in order to train the different phases of the sprint
(i.e., acceleration, maximum speed and speed–endurance); thus, the distances included in
this study may help to elucidate specific improvements. In order to avoid interference
with the athletes’ training schedules, the sprint tests were carried out as follows: Tuesday
10 and 40m, Wednesday 80m, Thursday 150m and Friday 300m (Figure 1). After 40 min
of standard warm-up led out by their coach, the athletes started the tests. Microgate Witty
photocells (Microgate, Italy) were used to measure the times, and were activated when
crossed. The athletes started their attempts just before the first photocell, and the timer
started at their very first movement. In order to have a faster and more reliable start, the
participants were told to start at will: when they wanted.
As stated before, the 10m and 40m sprint tests were conducted over the same sprint, during which the SMPs were also recorded. Three pairs of photocells were positioned at distances of 0, 10 and 40m. The athletes performed two trials with 6 min rest in between. For the 80m sprint test, two pairs of photocells were placed at distances of 0 and 80m. The athletes again performed two attempts with 15 min rest in between. For the 150m and 300m tests, only one attempt was performed, and two pairs of photocells were placed at distances of 0 and 150m, and 0 and 300m, respectively. The best time over each sprint distance was used for further analysis.

Muscle volumes

For MV assessment, series of cross-sectional images of each subject’s thighs were obtained by MRI with an Avanto 1.5T (Magnetom Avanto, Siemens Healthineers, Germany). Transaxial images (slice thickness, 2mm; increment, 2mm) were acquired in a 320x320 matrix, 40x40 field of view in 20-second blocks. The volunteers were placed supine inside the scan with their heads outside the MR-bore, thighs covered with a leg coil and limb position was fixed with a custom-made foot-restraint. Between 280 and 320 (depending on each subject’s thigh length) images of both legs were obtained from the iliac spine to the patella. All scans were performed on Monday, after at least 48h of recovery after the previous training session, to account for hypertrophic changes and avoid any influence of acute muscle swelling (Damas et al., 2016).

Vastus lateralis, vastus intermedius, vastus medialis and rectus femoris were outlined together and identified as quadriceps. Biceps femoris long head, biceps femoris short head, semitendinosus and semimembranosus were outlined together and identified as hamstrings. The same approach was adopted for the assessment of adductor MV, which included the pectineus, adductor longus, brevis, magnus and gracilis. The edges of the
quadiceps, hamstrings and adductors were manually outlined image-by-image, by the same researcher, following the reference method proposed by Nordez et al. (2009), using Osirix 8.5.2 (Pixmeo, Geneva, Switzerland). The total volume of each muscle was calculated from the range between the last image in which the ischial tuberosity was visible and the last image where the muscle was visible (Figure 2). MV results are shown as the average of right and left thighs. The intra-investigator coefficient of variation for muscle segmentation was 1.1% ± 0.4% for the muscles assessed; similar to previous estimations of error using this method (Illera-Dominguez et al., 2018; Nordez et al., 2009).

***Insert Figure 2 near here***

Sprint mechanical parameters

Instantaneous velocity over a 40m sprint was measured by radar (Stalker ATSII, Plano, Texas), as previously validated in human sprint experiments (Rabita et al., 2015; Samozino et al., 2016). The device was placed on a tripod 1.5m behind the subject at a height of 1m; approximately the average subject’s centre of gravity. Subjects were instructed to keep static the starting position for about one second, in order to record a “0 velocity” signal, and then to start running forward without any countermovement. The fastest trial, based on photocell times, was selected for further analysis. The resultant data were subsequently analysed using the simple field method validated by Samozino et al. (2016). Briefly, this computation method is based on macroscopic inverse dynamics analysis of the centre-of-gravity motion. Velocity–time data are fitted to an exponential function, after which instantaneous velocity is derived to compute the net horizontal
anteroposterior GRF and power. Individual force–velocity relationships are then extrapolated to calculate $F_0$ and $V_0$ capabilities, and the underlying $P_{\text{max}}$, as described elsewhere (Morin et al., 2011; Rabita et al., 2015; Samozino et al., 2016). An index of force application ($D_{RF}$) was also calculated from the linear force–velocity relationship, which represents the ability to apply horizontal force as running speed increases (Morin et al., 2011; Samozino et al., 2016).

