Sprint Running Performance and Technique Changes in Athletes during Periodized Training:

An Elite Training Group Case Study

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ABSTRACT:

Purpose: To understand how training periodization influences sprint performance and key step characteristics over an extended training period in an elite sprint training group. *Methods:* Four sprinters were studied during five months of training. Step velocities, step lengths and step frequencies were measured from video of the maximum velocity phase of training sprints. Bootstrapped mean values were calculated for each athlete for each session and 139 within-athlete, between-session comparisons were made with a repeated measures ANOVA. *Results:* As training progressed, a link in the changes in velocity and step frequency was maintained. There were 71 between-session comparisons with a change in step velocity yielding at least a large effect size (>1.2), of which 73% had a correspondingly large change in step frequency in the same direction. Within-athlete mean session step length remained relatively constant throughout. Reductions in step velocity and frequency occurred during training phases of high volume lifting and running, with subsequent increases in step velocity and frequency happening during phases of low volume lifting and high intensity sprint work. *Conclusions:* The importance of step frequency over step length to the changes in performance within a training year was clearly evident for the sprinters studied. Understanding the magnitudes and timings of these changes in relation to the training program is important for coaches and athletes. The underpinning neuro-muscular mechanisms require further investigation, but are likely explained by an increase in force producing capability followed by an increase in the ability to produce that force rapidly.

Keywords: track and field, athletics, velocity, longitudinal, biomechanics.

INTRODUCTION:

There has been continued interest into the effect of step length and step frequency on sprint performance (velocity), specifically recently looking at the acceleration phase of the sprint.[1-3] Further, research into the maximum velocity phase has been inconclusive in identifying the most important contributing factor to sprint performance.[4-7] Differing responses when taking an individual- or group-based approach to the analysis are well documented in the acceleration phase[8] and individualized responses have clearly been demonstrated in elite sprinters in competition.[9] Yet, it is still unknown how the individual manipulates step length and frequency to create their optimum sprint performance.

Sprinters routinely use a periodized program containing resistance training, plyometrics and sprint work in order to improve performance.[10, 11] Perhaps due to inherent difficulties in conducting in-depth scientific interventions in elite sport,[12, 13] there is little published research investigating training-based interventions in elite sprinters.[10] Much of the research into the effect of training on sprint performance has been conducted on team-sports players for whom sprinting is merely one component of performance.[14] One study of trained sprinters involved national-level juniors undertaking seven weeks of either high- or low-velocity resistance training.[15] Although both groups improved performance, no between-group differences in sprint acceleration or strength measures were found. However, with only nine participants across the two training groups, consideration of individual responses to training may have been more revealing.

Salo et al.[9] identified a lack of longitudinal analyses investigating the effect of sprint training in an elite applied setting. To the authors' knowledge, studies that have used elite sprinters as participants, involved a training intervention, and investigated multiple training modalities within the same athletes are still lacking. The primary limitations of much of the current literature investigating the effect of various training programs on sprint performance are that they typically include only one training modality per study (i.e. no investigation of the longitudinal effects of periodization), or per group of athletes,[16] or are not based on highly-trained sprinters.[10]

An approach that documents and explains the changes in sprint performance and underpinning variables alongside the training program being followed will provide a unique scientific insight into the effects of a periodized training program on sprint performance. Therefore, the purpose of this study was to understand how training periodization influences sprint performance and key step characteristics over an extended training period in an elite sprint training group.

METHODS:

Participants and design: Four male sprinters (see Table 1) gave written informed consent to participate, following approval by the local regional ethics committee. All participants were fit and healthy for the duration of data collection, and reported no recent injuries. We adopted an observational, multiple-participant case study design.

Table 1. Participant information. Stature and body mass were recorded at the first session each participant attended.

Participant	Age [years]	Event	Event PB [s]	Stature [m]	Mass [kg]
A1	29	100 m	9.98	1.76	75.0
A2	23	100 m	10.30	1.73	76.3
A3	18	100 m	10.20	1.79	81.4
A4	24	200 m	23.67	1.72	65.0

Methodology: We conducted fifteen data collection sessions at an indoor sprint track from the indoor competition season (late February) to the subsequent outdoor competition season (early August). Athletes attended a varying number of sessions (see Table 2) depending on individualized competition and training schedules set by their coach. Data collections occurred during normal training sessions where the athletes were performing ‘speed work’: i.e. the specific goal of each individual sprint was to reach and maintain maximum velocity for a set distance with minimal effect of fatigue from previous runs. Typical trials comprised a 30 m acceleration followed by a photocell-timed 30 m at maximum velocity, or a 20 m acceleration followed by 50 m at maximum velocity and a further 20 m at sub-maximum velocity. Sessions typically comprised six to eight runs in the early spring and three to four runs by late spring and summer with recovery times between runs ranging from five to ten minutes. Training plan information was retrospectively gathered in discussion with the athletes’ coach. Details of the training of A1 are presented in the supplementary file.

Table 2. Session dates and athlete participation

Session	Date	Athletes present			
S1	23rd Feb	A1	A2	A3	
S2	1st Mar	A1			
S3	24th Mar	A1		A3	
S4	31st Mar	A1	A2	A3	A4
S5	7th Apr	A1		A3	A4
S6	14th Apr	A1	A2		
S7	21st Apr	A1	A2		
S8	5th May	A1	A2		A4
S9	12th May		A2	A3	
S10	19th May		A2		A4
S11	2nd June	A1	A2	A3	
S12	16th June			A3	A4
S13	23rd June	A1		A3	A4
S14	30th June			A3	A4
S15	11th Aug			A3	
Total		10	8	10	7

Two 50 Hz digital cameras (DCR-TRV 900E, Sony Corporation, Japan) were mounted 6.40 m apart, 4.25 m above track level and 7.20 m from the center of the lane in which trials took place. Each camera was set with a shutter speed of 1/600 s and field of view of 6.2 m in the lane of interest. There was a 2.5 m overlap of the two cameras' views at the center of the global field of view. The cameras were separately calibrated using six control points in two orthogonal planes: a 6.00 x 1.17 m transverse plane at track level for the determination of step length, and a 5.50 x 2.06 m sagittal plane at the center of the lane for the determination of velocity. Video images of the runs were recorded during the maximal velocity phase of a sprint, at least 40 m from the start. The coach used photocell times on most occasions to give feedback immediately after each run.

