ELITE SPRINTING:

ARE ATHLETES INDIVIDUALLY STEP FREQUENCY OR STEP LENGTH RELIANT?

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ABSTRACT:

Purpose: The aim of this study was to investigate the step characteristics amongst the very best 100 m sprinters in the world in order to understand whether the elite athletes are individually more reliant on step frequency (SF) or step length (SL). **Methods:** A total of 52 male elite level 100 m races were recorded from publicly available television broadcasts with 11 analysed athletes performing in 10 or more races. For each run of each athlete, the average SF and SL over the whole 100 m distance was analysed. To determine any SF or SL reliance for an individual athlete, the 90% confidence interval (CI) for the difference between the SF: time vs. SL: time relationships was derived using a criterion nonparametric bootstrapping technique. **Results:** Athletes performed these races with various combinations of SF and SL reliance. Athlete A10 yielded the highest positive 90% CI difference (SL reliance) with a value of 1.05 (CI range 0.50 to 1.53). The largest negative difference (SF reliance) occurred for athlete A11 as -0.60 with the CI range of -1.20 to 0.03. **Conclusion:** Previous studies have generally identified only one of these variables to be the main reason for faster running velocities. However, this study showed that there is a large variation of performance patterns amongst the elite athletes, and overall, SF or SL reliance is a highly individual occurrence. It is proposed that athletes should take this reliance into account in their training with SF reliant athletes needing to keep their neural system ready for fast leg turnover and SL reliant athletes requiring more concentration on maintaining strength levels.

KEYWORDS: Athletics, Biomechanics, Coaching, Individual analysis, Single subject, Sprint running

INTRODUCTION:

Paragraph Number 1 An athlete's running velocity is the product of step frequency (SF) and step length (SL) – a step being from one-foot contact to the next contact of the contra-lateral foot. The term stride is also used in the literature which is equal to two consecutive steps. Whilst the equation of velocity equals SF multiplied by SL is very straightforward and simple in theory, athletes face problems in practice, as the relationship between SF and SL is generally an inverse relationship at maximum effort. Thus, an increase in one parameter could typically lead to a decrease in the other. This is due to the negative interaction apparent in the production of these variables (11). Consequently, this relationship has attracted attention in the biomechanics literature.

Paragraph Number 2 Luhtanen and Komi (16) were amongst the first to comprehensively analyse the relationship between SF and SL and presented the development of SF and SL in track athletes when running velocity was increased from jogging at 3.9 $m \cdot s^{-1}$ to sprinting at 9.3 $m \cdot s^{-1}$. However, this study is not directly relevant to elite sprint athletes who always need to run at very high individual velocities in competition. In a study of 28 sprint-related sportsmen (background e.g., in athletics, soccer, touch rugby, etc.), Hunter et al. (11) found that at the group level SL was significantly related to running velocity while SF was not. However, at the individual level the subjects performed with a significantly higher SF in their fastest trial in comparison to their third fastest trial. Step length did not reveal significant differences in the individual analysis (11). The authors offered a potential explanation for these differences between individual and group analysis by stating that SF may be the more important factor in the short term while longer steps may require the development of strength and power over a longer period of time. Hunter et al. (11) also offered further detailed explanations of the technique issues which were behind the aforementioned negative interaction between SL and SF. The sprinting velocities, however, ranged from 7.44 m·s^{-1} to 8.80 m·s^{-1} (11) and were measured only 16 m into the sprint. Thus, while the paper provides general information about step characteristics and can be helpful to developing athletes, it is not fully applicable to elite sprinters, whose running velocities are much higher.

Paragraph Number 3 To fully explore how elite athletes could fine tune their performances, it would be necessary to understand how they perform in competition. Mann and Herman (17) analysed the first, second and eighth placed finishers in the 1984 Olympic men's 200 m final and highlighted the fact that the major difference between the three athletes (especially those in first and second) was SF. Interestingly, all three athletes increased velocity, SF and SL between the non-fatigued (125 m mark) and fatigued (180 m mark) phases of the sprint.

Paragraph Number 4 Ae et al. (1) analysed the final of the men's 100 m from the 1991 World Championships in Athletics. One of the key points highlighted by Ae et al. (1) in their conclusions was that the gold medallist generally exhibited a shorter SL and higher SF than the silver medallist, although this was not consistent throughout the whole race. A similar type of analysis over each 10 metres was performed by Gajer et al. (8) from the semi-finals and final of the men's 100 m at the 1996 French Championships. The six fastest (10.18 ± 0.05 s) and six slowest athletes (10.52 ± 0.08 s) were divided into separate groups. Step length was consistently higher in the faster group, and significantly higher in seven out of 10 sections. On the other hand, SF was higher in the slower group in all but the last 10 m section, although it was significantly higher only in one section out of 10. The authors (8) drew the conclusion from their results that SL was the more important factor at the highest level. Recent competition analysis from the World Championships in Helsinki 2005 (13) provided a similar trend to that of Gajer et al. (8). Eighteen male sprinters from the 100 m heats were divided into faster and slower groups (nine athletes in each group; high performance group 10.12-10.32 s, lower performance group 10.40-10.90 s). In the full stride phase (around 60 m) the longest SL was significantly longer ($p<0.003$) by 0.12 ± 0.03 m for the faster group than slower group, while there were no significant differences in SF.