Sprint-based training macrocycle

For the study to be ecological, we did not interfere in the athletes’ training processes; we did, however, exhaustively record the daily training regime of each athlete. A training diary was used to quantify the real, not the planned, external training load. Details of SBTM are presented in Supplemental Content 2.

Statistical analysis

All data are presented as mean ± SD. Statistical analysis was performed using SPSS v.23.0.0.0 (IBM, Armonk, New York). The normal distribution of the data was checked using the Shapiro-Wilk test. One-way repeated-measures ANOVA was used to identify the effect of time on the different variables analysed. If significant effects were found, a post-hoc Bonferroni corrected paired $t$-test was applied to identify significant differences between the PRE, IN and POST values. Statistical significance was set at $P < 0.05$. Effect size (ES) were calculated to compare the magnitude of the differences between PRE, IN and POST (Hopkins et al., 2009). Due to the great anthropometric variability between subjects (i.e.: 88 kg heaviest male vs. 52 kg lightest female) that affects the SD of
averaged MV, these values were normalised by height–mass in order to have a more accurate ES, which depends on the magnitude of the SD (Handsfield et al., 2017). Pearson’s correlation coefficient was employed to evaluate the association between the normalised MV and sprint performance at POST, and changes in normalised MV and in sprint performance, with thresholds being 0.40-0.59, moderate; 0.60-0.79, strong; 0.80-1, very strong.

**Results**

Data for the different variables (sprint performance, normalised MVs and SMPs) measured at PRE, IN and POST, are presented in Table 1.

***Insert Table 1 near here***

*Sprint performance*

Sprint performance improved throughout the SBTM. The 10m and 40m times were reduced significantly from PRE to POST: by 7.0% and 4.9% (ES = -1.11 and -0.61, \(P < 0.01\)) respectively; and from IN to POST: 5.6% and 3.3% (ES = -1.00 and -0.54, \(P < 0.05\)) respectively, although no significant changes were seen from PRE to IN. The 80m and 150m times were significantly reduced from PRE to IN: 3.2% and 3.4% (ES = -0.31 and -0.32, \(P < 0.01\)) respectively; and from PRE to POST: 4.4% and 4.5% (ES = -0.51 and -0.46, \(P < 0.01\)) respectively, but here there were no significant changes from IN to POST. Significant time reductions were seen at all points in the 300m sprint test; with 3.6% (ES = -0.29, \(P < 0.01\)) from PRE to IN, 1.8% (ES = -0.20, \(P < 0.01\)) from IN to
POST and 5.1% (ES = -0.50, \( P < 0.01 \)) from PRE to POST. Absolute values of sprint performance are shown in Table 1.

**Muscle volumes**

The MVs of the three muscle groups analysed increased throughout the SBTM. Quadriceps increased 5.6% (ES = 0.35, \( P < 0.01 \)) from PRE to IN and 6.7% (ES = 0.41, \( P < 0.01 \)) from PRE to POST. Hamstrings increased 9.2% (ES = 0.58, \( P < 0.01 \)) from PRE to IN and 10.1% (ES = 0.62, \( P < 0.01 \)) from PRE to POST. Adductors increased 11.7% (ES = 0.83, \( P < 0.01 \)) from PRE to IN and 12.1% (ES = 0.87, \( P < 0.01 \)) from PRE to POST. Normalised values of MV are presented in Table 1, whereas absolute values are displayed in Figure 3.

Normalised hamstring MV was strongly correlated with all sprint distance times (range: \( r = -0.727 \) to -0.796, \( P < 0.01 \)). Normalised adductor MV was strongly associated with 40m, 80m and 150m sprint times (\( r = -0.689; -0.688; -0.680, P < 0.05 \), respectively). Normalised quadriceps MV was only associated with 40m sprint time (\( r = -0.644, P < 0.05 \)). No correlations were found between changes in MV and changes in sprint performance during the macrocycle (Supplemental Content 3).