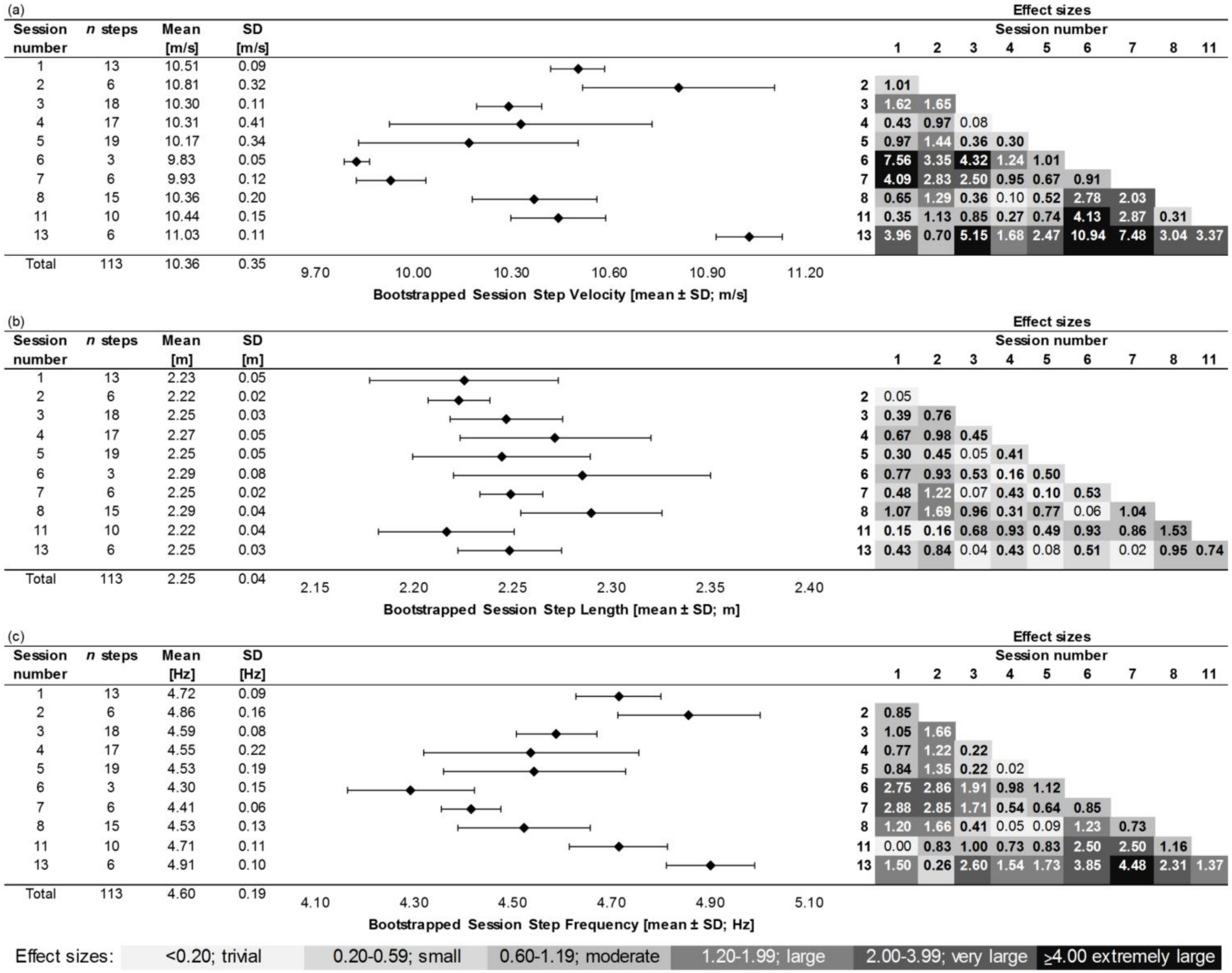
Data Processing: Video data were imported into Target (Loughborough Innovations Limited, UK) for digitizing. The last field before touchdown and the first field after touchdown were visually identified and digitized for each foot contact. A 20-point model of the human body was used: apex of head, C7; and shoulder, elbow, wrist, hip, knee, ankle and metatarsophalangeal joint centers, and tips of the third fingers and second toes. The toe of the ground foot was digitized thrice, non-consecutively, during the first field after touchdown to minimize error in the calculation of step length. Digitized trial sequences were reconstructed using a 2D DLT routine with lens correction added.[17] Calculation of variables for each individual step was always carried out with the data gathered from a single camera ensuring that only one calibration was used, i.e. no step variables were calculated from mixed camera views. Depending on the location of foot contacts within the combined field of view, either three or four consecutive steps per trial were typically analyzed.

Velocity, length and frequency values were calculated for each individual step. Step lengths were calculated by subtracting the mean of the three reconstructed contact-foot toe locations from one contact in the direction of the run from the corresponding mean contact foot toe location of the contralateral foot at the next contact. Step velocity (average center of mass velocity across the whole step) was calculated as the difference between the mean center of mass displacements from the two digitized fields at two consecutive contacts divided by the time between them. Inertia data were taken from de Leva[18] apart from the feet[19], with 200 g added due to the mass of the running spike.[8] Step frequency was calculated by dividing the step velocity by the step length. Comparisons against known locations on the track surface and repeat digitizations in the horizontal plane revealed maximum step length errors of ± 0.01 m. Comparisons of sagittal plane results to sequences in which all fields across the whole step were digitized revealed maximum velocity errors of ± 0.01 m/s. Therefore maximum calculated errors in step frequency were ± 0.03 Hz. Further details and validation of the calculations can be found in Bezodis et al.[20]

Statistical Analysis: While the overall design was repeated measures, periodized training schedules meant an unequal number of steps were measured per session per athlete. To ameliorate this issue we used a bootstrap resampling procedure with replacement[21] to generate a total sample size of n = 1000 data points (steps) per session per athlete. We then analyzed differences between means across all sessions by fitting a repeated measures analysis of variance (ANOVA RM (GLM 4)) to the resampled data for step velocity, step length and step frequency. All residuals were confirmed as being drawn from a population that was normally distributed on the variables of interest (Anderson-Darling's test). In considering sphericity, homoscedastic (additive) error was confirmed in all cases by correlating (Pearson's) absolute residuals against fitted vales ($P > 0.05$). The extent of the linearity between these variables was determined with reference to un-weighted ordinary least squares linear regression analyses. When main effects were identified as statistically significant ($P \leq 0.05$) by the ANOVA RMs, paired samples *t*-tests with a Dunn-Sidák correction (α') to the level of statistical significance (α) were used as the *post-hoc* tests for statistically significant *F*-ratios: $\alpha' = 1 - (1 - \alpha)^{1/c}$, where $c = (k(k - 1)/2)$ and k = the number of session means being considered. To determine the meaningfulness of the effects identified by the *t*-ratios, Cohen's *d* was computed for all pairwise comparisons with the magnitude of the effect quantified according to Hopkins et al.[22] Data are reported as within athlete means ± standard deviations unless otherwise highlighted. Analyses were performed using Minitab v17 (Minitab Inc., State College, PA, USA).