Paragraph Number 5 Gajer et al. (8) also re-analysed the data of Ae et al. (1) by splitting the eight finalists into two groups: the first to fourth and fifth to eighth placed finishers. The four fastest athletes had a higher average SL in nine of the 10 intervals, whilst the four slowest athletes had a higher average SF in seven of the intervals. This was presented by Gajer et al. (8) as further evidence to support their own conclusions. Thus, at the group level the finding was opposite to the conclusion of Ae et al. (1) regarding the first and second place finishers. It seems, though, that the results are very dependent on the grouping. The grouping used by Gajer et al. (8) for the data from Ae et al. (1) meant that the groups were equal in number, each containing four athletes. When the finishing times for the eight athletes were examined, a different method of grouping could be justified. The first six finishers all completed the race in times in a close range of 9.86 – 9.96 s. The last two finishers were considerably slower, finishing with times of 10.12 and 10.14 s. New calculations reveal the opposite trend to that presented by Gajer et al. (8). With the modified groupings based on the absolute level of performance, the six fastest athletes recorded a higher SF in nine of the 10 intervals, whilst the slowest two athletes had a higher SL in seven of the intervals. This change occurred because the fifth and sixth placed athletes typically displayed short SL and high SF values when compared to the other six athletes. This example shows that an average, group based analysis can actually mask important issues at the individual level. Due to this problem, Dixon and Kerwin (6) called for a multiple-single subject approach in studies where important individual differences may be present that are not visible in general trends of a group analysis. This might be even more important for individual elite athletes, as any improvement in their performance may give them an advantage over the competitors. Thus, when elite sprinters try to improve their performance by seeking to cut hundredths of a second from their race time, it is very important to understand the individual performance and step characteristics issues rather than analyse them at the group level. Recently in track and field biomechanics, there have been single subject analyses published in sprinting (3) and sprint hurdling (22).

Paragraph Number 6 It is clear from the results presented on elite athletes in a competition situation that there is no consensus of opinion over which factor, SF or SL, is the more important at this level of competition. These are important findings, nonetheless, since they give a good insight into the performance of the very best athletes in a competitive situation, something that a laboratory or training based study is not capable of doing. There is, however, a lack of consideration for the possibility that individual athletes may adopt differing strategies from one another, with regard to optimising SF and SL. Further insight could be realised, if the same elite athletes were analysed over several runs. Such analysis is clearly missing from the current biomechanics literature. Thus, the aim of this study was to investigate the step characteristics amongst the very best 100 m sprinters in the world in order to understand whether the elite athletes are individually more reliant on SF or SL.

METHODS:

Paragraph Number 7 A total of 52 male elite level 100 m races were recorded from publicly available television broadcasts. The competitions included several Olympic, World and European Championships, International Association of Athletics Federations (IAAF) Grand Prix series competitions, European Cups and some national Championships. The summary of competitions is in table 1. Data were collected from semi-finals and finals of the major championships and heats and finals of individual Grand Prix series competitions. Official race times were recorded from the IAAF website (12). A similar approach of analysing publicly available data from sport competitions for research purposes has been carried out by Stewart and Hopkins (23), who analysed consistency of performance between swimming strokes, race distances and two competitions across 221 swimmers. In the current study athletes' individual races were analysed if the athlete ran fully through the finish line. Thus, individual races in which an athlete clearly eased off before the finish line (e.g. in some heats or semi-finals), sustained an injury, or in any way was deemed not to perform normally, were disregarded from the analysis. Consequently, the worst individual race time analysed was 10.39 s. It is clear that not every analysed athlete was involved in each competition. All athletes who performed in 10 or more races were taken for this analysis yielding in total of 11 athletes. The number of races per athlete is listed in table 2. Nine of these 11 athletes ran under 10.00 s at least once in these competitions.

Table 1. Summary of analysed competitions

	Final	Semi-final*
Olympic Games	1	2
World , European Championships and Commonwealth Games	5	7
IAAF Golden League	10	2
IAAF Grand Prix	11	7
European Cup	2	
National Championships	2	3

* Semi-final column contains Golden League and Grand Prix heats, as these competitions do not have separate semi-finals.

Table 2. Number of races with the mean official race time (and SD) for each individual athlete in those races.