***Insert Figure 3 near here***

**Sprint mechanical parameters**

A significant increase in \( V_0 \) of 3.7% (ES = 0.21, \( P < 0.01 \)) was seen from PRE to IN; and 5.3% (ES = 0.40, \( P < 0.01 \)) from PRE to POST. Similarly, \( D_{RF} \) improved by 6.2% (ES = 0.80, \( P < 0.05 \)) from PRE to IN; and by 7.2% (ES = 0.91, \( P < 0.01 \)) from PRE to POST.
No significant changes were seen in either $V_0$ or $D_{RF}$ from IN to POST. No significant changes were seen in either $F_0$ or $P_{\text{max}}$. Absolute values of SMPs are shown in Table 1.

**Discussion**

The aim of this study was to analyse changes in sprint performance, MVs and SMPs in national-level sprinters during an indoor SBTM. We found that the SBTM was likely effective in developing sprint performance and the improvements were accompanied by a significant increment of the thigh muscle groups measured (quadriceps, hamstrings and adductors). Interestingly, the relative increase in hamstring and adductor MVs was almost the same, and double the relative increase in quadriceps. Finally, performance enhancement was accompanied by significant increases in $V_0$ and $D_{RF}$, confirming that these parameters seem to be the most determinant of performance in sprinters.

*Sprint performance*

Small to moderate improvements in sprint performance occurred throughout the SBTM. Interestingly, greater improvements over short distances (i.e. 10m and 40m) took place during P2; while slightly greater improvements over longer distances (i.e. 80m to 300m) took place during P1 (Table 1). Lower volumes and higher intensities are expected to improve sprinting speed. In fact, in a recent study analysing the effects of an extended training period on sprinters, Bezodis et al. (2018) found that improvements in sprint performance occurred during training phases of low-volume lifting and high-intensity sprint work. However, in our work, P1 involved higher volumes and lower intensities than P2 (Supplemental Content 2); thus, our results are partially in accordance with those of Bezodis et al. (2018). We should also mention that in our study the athletes started in
a highly detrained status, after 6 weeks of rest, thus the margin for improvement that they had in P1 was much greater than that in P2.

Our results are also in agreement with Rumpf et al. (2016) who found that while complementary training modalities, such as resistance-training (strength and power) and plyometric training, influence sprinting speed to some extent, sprint-specific training (sprinting and sled-resisted sprint) was crucial to ensure performance improvements over different distances (ranging from 10 to \( > 30 \)m) in athletes from different sports disciplines.

**Muscle volumes**

Sprint performance enhancements were accompanied by significant MV increases in all three muscle groups analysed. Moderate increases were found in hamstrings and adductors, whereas small increases were found in quadriceps. Moreover, we observed a highly consistent pattern of change in all three muscle groups analysed, with increases in P1 (from PRE to IN) and maintenance during P2 (from IN to POST) (Figure 3).

Since the sprinters were enrolled on an SBTM which was mainly composed of sprint-specific training, the moderate increase in hamstring MV might be linked with the crucial role of this muscle group in sprinting. In this regard, hamstring MV showed strong correlations with all sprint distance times analysed. Previous studies have found a peak in hamstring activity from mid swing until terminal stance (Morin et al., 2015; Schache et al., 2012). In the mid and late swing, the hamstrings work eccentrically to decelerate the knee extension; and then during the whole stance phase, they work concentrically, as hip extensors, to produce forward movement (Higashihara et al., 2018; Wiemann & Tidow, 1995). The amount of horizontal GRF produced during sprinting acceleration is
related to hamstring activation just before ground contact and eccentric knee flexor peak torque (Morin et al., 2015; Schache et al., 2012). Moreover, hamstrings are key hip extensor muscles, showing a large and stable moment arm in the whole sagittal hip range of motion (Nemeth & Ohlsen, 1985).