RESULTS:

Due to the individualized nature of the data, we primarily present the results of the fastest athlete (A1), then add general observations for all athletes. The two fastest sessions (by mean step velocity) for A1 were S2 and S13 (10.81 ± 0.29 and 11.03 ± 0.10 m/s, respectively), when mean step frequency was also at its highest (4.86 ± 0.14 and 4.90 ± 0.09 Hz, respectively, see Figure 1). Conversely, step lengths in the two fastest sessions were 2.22 ± 0.02 and 2.25 ± 0.03 m. These were respectively less than and equal to the athlete's mean step length values across all sessions.



(a)

Session number	*n* steps	Mean [m/s]	SD [m/s]	Effect sizes Session number 1	2	3	4	5	6	7	8	11
1	13	10.51	0.09									
2	6	10.81	0.32	**1.01**								
3	18	10.30	0.11	**1.62**	**1.65**							
4	17	10.31	0.41	**0.43**	**0.97**	0.08						
5	19	10.17	0.34	**0.97**	**1.44**	**0.36**	**0.30**					
6	3	9.83	0.05	**7.56**	**3.35**	**4.32**	**1.24**	**1.01**				
7	6	9.93	0.12	**4.09**	**2.83**	**2.50**	**0.95**	**0.67**	**0.91**			
8	15	10.36	0.20	**0.65**	**1.29**	**0.36**	0.10	**0.52**	**2.78**	**2.03**		
11	10	10.44	0.15	**0.35**	**1.13**	**0.85**	**0.27**	**0.74**	**4.13**	**2.87**	**0.31**	
13	6	11.03	0.11	**3.96**	**0.70**	**5.15**	**1.68**	**2.47**	**10.94**	**7.48**	**3.04**	**3.37**
Total	113	10.36	0.35									

(b)

Session number	*n* steps	Mean [m]	SD [m]	Effect sizes Session number 1	2	3	4	5	6	7	8	11
1	13	2.23	0.05									
2	6	2.22	0.02	0.05								
3	18	2.25	0.03	**0.39**	**0.76**							
4	17	2.27	0.05	**0.67**	**0.98**	**0.45**						
5	19	2.25	0.05	**0.30**	**0.45**	0.05	**0.41**					
6	3	2.29	0.08	**0.77**	**0.93**	**0.53**	**0.16**	**0.50**				
7	6	2.25	0.02	**0.48**	**1.22**	0.07	**0.43**	**0.10**	**0.53**			
8	15	2.29	0.04	**1.07**	**1.69**	**0.96**	**0.31**	**0.77**	0.06	**1.04**		
11	10	2.22	0.04	**0.15**	**0.16**	**0.68**	**0.93**	**0.49**	**0.93**	**0.86**	**1.53**	
13	6	2.25	0.03	**0.43**	**0.84**	0.04	**0.43**	0.08	**0.51**	0.02	**0.95**	**0.74**
Total	113	2.25	0.04									

(c)

Session number	*n* steps	Mean [Hz]	SD [Hz]	Effect sizes Session number 1	2	3	4	5	6	7	8	11
1	13	4.72	0.09									
2	6	4.86	0.16	**0.85**								
3	18	4.59	0.08	**1.05**	**1.66**							
4	17	4.55	0.22	**0.77**	**1.22**	**0.22**						
5	19	4.53	0.19	**0.84**	**1.35**	**0.22**	0.02					
6	3	4.30	0.15	**2.75**	**2.86**	**1.91**	**0.98**	**1.12**				
7	6	4.41	0.06	**2.88**	**2.85**	**1.71**	**0.54**	**0.64**	**0.85**			
8	15	4.53	0.13	**1.20**	**1.66**	**0.41**	0.05	0.09	**1.23**	**0.73**		
11	10	4.71	0.11	0.00	**0.83**	**1.00**	**0.73**	**0.83**	**2.50**	**2.50**	**1.16**	
13	6	4.91	0.10	**1.50**	**0.26**	**2.60**	**1.54**	**1.73**	**3.85**	**4.48**	**2.31**	**1.37**
Total	113	4.60	0.19									

Effect sizes: <0.20; trivial | 0.20-0.59; small | 0.60-1.19; moderate | 1.20-1.99; large | 2.00-3.99; very large | ≥4.00 extremely large

Figure 1. Within-session mean and standard deviation of step velocity (a), step length (b) and step frequency (c) for athlete A1. ***n* steps** is the number of individual steps measured within each session. For comparison, between session effect sizes are shown, with their magnitudes categorized according to Hopkins et al.[22] Statistically significant differences (after Dunn-Sidák correction; P ≤ 0.001) are highlighted in **bold**.