It is well documented that adductor magnus is a powerful hip extensor when the hip is flexed (Dostal, Soderberg, & Andrews, 1986; Nemeth & Ohlsen, 1985; Neumann, 2010). In contrast, the other adductors (pectineus, adductor longus, adductor brevis and gracilis) are in fact hip flexors, especially when the hip is extended (Dostal et al., 1986; Nemeth & Ohlsen, 1985; Neumann, 2010). In the early swing, when hip flexors are stretched, adductors play an important role in assisting hip flexion, and in neutralising the abduction and external rotation caused by tensor fascia latae and sartorius (Wiemann & Tidow, 1995). Meanwhile, during the mid to late swing, when the hip is flexed, adductors work as a synergist of gluteus maximus, helping with hip extension and counterbalancing its external rotation. In this sense, we found strong associations between adductor MV and 40m, 80m and 150m sprint times. Furthermore, Tottori et al. (2017) studied the relation between adductors and sprint performance in preadolescent sprinters, and showed that larger adductors are related with better sprint performance. Taking into account the importance of adductors in sprint-specific training and in complementary training, the moderate adductor MV increment observed in our work could reasonably be expected.

Despite the importance of knee extensors in sprinting and their contribution to generating vertical GRF (Dorn, Schache, & Pandy, 2012; Tottori et al., 2017; Wiemann & Tidow, 1995), it seems that quadriceps only contribute in the forward acceleration during the first steps, when the body leans forward due to the projection of the centre of gravity, ahead of the support base (Higashihara et al., 2018; Wiemann & Tidow, 1995). When sprinting, knee extensor activation is required during the stance, first to decelerate
the vertical displacement of the centre of gravity and to stabilise the knee joint, and then
to accelerate the centre of gravity vertically (Wiemann & Tidow, 1995). Recent literature
supports the idea that the muscularity of the quadriceps is not related with sprint
performance (Miyake et al., 2017; Sugisaki et al., 2017); however, this is still a matter of
debate. In the present study, quadriceps MV was only correlated with 40m and to a lesser
degree than for hamstrings and adductors. It seems that enlargement of these muscles
would increase the lower limb moment of inertia and hence reduce the limb angular
acceleration (Sugisaki et al., 2017). The lesser contribution of quadriceps during sprinting
compared to hamstrings and adductors, might explain the smaller increase found in them.

Changes in MVs were not related with changes in sprint performance throughout the
SBTM (Supplemental Content 3). From the findings in this study it would appear that the
MV of the hamstrings and adductors are related with sprint performance, however, the
increment of these muscles do not seem to transfer to improvements in sprint
performance. Therefore, improvements of force-related factors (i.e. magnitude and
direction), and kinematic factors (i.e. contact time, step frequency) are most likely related
with performance improvements. In addition, the small sample size is probably a limiting
factor for the correlation.

Another finding of this study is the time course of the hypertrophic process, with
moderate increases in MV during P1 and maintenance in P2 (Table 1 and Figure 3). We
therefore worked with two different hypotheses concerning the cause of this: 1) the prior
detraining process, since athletes started the SBTM after 6 weeks of rest; and 2) the
relatively large training volumes achieved in P1 in comparison with P2 (Supplemental
Content 2) throughout the SBTM. During the detraining period, the fastest rate of muscle
atrophy, especially the degradation of contractile protein, takes place in the first two
weeks (Ross & Leveritt, 2001). These changes result from lower glycogen content in the
muscle, and especially from protein breakdown, as a result of inhibition of anabolic cellular pathways (Kandarian & Jackman, 2006). Moreover, it has been reported that after sprint training, there is a loss of muscle fibre cross-sectional area of 5% to 13% over a period of two to seven weeks after the cessation of training (Ross & Leveritt, 2001). However, Bruusgaard et al. (2010) showed that muscle acquires newly formed myonuclei after a training process, which are not lost during detraining and the subsequent atrophy; this thereby accelerates the incoming hypertrophic process and explains why previously trained individuals are more easily retrained. In addition, Seaborne et al. (2018) identified some epigenetically sensitive genes with enhanced expression after the detraining process, which result in almost twice the hypertrophic changes after retraining. Furthermore, it is assumed that training volume is a crucial factor for hypertrophy (Figueiredo et al., 2018); here, higher training volumes are observed in P1 than in P2 (Supplemental Content 2). Therefore, loss of MV during detraining and newly formed myonuclei, together with higher training volumes, could explain the larger increases in MVs following P1 compared to P2.

Sprint mechanical parameters

Enhanced sprint performance were also accompanied by significant changes in SMPs. $V_0$ and $D_{RF}$ were significantly improved from PRE to IN and from PRE to POST (Table 1). These improvements mean that after the SBTM, the athletes were able to achieve higher maximum speeds and to apply force onto the ground more effectively over the entire acceleration (Morin et al., 2011). In other words, following the SBTM, athletes shifted their individual force–velocity profile towards “velocity-oriented”. Along similar lines, Morin et al. (2012) found that $V_0$ and $D_{RF}$ are the most determinant variables predicting
sprint performance, as well as the variables that differ the most when comparing elite with average sprinters (they found no differences in $F_0$). Thus, when we analysed 40m, 80m and 150m performance, which presumably are more closely determined by $V_0$, we found an expected improvement; this is also in accordance with the conclusions of Morin et al. (2011, 2012) and Rabita et al. (2015).

$F_0$ is related to very initial acceleration capabilities, since it is the theoretical maximal horizontal force a subject can apply onto the floor (Morin et al., 2011; Samozino et al., 2016). Despite part of the training being oriented to improving acceleration, $F_0$ did not change during the SBTM. One reason that might explain this is that $F_0$ is the theoretical maximal horizontal force at zero velocity, which is not the actual case during acceleration, where the velocity is increasing right from the first moment. In contrast, $D_{RF}$, or the ability to apply horizontal force during the acceleration phase, showed a significant increase. Nevertheless, the improvement in 10m sprint performance without any change in $F_0$ is remarkable. Finally, since power output is the product of force and velocity, the maintenance of $P_{max}$ seems reasonable, because of the absence of changes in force capabilities.

**Conclusions**

The SBTM was likely effective in developing sprint performance over all the distances assessed in national-level athletes. Sprint performance enhancements were accompanied by significant increases of quadriceps, hamstring and adductor MVs, especially during P1, when higher training volumes were achieved. This supports the notion that training volumes have a crucial impact on hypertrophy. Moreover, the relatively higher hypertrophic changes of hamstrings and adductors, compared to quadriceps, might be
related to the prominent role of the former muscle groups in sprinting. Finally, sprint performance increases were also accompanied by an enhancement of SMPs, supporting the notion that $V_0$ or the “velocity-oriented” force–velocity profile is determinant of performance in sprinters.

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The authors declare no conflicts of interest related to this paper.
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Figure 1. Overview of the study design and testing procedures. a) Schematic overview of the experimental design. A total of three testing periods were spread over the athletics indoor season. All the tests were repeated in the same order and under the same conditions. PRE, Pre-training test. IN, In-training test. POST, Post-training test. P1, period of training between PRE and IN. P2, period of training between IN and POST. b) Schematic overview of the testing procedures throughout the testing week.

Figure 2. Representative example of changes in cross-sectional area (=50% length of the thigh) and muscle volumes of right and left thighs during the period (subject no. 7).

Figure 3. Absolute changes in muscle volumes throughout the SBTM. PRE, Pre-training test. IN, In-training test. POST, Post-training test. ** Indicates significant differences from PRE value, at P < 0.01.

Table 1. Absolute values of the variables measured throughout the sprint-based training macrocycle.