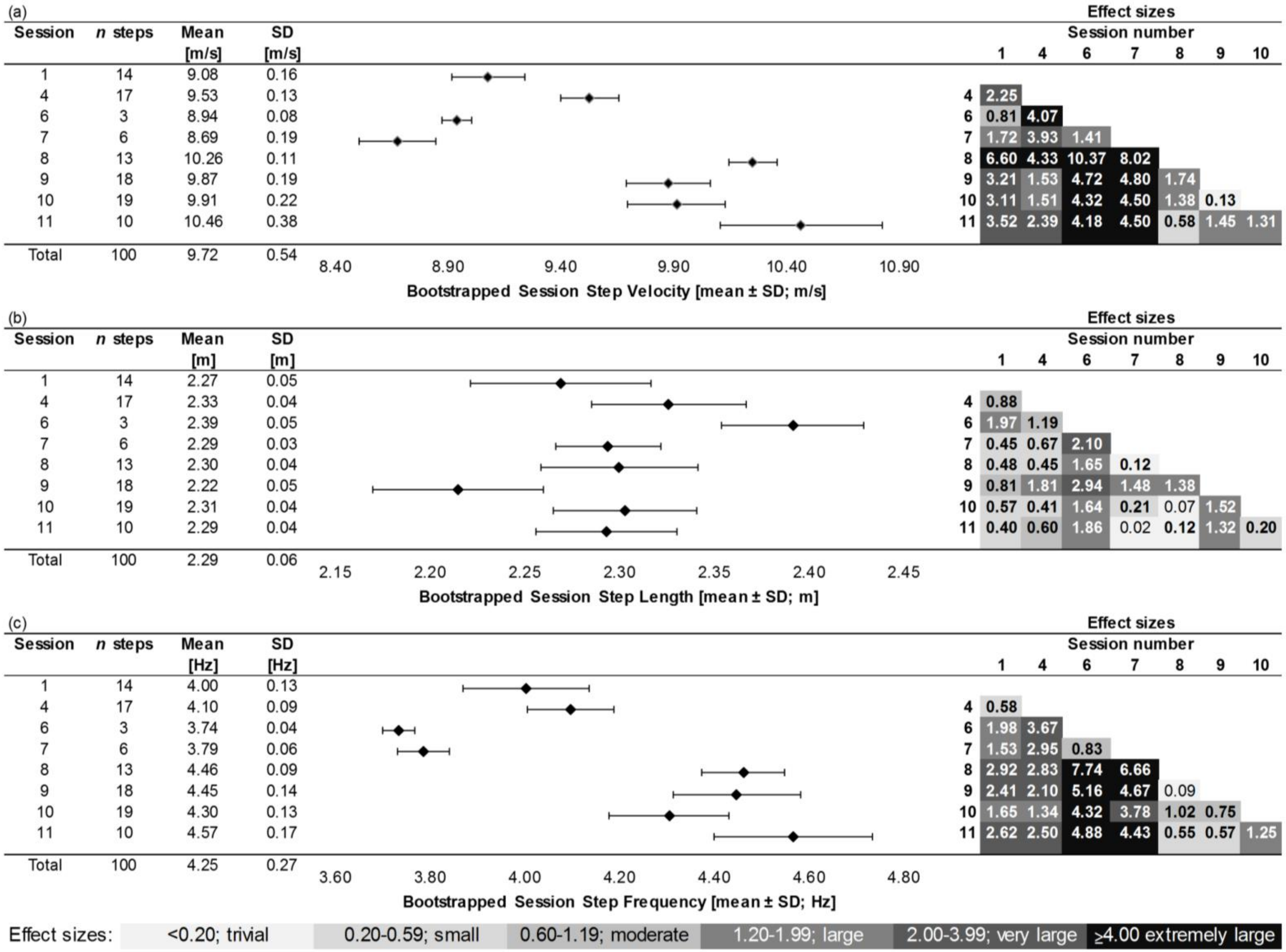
Of the 45 between-session comparisons for A1 for step velocity, 23 were quantified as having at least a large effect (i.e. $d \geq 1.2$).[22] Similarly, 22 of the 45 between session comparisons for step frequency showed at least a large effect, whilst for step length only two of those comparisons showed at least a large effect (Table 3). Furthermore, when comparing the between-session differences for step velocity and step frequency, 20 of those effects that were at least large occurred in the same between session comparison (e.g. S2-S3, *d* for step velocity = 1.65; for step frequency = 1.66). In all 20 of these cases, the direction of change for step velocity and step frequency was the same, i.e. when velocity increased, so did frequency, and when velocity decreased so did frequency (e.g. S2-S3, change in step velocity = -0.31 m/s, change in step frequency = -0.27 Hz).

In the two cases for A1, where the comparisons of step velocity and step length both yielded large effect sizes (S2-S7 and S2-S8), the changes were in the opposite direction, i.e. velocity decreased in both cases from S2 (by -0.88 and -0.45 m/s respectively), but step length increased (by 0.03 and 0.07 m, respectively). The similarities in the magnitude and direction of the between session comparisons between step velocity and step frequency, and their differences to step length are represented visually in the shading of the effect size cells in Figure 1 and summarized for all athletes in Table 3.

The other athletes followed a similar, but not identical pattern, where the sessions with faster mean step velocities tended to correspond to those with the higher step frequencies and with those step lengths close to their individual mean value across the data collection period (Figures 2-4). The between session differences in step length, shown by effect sizes, were consistently the smallest across the three dependent variables. In total, there were 139 between-session comparisons across the four athletes (Table 3). Of those, there were 52 instances where the effect size for the change in both step velocity and step frequency was at least large and both variables changed in the same direction. This was the most common pairing for each athlete. Conversely, there were ten instances of the changes in both step velocity and step length being at least large and the two variables changing in opposite directions (Table 3).

Table 3. Summary of between-session comparisons with an effect size ≥ 1.2 for each athlete and the whole group.

	A1	A2	A3	A4	Total
Total number of between-session comparisons	45	28	45	21	139
Step velocity comparisons with *d* ≥ 1.2	23	25	14	9	71
Step frequency comparisons with *d* ≥ 1.2	22	21	12	5	60
Step length comparisons with *d* ≥ 1.2	2	11	10	0	23
Step velocity and step frequency comparison both with *d* ≥ 1.2, change in variables in same direction	20	20	7	5	52
Step velocity and step frequency comparison both with *d* ≥ 1.2, change in variables in opposite direction	0	0	0	0	0
Step velocity and step length comparison both with *d* ≥ 1.2, change in variables in same direction	0	3	1	0	4
Step velocity and step length comparison both with *d* ≥ 1.2, change in variables in opposite direction	2	6	2	0	10



(a)

Session	*n* steps	Mean [m/s]	SD [m/s]
1	14	9.08	0.16
4	17	9.53	0.13
6	3	8.94	0.08
7	6	8.69	0.19
8	13	10.26	0.11
9	18	9.87	0.19
10	19	9.91	0.22
11	10	10.46	0.38
Total	100	9.72	0.54

Effect sizes Session number	1	4	6	7	8	9	10
4	**2.25**						
6	**0.81**	**4.07**					
7	**1.72**	**3.93**	**1.41**				
8	**6.60**	**4.33**	**10.37**	**8.02**			
9	**3.21**	**1.53**	**4.72**	**4.80**	**1.74**		
10	**3.11**	**1.51**	**4.32**	**4.50**	**1.38**	**0.13**	
11	**3.52**	**2.39**	**4.18**	**4.50**	**0.58**	**1.45**	**1.31**

(b)

Session	*n* steps	Mean [m]	SD [m]
1	14	2.27	0.05
4	17	2.33	0.04
6	3	2.39	0.05
7	6	2.29	0.03
8	13	2.30	0.04
9	18	2.22	0.05
10	19	2.31	0.04
11	10	2.29	0.04
Total	100	2.29	0.06

Effect sizes Session number	1	4	6	7	8	9	10
4	**0.88**						
6	**1.97**	**1.19**					
7	**0.45**	**0.67**	**2.10**				
8	**0.48**	**0.45**	**1.65**	**0.12**			
9	**0.81**	**1.81**	**2.94**	**1.48**	**1.38**		
10	**0.57**	**0.41**	**1.64**	**0.21**	0.07	**1.52**	
11	**0.40**	**0.60**	**1.86**	0.02	**0.12**	**1.32**	**0.20**

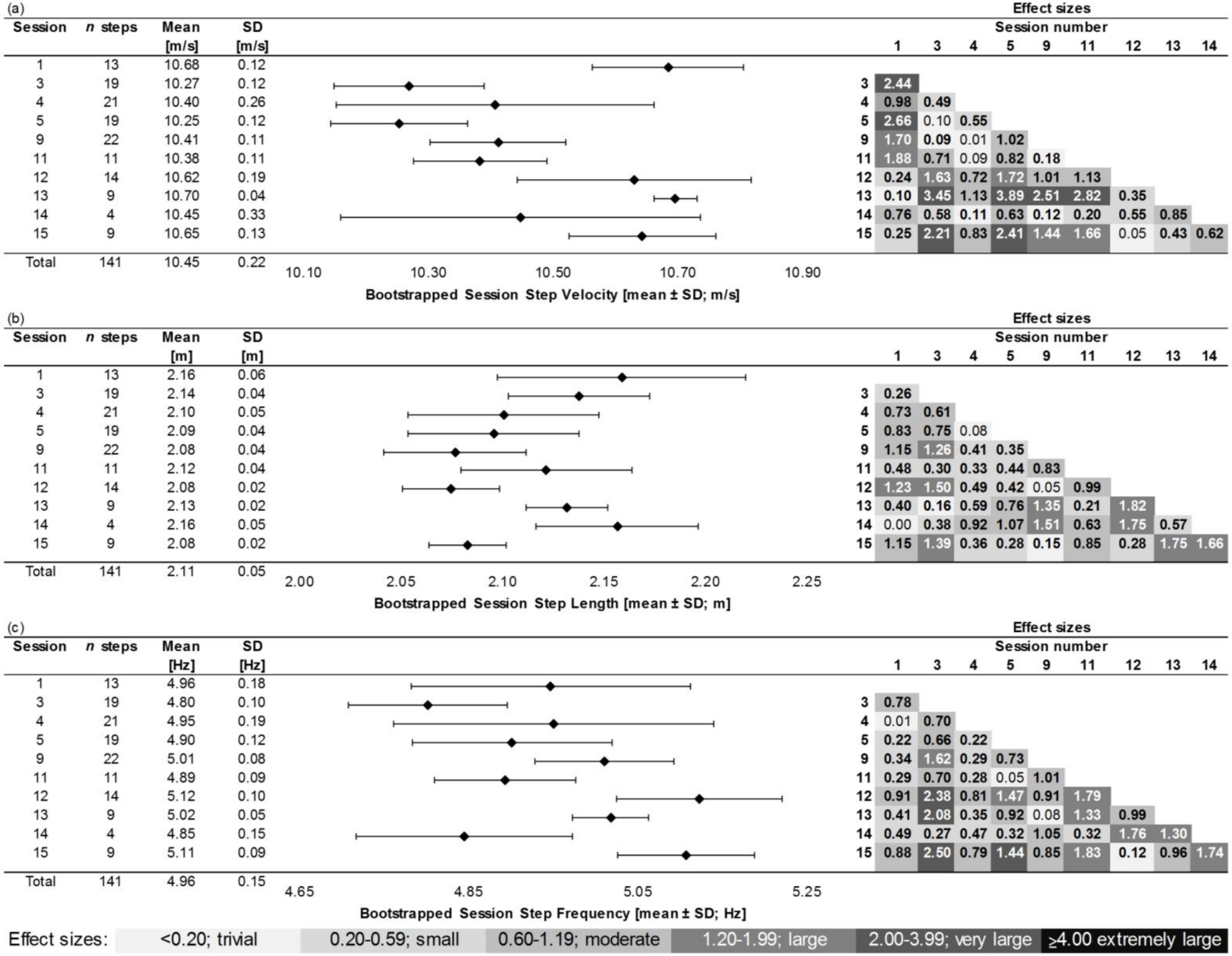
(c)

Session	*n* steps	Mean [Hz]	SD [Hz]
1	14	4.00	0.13
4	17	4.10	0.09
6	3	3.74	0.04
7	6	3.79	0.06
8	13	4.46	0.09
9	18	4.45	0.14
10	19	4.30	0.13
11	10	4.57	0.17
Total	100	4.25	0.27

Effect sizes Session number	1	4	6	7	8	9	10
4	**0.58**						
6	**1.98**	**3.67**					
7	**1.53**	**2.95**	**0.83**				
8	**2.92**	**2.83**	**7.74**	**6.66**			
9	**2.41**	**2.10**	**5.16**	**4.67**	0.09		
10	**1.65**	**1.34**	**4.32**	**3.78**	**1.02**	**0.75**	
11	**2.62**	**2.50**	**4.88**	**4.43**	**0.55**	**0.57**	**1.25**

Effect sizes:	<0.20; trivial	0.20-0.59; small	0.60-1.19; moderate	1.20-1.99; large	2.00-3.99; very large	≥4.00 extremely large

Figure 2. Within-session mean and standard deviation of step velocity (a), step length (b) and step frequency (c) for athlete A2. ***n* steps** is the number of individual steps measured within each session. For comparison, between session effect sizes are shown, with their magnitudes categorized according to Hopkins et al.[22] Statistically significant differences (after Dunn-Sidák correction; P ≤ 0.002) are highlighted in **bold**.



(a)

Session	*n* steps	Mean [m/s]	SD [m/s]	Effect sizes Session number 1	3	4	5	9	11	12	13	14
1	13	10.68	0.12									
3	19	10.27	0.12	**2.44**								
4	21	10.40	0.26	**0.98**	**0.49**							
5	19	10.25	0.12	**2.66**	0.10	**0.55**						
9	22	10.41	0.11	**1.70**	**0.09**	0.01	**1.02**					
11	11	10.38	0.11	**1.88**	**0.71**	0.09	**0.82**	**0.18**				
12	14	10.62	0.19	**0.24**	**1.63**	**0.72**	**1.72**	**1.01**	**1.13**			
13	9	10.70	0.04	**0.10**	**3.45**	**1.13**	**3.89**	**2.51**	**2.82**	**0.35**		
14	4	10.45	0.33	**0.76**	**0.58**	**0.11**	**0.63**	**0.12**	**0.20**	**0.55**	**0.85**	
15	9	10.65	0.13	**0.25**	**2.21**	**0.83**	**2.41**	**1.44**	**1.66**	0.05	**0.43**	**0.62**
Total	141	10.45	0.22									