<table>
<thead>
<tr>
<th>Variable measured</th>
<th>PRE</th>
<th>IN</th>
<th>POST</th>
<th>ES (Pre vs. In)</th>
<th>ES (In vs. Post)</th>
<th>ES (Pre vs. Post)</th>
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</thead>
<tbody>
<tr>
<td><strong>Sprint performance</strong></td>
<td></td>
<td></td>
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<tr>
<td>tests (n=12)</td>
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<tr>
<td>10 m (s)</td>
<td>2.00 ± 0.14</td>
<td>1.98 ± 0.13</td>
<td>1.86 ± 0.11</td>
<td>-0.15</td>
<td>-1.00</td>
<td>-1.11</td>
</tr>
<tr>
<td>40 m (s)</td>
<td>5.70 ± 0.42</td>
<td>10.02 ± 0.44</td>
<td>5.42 ± 0.31</td>
<td>-0.31</td>
<td>-0.21</td>
<td>-0.51</td>
</tr>
<tr>
<td>80 m (s)</td>
<td>0.49 ± 0.16</td>
<td>0.86 ± 0.21</td>
<td>0.42 ± 0.20</td>
<td>-0.32</td>
<td>-0.16</td>
<td>-0.46</td>
</tr>
<tr>
<td>150 m (s)</td>
<td>10.30 ± 0.23</td>
<td>18.76 ± 1.62</td>
<td>9.84 ± 0.29</td>
<td>-0.29</td>
<td>-0.20</td>
<td>-0.50</td>
</tr>
<tr>
<td>300 m (s)</td>
<td>0.95 ± 0.18</td>
<td>1.80 ± 0.21</td>
<td>0.86 ± 0.20</td>
<td>-1.86</td>
<td>1.94</td>
<td></td>
</tr>
<tr>
<td></td>
<td>19.34 ± 1.65</td>
<td>41.45 ± 2.13</td>
<td>18.47 ± 1.29</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>42.78 ± 2.66</td>
<td>40.59 ± 2.26</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Muscle volumes (n=10)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quadriceps (cm³·kg⁻¹·m⁻¹)</td>
<td>16.17 ± 2.53</td>
<td>17.03 ± 2.39</td>
<td>17.20 ± 2.47</td>
<td>0.35</td>
<td>0.07</td>
<td>0.41</td>
</tr>
<tr>
<td>Hamstrings (cm³·kg⁻¹·m⁻¹)</td>
<td>7.75 ± 1.24</td>
<td>8.45 ± 1.27</td>
<td>8.53 ± 1.27</td>
<td>0.83</td>
<td>0.03</td>
<td>0.87</td>
</tr>
<tr>
<td>Adductors (cm³·kg⁻¹·m⁻¹)</td>
<td>8.69 ± 1.17</td>
<td>9.70 ± 1.32</td>
<td>9.74 ± 1.32</td>
<td>0.56</td>
<td>0.20</td>
<td>0.30</td>
</tr>
<tr>
<td><strong>Sprint mechanical parameters (n=12)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F₀ (N/kg)</td>
<td>8.8 ± 1.0</td>
<td>9.0 ± 0.9</td>
<td>9.2 ± 0.9</td>
<td>0.21</td>
<td>0.21</td>
<td>0.40</td>
</tr>
<tr>
<td>V₀ (m/s)</td>
<td>17.7 ± 4.0</td>
<td>16.9 ± 3.4</td>
<td>1.0 ± 0.2</td>
<td>-0.22</td>
<td>0.27</td>
<td>0.05</td>
</tr>
<tr>
<td>P_max (W/kg)</td>
<td>-0.072 ± 0.068</td>
<td>17.9 ± 3.9</td>
<td>0.80</td>
<td>0.18</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td>D_RF</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
-0.067 ± 0.006**

PRE, Pre-training test. IN, in-training test. POST, Post-training test. ES, Effect Size. 10 m, time achieved over 10-metre sprint. 40 m, time achieved over 40-metre sprint. 80 m, time achieved over 80-metre sprint. 150 m, time achieved over 150-metre sprint. 300 m, time achieved over 300-metre sprint. \( F_0 \), theoretical maximal horizontal force. \( V_0 \), theoretical maximal horizontal velocity. \( P_{\text{max}} \), theoretical maximal horizontal power. \( D_{RF} \), rate of decrease of ratio of force with increasing speed, during sprint acceleration. Values are mean ± SD of the group of athletes. * Indicates significant difference from PRE value, at \( P < 0.05 \). ** Indicates significant difference from PRE value, at \( P < 0.01 \). # Indicates significant difference from IN value, at \( P < 0.05 \). ## Significantly different from IN value, at \( P < 0.01 \).
## Supplemental Content 1