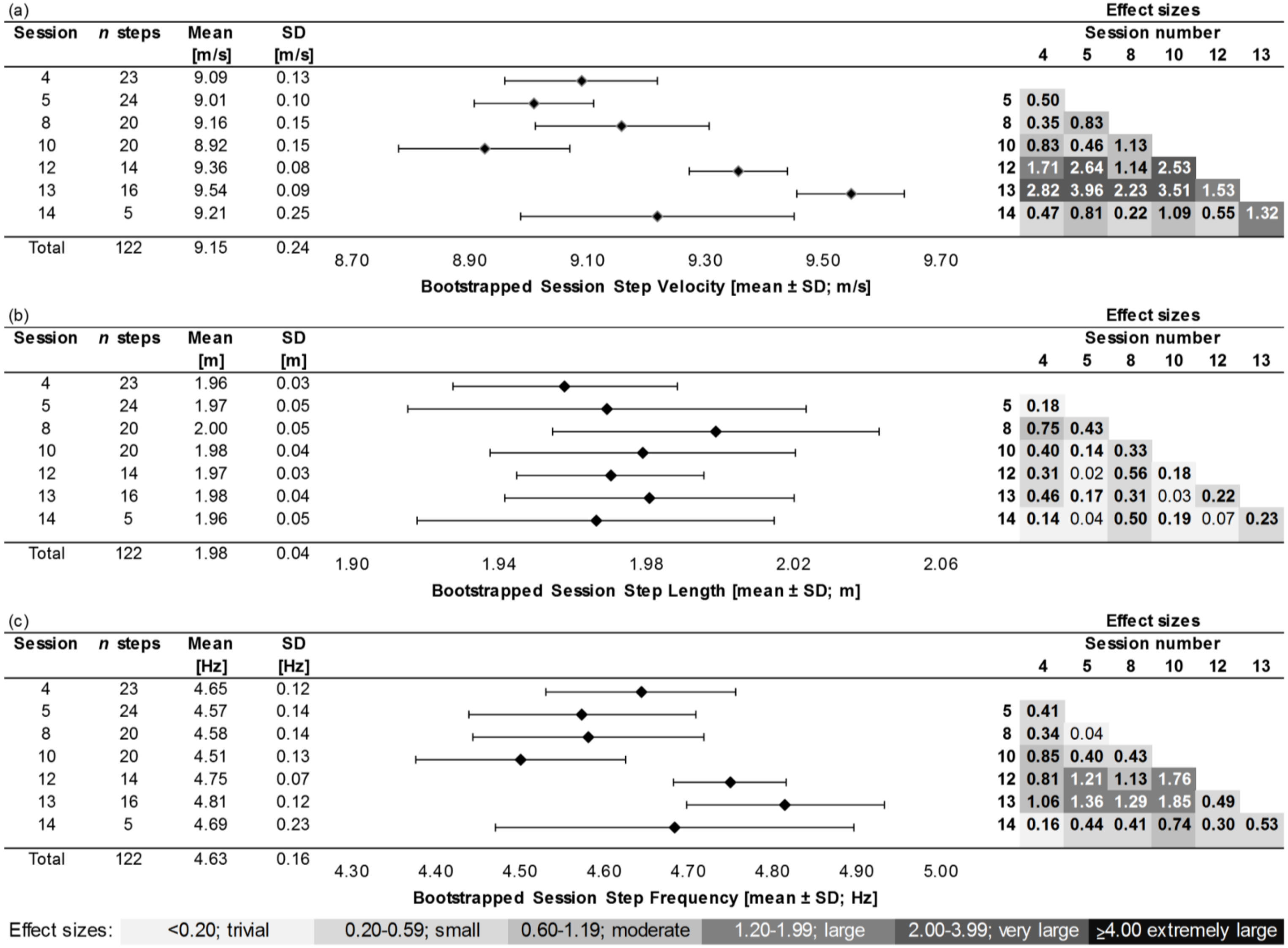
(b)

Session	*n* steps	Mean [m]	SD [m]	Effect sizes Session number 1	3	4	5	9	11	12	13	14
1	13	2.16	0.06									
3	19	2.14	0.04	**0.26**								
4	21	2.10	0.05	**0.73**	**0.61**							
5	19	2.09	0.04	**0.83**	**0.75**	0.08						
9	22	2.08	0.04	**1.15**	**1.26**	**0.41**	**0.35**					
11	11	2.12	0.04	**0.48**	**0.30**	**0.33**	**0.44**	**0.83**				
12	14	2.08	0.02	**1.23**	**1.50**	**0.49**	**0.42**	0.05	**0.99**			
13	9	2.13	0.02	**0.40**	**0.16**	**0.59**	**0.76**	**1.35**	**0.21**	**1.82**		
14	4	2.16	0.05	0.00	**0.38**	**0.92**	**1.07**	**1.51**	**0.63**	**1.75**	**0.57**	
15	9	2.08	0.02	**1.15**	**1.39**	**0.36**	**0.28**	**0.15**	**0.85**	**0.28**	**1.75**	**1.66**
Total	141	2.11	0.05									

(c)

Session	*n* steps	Mean [Hz]	SD [Hz]	Effect sizes Session number 1	3	4	5	9	11	12	13	14
1	13	4.96	0.18									
3	19	4.80	0.10	**0.78**								
4	21	4.95	0.19	0.01	**0.70**							
5	19	4.90	0.12	**0.22**	**0.66**	**0.22**						
9	22	5.01	0.08	**0.34**	**1.62**	**0.29**	**0.73**					
11	11	4.89	0.09	**0.29**	**0.70**	**0.28**	0.05	**1.01**				
12	14	5.12	0.10	**0.91**	**2.38**	**0.81**	**1.47**	**0.91**	**1.79**			
13	9	5.02	0.05	**0.41**	**2.08**	**0.35**	**0.92**	0.08	**1.33**	**0.99**		
14	4	4.85	0.15	**0.49**	**0.27**	**0.47**	**0.32**	**1.05**	**0.32**	**1.76**	**1.30**	
15	9	5.11	0.09	**0.88**	**2.50**	**0.79**	**1.44**	**0.85**	**1.83**	**0.12**	**0.96**	**1.74**
Total	141	4.96	0.15									

Figure 3. Within-session mean and standard deviation of step velocity (a), step length (b) and step frequency (c) for athlete A3. ***n* steps** is the number of individual steps measured within each session. For comparison, between session effect sizes are shown, with their magnitudes categorized according to Hopkins et al.[22] Statistically significant differences (after Dunn-Sidák correction; P ≤ 0.001) are highlighted in **bold**.



(a)

Session	*n* steps	Mean	SD	Effect sizes: Session number 4	5	8	10	12	13
		[m/s]	[m/s]						
4	23	9.09	0.13						
5	24	9.01	0.10	**0.50**					
8	20	9.16	0.15	**0.35**	**0.83**				
10	20	8.92	0.15	**0.83**	**0.46**	**1.13**			
12	14	9.36	0.08	1.71	**2.64**	**1.14**	**2.53**		
13	16	9.54	0.09	**2.82**	**3.96**	**2.23**	**3.51**	1.53	
14	5	9.21	0.25	**0.47**	**0.81**	**0.22**	**1.09**	**0.55**	1.32
Total	122	9.15	0.24						

(b)

Session	*n* steps	Mean	SD	Effect sizes: Session number 4	5	8	10	12	13
		[m]	[m]						
4	23	1.96	0.03						
5	24	1.97	0.05	**0.18**					
8	20	2.00	0.05	**0.75**	**0.43**				
10	20	1.98	0.04	**0.40**	**0.14**	**0.33**			
12	14	1.97	0.03	**0.31**	0.02	**0.56**	**0.18**		
13	16	1.98	0.04	**0.46**	**0.17**	**0.31**	0.03	**0.22**	
14	5	1.96	0.05	**0.14**	0.04	**0.50**	**0.19**	0.07	**0.23**
Total	122	1.98	0.04						

(c)

Session	*n* steps	Mean	SD	Effect sizes: Session number 4	5	8	10	12	13
		[Hz]	[Hz]						
4	23	4.65	0.12						
5	24	4.57	0.14	**0.41**					
8	20	4.58	0.14	**0.34**	0.04				
10	20	4.51	0.13	**0.85**	**0.40**	**0.43**			
12	14	4.75	0.07	**0.81**	1.21	**1.13**	1.76		
13	16	4.81	0.12	**1.06**	1.36	1.29	1.85	**0.49**	
14	5	4.69	0.23	**0.16**	**0.44**	**0.41**	**0.74**	**0.30**	**0.53**
Total	122	4.63	0.16						

Figure 4. Within-session mean and standard deviation of step velocity (a), step length (b) and step frequency (c) for athlete A4. ***n* steps** is the number of individual steps measured within each session. For comparison, between session effect sizes are shown, with their magnitudes categorized according to Hopkins et al.[22] Statistically significant differences (after Dunn-Sidák correction; P ≤ 0.002) are highlighted in **bold**.

DISCUSSION:

The purpose of this study was to investigate the changes in sprint performance and technique over an extended training period in an elite sprint training group. All four athletes showed large and meaningful changes in sprint performance (step velocity) between sessions, which were often synchronous with large and meaningful changes in step frequency. When this was the case, step velocity and step frequency always both decreased (mainly during phases of high volume lifting and running) or both increased (mainly during phases of low volume lifting and high intensity sprint training, see supplementary file). Conversely, on the rarer occasions that there were large and meaningful changes in both step velocity and step length, these changes were more likely to be in the opposite than the same direction. This clearly shows that, for the athletes studied here, when sprinting maximally in a training environment, improvements in velocity were achieved through large and meaningful increases in step frequency, not step length.

The clear association of step frequency with the performance of the athletes in this study does not definitively show that step frequency is more important than step length, as this key finding contradicts some previous research,[4, 5] but supports others.[6, 7] However, the individualized and longitudinal nature of the research design adopted here reveals novel developments to the understanding of sprint biomechanics. Salo et al[9] developed an individualized approach for understanding elite athletes' reliance on step length or frequency for sprint performance. This showed that whilst some sprinters created their best competition performances with a long step length compared to their own average performance, others did so with a high step frequency compared to their own average performances. Interestingly, athlete A1 in this study was found to be step frequency reliant by Salo et al. (A11[9]), confirming the importance of step frequency to that individual in both training and competition. Recently, despite a cross-sectional design that measured one sprint each in 21 sprinters, Nagahara et al.[2] similarly found an individualized response to the relative importance of step length and frequency in the maximum velocity phase.

The longitudinal nature of this study reveals new insights into how the performance and technique outcomes are associated with the periodized training program in elite sprinters. Although the athletes were part of the same training group with the same coach, each had an individualized program designed around their needs and competition schedule. Nonetheless, consistent patterns emerged. Athletes A1 and A3 were in the competition phase of their indoor season at the start of data collections in February, and therefore achieved high step velocities and frequencies at this time. Throughout the spring, velocity and frequency reduced, before reaching a second peak from June onwards. It is interesting to note that some of the step frequencies achieved by A3 (up to 5.28 Hz) were higher than 5.12 Hz[23] and 5.19 Hz[9], which were believed to be the highest previously recorded. Athletes A2 and A4 had finished their indoor seasons before data collection started, so in early- to mid-spring were sprinting with relatively low velocities and frequencies, but by May (A2) and June (A4) had achieved high velocities and frequencies.

For all athletes, it is clear that the fastest session velocities (group mean = 10.43 m/s) and highest session step frequencies (group mean = 4.85 Hz) in this study were achieved during competition phases, when training was focused on low volume, high intensity sprint work with only one lifting session per week. Low velocities and step frequencies coincided with higher volumes of lifting (up to three sessions per week) and higher volumes and lower intensities of sprint work. Interestingly, the lowest values in these variables (9.42 m/s and 4.34 Hz) came towards the end of these training blocks. This corresponded to a 9.7 and 10.5%

drop, respectively, from their highest values. The decreases in step velocity were as expected and are readily explained by the underpinning theories of periodization,[16] which are widely adopted in applied practice. However, the concurrent changes in step frequency and delayed response of both velocity and frequency to training have not previously been demonstrated.

It has previously been suggested[9] that training induced increases in step length are predominantly due to increased force production,[24] but that increases in step frequency may predominantly result from faster force production due to neural adaptations,[25] which may reduce contact time at maximum velocity.[14] However, the mechanisms that underpin this are not well understood. Nonetheless, evidence can be pieced together from numerous studies to provide explanation for the current findings, which are based on multiple training modalities in elite sprinters and have quantified both performance and step characteristics.