<table>
<thead>
<tr>
<th>Participant</th>
<th>Sex</th>
<th>Event</th>
<th>Event PB (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Female</td>
<td>400 m</td>
<td>58.39</td>
</tr>
<tr>
<td>02</td>
<td>Female</td>
<td>400 m</td>
<td>58.97</td>
</tr>
<tr>
<td>03</td>
<td>Male</td>
<td>100 m</td>
<td>11.21</td>
</tr>
<tr>
<td>04</td>
<td>Female</td>
<td>200 m</td>
<td>24.98</td>
</tr>
<tr>
<td>05</td>
<td>Female</td>
<td>200 m</td>
<td>25.32</td>
</tr>
<tr>
<td>06</td>
<td>Female</td>
<td>200 m</td>
<td>26.87</td>
</tr>
<tr>
<td>07</td>
<td>Male</td>
<td>100 m</td>
<td>10.95</td>
</tr>
<tr>
<td>08</td>
<td>Female</td>
<td>400 m</td>
<td>59.19</td>
</tr>
<tr>
<td>09</td>
<td>Male</td>
<td>200 m</td>
<td>21.13</td>
</tr>
<tr>
<td>10</td>
<td>Male</td>
<td>400 m</td>
<td>48.14</td>
</tr>
<tr>
<td>11</td>
<td>Male</td>
<td>100 m</td>
<td>11.06</td>
</tr>
<tr>
<td>12</td>
<td>Male</td>
<td>100 m</td>
<td>10.71</td>
</tr>
</tbody>
</table>

Sprinter’s sex and event characteristics
Supplemental Content 2

Sprint-based training macrocycle

Similar weekly organization was followed during the SBTM, with training taking place of five days out of seven, as follows. Mondays: sprint-technique drills, plyometrics and short-distance sprints from 10 to 80m; Tuesdays: resistance-training, plyometrics and sled-resisted sprint; Wednesdays: sprint-technique drills and long-distance sprints from 150 to 400m; Thursdays: rest day; Fridays: resistance-training, plyometrics and sled-resisted sprint; Saturdays: sprint-technique drills and short- to middle-distance sprints from 60 to 150m. It must be noted that the long-distance sprints included in Wednesday training differed between “short-distance sprinters” and “long-distance sprinters”, with slightly shorter distances for the firsts (i.e., 300m vs. 500m). The SBTM was mostly composed of sprint-specific training, and linear periodization was used to improve performance, starting with relatively large volumes and low intensities, and progressively reducing the former and increasing the latter.

For the sprinting, the time and distance of each run were recorded. For sled-resisted sprint, the number of sprint bouts and the load relative to bodyweight were registered (the distance was 20m). For sprint-technique drills, the number of runs and the different types of drills were recorded (the distance was 30m). For resistance-training, the number of sets, repetitions and weight (relative to repetition maximum or body weight) were recorded. For plyometrics, the total numbers of horizontal and vertical jumps were also registered.

***Figure Supplemental Content 2***
# SPRINT-BASED TRAINING MACROCYCLE

## P1

<table>
<thead>
<tr>
<th>Distance</th>
<th>Training</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-30m</td>
<td>Sprint</td>
<td>V: 161 ± 28 m/s, %Vmax</td>
</tr>
<tr>
<td>40-60m</td>
<td>Sprint</td>
<td>V: 200 ± 28 m/s, %Vmax</td>
</tr>
<tr>
<td>90-180m</td>
<td>Sprint</td>
<td>V: 300 ± 28 m/s, %Vmax</td>
</tr>
<tr>
<td>&gt;200m</td>
<td>Sprint</td>
<td>V: 500 ± 28 m/s, %Vmax</td>
</tr>
</tbody>
</table>

## P2

<table>
<thead>
<tr>
<th>Distance</th>
<th>Training</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-30m</td>
<td>Sprint</td>
<td>V: 161 ± 28 m/s, %Vmax</td>
</tr>
<tr>
<td>40-60m</td>
<td>Sprint</td>
<td>V: 200 ± 28 m/s, %Vmax</td>
</tr>
<tr>
<td>90-180m</td>
<td>Sprint</td>
<td>V: 300 ± 28 m/s, %Vmax</td>
</tr>
<tr>
<td>&gt;200m</td>
<td>Sprint</td>
<td>V: 500 ± 28 m/s, %Vmax</td>
</tr>
</tbody>
</table>