A 14-week resistance training program in a group of untrained males increased late rate of force development (>200 ms) but did not change early rate of force development (<100 ms) in a maximal voluntary isometric contraction of the quadriceps.[26] Holtermann et al.[27] found that instructions to “generate force as fast and forcefully as possible” as opposed to “generate maximum force” led to increased rate of force development, but with no change in maximum force in an isometric dorsiflexion task. Elite sprinters contact the ground for less than 100 ms at maximum velocity,[20] and the most effective pattern of vertical force production is to create a large force in a short time to maintain the necessary vertical impulse.[28] Further, a study of a four-week drop-jump training program in national-level sprinters and jumpers[29] found an increase in drop-jump performance with no increase in strength. The performance improvement was attributed to neural factors regulating activation patterns, which could lead to improved rate of force development. Taken together, this evidence suggests that the periodized program adopted in this study allowed the athletes to improve their underlying maximal strength through the lifting undertaken, and then transfer the gains from this overload to their sprint technique through the medium of speed work. Sprinting at maximum effort and velocity implicitly requires the athlete to generate force as fast and forcefully as possible, and would be expected to have a similar plyometric training effect as seen in drop-jump training.[29] More so, speed work has inherently similar kinematics and kinetics to competition sprint performance, meaning the overall training program supplements the overload of the lifting with the specificity of the speed work to enhance sprint performance.

Macaluso and De Vito[30] suggested that the mechanisms underlying the improvement in peak power through training could include increases in cross-sectional area of type II fibers, increases in specific force and shortening velocity of individual muscle fibers, as well as earlier activation and enhanced maximal firing rate of motor units. It is likely that a combination of these neuromuscular factors led to the concurrent increases in step frequency and therefore velocity in the athletes studied here. However, to our knowledge, these factors have yet to be investigated in elite sprinters alongside changes in their performance and technique. Such research would provide new insights into those mechanisms that cause improvements in sprint performance as a result of a periodized training program.

There are three potential explanations for why the four athletes in this study showed a consistent response that highlighted the importance of step frequency. First, all athletes had the same coach, whose methods may have influenced them to become step frequency reliant. It may also be that a step length reliant athlete was simply not included in our small sample. Finally, it is possible that, with data collected through an indoor competition season, basic training, a preparation phase and outdoor competition, any trained athlete would have responded in a similar manner. Indeed, it has previously been speculated that improvements to performance between annual training cycles are more due to increases in step length and that the decisive factor for improvements within annual training cycles is step frequency.[8] There is, however, presently limited evidence to support this claim.

PRACTICAL APPLICATIONS:

Coaches should be aware of the effects of their training programs, not just on performance, but also on the underpinning technique. Sprint training programs should be designed to take account both of these changes and the variable timings with which they occur. Although coaches are generally aware of these changes, it is important to acknowledge the magnitude of the changes and how periodization can acutely affect performance. Here, step frequency was more sensitive to short-term training-induced changes than step length, with reductions due to high-volume lifting and running sessions. It may be critical that this induced reduction is not too large, as otherwise it may take too long for step frequency to recover to achieve the highest possible velocities, and therefore performance.

Limitations of the current study include the relatively small sample of highly-trained sprinters. Given the ranges in velocities recorded within each athlete, it is possible that maximum effort wasn't maintained throughout the study, although athletes were specifically instructed to sprint maximally by the coach at each session. Additionally, data gathered here were limited to kinematics and training plan information. Follow-up investigations should seek to perform experimental studies of training with elite athletes, although this can be challenging in a high-performance environment.[12, 13] Furthermore, investigations into the neuromuscular mechanisms[30] thought to underpin the delayed response to periodized training are necessary to fully explain why the changes observed here occur. This would facilitate further developments to training program design to target the factors that lead to performance improvements.

CONCLUSION:

The importance of step frequency over step length to the development of performance within a training year was clearly evident for the sprinters studied here. This is the first study of its kind to adopt such a longitudinal approach to the biomechanical monitoring of sprint performance, and therefore revealed previously undocumented responses of elite athletes to training. Across all four athletes both step velocity and frequency responded to training in a delayed, but cyclical manner.

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Supplemental Information

Overview of training plan for A1:

Training from 30th January to 5th March (includes sessions S1 & S2):

This was indoor competition season training, which generally included one lifting session and short circuit training and three sprint sessions with low volumes but high intensity. Sprint sessions were explicitly 'speed' sessions: either starts up to 30 m, or acceleration runs, or maximum effort 60 m runs. If there was a competition within a given week, that would replace one of the sprint training sessions. Four different types of circuit training were utilised throughout, two to three times a week (two circuits in each session). The main emphasis of these circuits were abdominal and upper body work. Only one of the circuits targeted the legs (hip flexors) and this was used sparingly during the competition season. This block culminated with the Continental Indoor Championships.

6th March to 19th March (no sessions included):

Training for the two weeks after the Championships was easy and light just to maintain some activity.

20th March to 16th April (S3 to S6):

This block went back to basic training. Lifting generally happened three times per week. Two lifting sessions were high volume lifting: four exercises with 3x6x75% 1RM with long circuit training at the end. One lifting session was a pyramid session geared towards to increasing maximum strength (with circuit training at the end). The circuit training sessions lasted three times longer than in the above indoor competition season. In addition to abdominal and upper body circuits, the general cardio-vascular and hip-flexor circuits had a more prominent presence during this period. Also, the athlete undertook three running sessions per week with emphasis on endurance for sprinting (interval-type training) in one session, full speed training in one session (three point starts and acceleration) and one speed endurance session.

17th April to 7th May (S7 & S8):

This period was starting to prepare for the outdoor competition season. There was still a reasonable volume of training, but training moved more towards maximum weights and specific high intensity sprinting. There were still three lifting sessions per week: the pyramid session getting towards maximum weights, also testing for 1RM. Two of the four circuit training programmes (see above) were done after each lifting session. Also, there were three running sessions per week: one endurance for sprinters (interval-type training), one specific 100 m speed endurance session, and the third session included starts from blocks and maximum velocity sprints with an emphasis on keeping ‘turnover’ high through a 30 m section.

8th May to 4th June (S11):

This was the specific competition preparation block. There was one lifting session if the week had a competition, and two lifting sessions if it did not have a competition (plus short circuit training – see the first block above). This was the only period when specific plyometric training was carried out, by mixing rebound jumps (straight legs with ankle plantarflexion). There were three running sessions per week: one specifically focussing on acceleration, one including block starts to 30 m and separate flying 30 m maximal sprints with the third session including speed and speed endurance runs.

5th June onwards (S13):

This was competition season initially focussing on preparing for the National Championships in early July. Training included one lifting session plus short circuit training per week (see above). There were three sprint sessions per week: one specific 100 m speed endurance, one easy session (i.e. only a few brief runs, but at high intensity), and one full speed session with starts and flying 30 m maximal sprints. Often there was either a competition or an extra speed or speed endurance running session on the weekend.