## Sprint Specific Training

<table>
<thead>
<tr>
<th>Distance</th>
<th>Training</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>80% BW</td>
<td>30m sprint</td>
<td>V: 104 ± 45 m/s</td>
</tr>
<tr>
<td>70% BW</td>
<td>20m sprint</td>
<td>V: 300 ± 395 m/s</td>
</tr>
<tr>
<td>60% BW</td>
<td>20m sprint</td>
<td>V: 100 ± 25 m/s</td>
</tr>
</tbody>
</table>

## Sprint Specific Training

<table>
<thead>
<tr>
<th>Distance</th>
<th>Training</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>80% BW</td>
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<td>V: 104 ± 45 m/s</td>
</tr>
<tr>
<td>70% BW</td>
<td>20m sprint</td>
<td>V: 300 ± 395 m/s</td>
</tr>
<tr>
<td>60% BW</td>
<td>20m sprint</td>
<td>V: 100 ± 25 m/s</td>
</tr>
</tbody>
</table>

## 30m DRILLS

- Walking on toes, walking on heels, Ankle bounding, Cycling, Skipping A, Skipping B, Skipping C, Skip Claw, Isolated quick leg, Fast leg bounding, Straight leg bound, Skip Claw, Progressive run outs...
  - V: 886 ± 1016 m
- Walking on toes, walking on heels, Ankle bounding, Cycling, Skipping A, Skipping B, Skipping C, Skip Claw, Isolated quick leg, Fast leg bounding, Straight leg bound, Skip Claw, Progressive run outs...
  - V: 724 ± 1077 m

## Complementary Training

<table>
<thead>
<tr>
<th>Distance</th>
<th>Training</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-30m</td>
<td>Strength</td>
<td>V: 173 ± 290 jumps</td>
</tr>
<tr>
<td>40-60m</td>
<td>Strength</td>
<td>V: 149 ± 290 jumps</td>
</tr>
<tr>
<td>90-180m</td>
<td>Strength</td>
<td>V: 200 ± 290 jumps</td>
</tr>
<tr>
<td>&gt;200m</td>
<td>Strength</td>
<td>V: 245 ± 290 jumps</td>
</tr>
</tbody>
</table>

## RM Based Exercises

- Clean, Squat, Deadlift, Hip Thrust, Bench Press, Lat Pull Down, Calf Raises
  - V: 28670 ± 1239 kg, V: 2733 ± 15 1 % BW

## BW Based Exercises

- Walking Lunge, Loaded Squat Jump, Step up, Calf Raises
  - V: 28670 ± 1239 kg, V: 2733 ± 15 1 % BW

## RM Based Exercises

- Clean, Half Squat, Hip Thrust, Bench Press, Lat Pull Down, Calf Raises, Thrust up
  - V: 23825 ± 1015 kg, V: 4053 ± 1015 kg

## BW Based Exercises

- Walking Lunge, Loaded Squat Jump, Step up, Calf Raises, Thrust up
  - V: 23825 ± 1015 kg, V: 4053 ± 1015 kg
Supplemental Content 3

Correlations between changes in normalised muscle volumes and changes in sprint performance.

<table>
<thead>
<tr>
<th></th>
<th>Quadriceps MV (cm³·kg⁻¹·m⁻¹)</th>
<th>Hamstrings MV (cm³·kg⁻¹·m⁻¹)</th>
<th>Adductors MV (cm³·kg⁻¹·m⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 m</td>
<td>-0.384 (0.274)</td>
<td>0.004 (0.991)</td>
<td>-0.081 (0.824)</td>
</tr>
<tr>
<td>40 m</td>
<td>-0.255 (0.477)</td>
<td>0.010 (0.979)</td>
<td>-0.153 (0.673)</td>
</tr>
<tr>
<td>80 m</td>
<td>0.084 (0.817)</td>
<td>0.227 (0.528)</td>
<td>0.092 (0.800)</td>
</tr>
<tr>
<td>150 m</td>
<td>-0.356 (0.313)</td>
<td>-0.351 (0.321)</td>
<td>-0.351 (0.188)</td>
</tr>
<tr>
<td>300 m</td>
<td>-0.616 (0.058)</td>
<td>-0.405 (0.246)</td>
<td>-0.564 (0.106)</td>
</tr>
</tbody>
</table>

Values are presented as Pearson correlation coefficient (P values). Note that no significant correlation were found.