Athlete	Number of races	Mean time [s]	SD [s]
A1	21	10.02	0.12
A2	27	10.08	0.09
A3	23	10.05	0.12
A4	20	10.12	0.12
A5	15	10.17	0.10
A6	15	10.12	0.13
A7	17	10.08	0.08
A8	16	10.16	0.08
A9	10	10.12	0.06
A10	14	10.17	0.12
A11	11	10.18	0.14
Mean	17	10.12	

Paragraph Number 8 For each run of each athlete, the average SL and SF over the whole 100 m distance were analysed as follows. The total number of steps taken in the race by each of the athletes of interest was counted by viewing the race in slow motion on a normal television and using a video player (Panasonic AG-7550, Japan), which yielded 50 video fields per second. Since the athlete did not necessarily complete a step exactly at 100 m, the displacement of the last step (S_{LS}) was defined. This was the overall displacement from the start line to the toe of the ground foot in the step closest to the finish line (either side). The displacement estimation was based on using the track markings, the length of the foot (approximately 0.3 m) and expected values for SL. Since the first step out from the starting blocks does not cover as much ground as all subsequent steps and it clearly takes the longest time, this step was disregarded from the calculations. In order to do that, a pilot test was set up. Four national level athletes (who provided informed consent) were videotaped with a high speed video camera (Motionscope 500C, Redlake Imaging Corporation, USA) at 250 Hz in order to estimate the length of the first step both as a distance and time (from the start signal to the instance of the first contact). Based on these four athletes' performances over 16 runs (4 each), a distance of 0.55 m and a time of 0.52 s was subtracted from the calculations. Average SL throughout the race was therefore calculated as follows:

$$\overline{SL} = (S_{LS} - 0.55\text{m})/(n_S - 1)$$

Paragraph Number 9 Where $\overline{SL}$ is average step length, S_{LS} is displacement of the last step, and n_S is number of full steps. The total number of steps that were taken over the exact 100 m (n_{S100}) was then calculated as follows (this provides the last step as a fraction):

$$n_{S100} = n_S + \left[(100\text{m} - S_{LS})/\overline{SL}\right]$$

Paragraph Number 10 From this, the average SF for the race was calculated as

$$\overline{SF} = (n_{S100} - 1)/(t_r - 0.52\text{s})$$

Paragraph Number 11 Where $\overline{SF}$ is the average step frequency and t_r is the official race time.

Statistical analysis:

Paragraph Number 12 All athletes were analysed individually. Step frequency, SL and race time data were natural log-transformed prior to analysis to normalise distributions and stabilise variance. To determine any SF or SL reliance for an individual athlete, the 90% confidence interval (CI) for the difference between the SF: time vs. SL: time relationships was derived using a criterion nonparametric bootstrapping technique (7) (Resampling Stats 4.0.7, Resampling Stats Inc., Arlington, Virginia). Briefly, for each set of *n* races for each individual athlete, 10,000 resamples with replacement (of *n* cases) of the race time, SF and SL variables were taken (maintaining case correspondence). On each bootstrap resample the SF: time and SL: time correlations (Pearson's *r*) were derived and the difference between these correlations calculated and stored (SF minus SL). The 90% CI (10) for the difference between the SF and SL correlations was obtained using a simple percentile method, from the 5^{th} and 95^{th} percentiles of the distribution of 10,000 differences. The threshold for a practically important difference between SF and SL correlations (in either direction) was set at a value of 0.1 – a 'small' effect size for the correlation coefficient (4). An athlete was declared SF reliant if the lower limit of the 90% CI was at or beyond the threshold of -0.1, with the upper limit $< +0.1$ (precluding SL reliance). Conversely, an athlete was declared SL reliant if the frequency-length correlation difference was positive (favouring length), with the 90% CI precluding frequency reliance (≤ -0.1). An effect was deemed 'unclear' if the 90% CI simultaneously extended into regions suggesting both SF and SL reliance; the athlete could be SF reliant, could be SL reliant, or there could be a trivial difference favouring neither step characteristic. Additionally, in order to investigate whether the elite athletes were more reliant on SF or SL, or whether height influenced this reliance, three further Pearson correlations were carried out: the point difference between the SF: time vs. SL: time correlation values from above was further correlated with the individual mean race times as well as with the athletes' personal best times (PB) and heights, which both were obtained from the athletes' biographical information on the IAAF web pages (12). These data were not natural log-transformed as the point difference yielded negative values which cannot be log-transformed. The 90% CIs were calculated and the threshold for a practically important difference was set at 0.1 as above.

RESULTS:

Paragraph Number 13 Table 3 provides the correlation coefficients for each athlete between the independent variables and the race time. The correlation values between SF and race time varied between 0.16 and -0.79. Contrary to SF, all athletes yielded negative correlation between SL and race time. The range of correlation values for SL varied from -0.16 to -0.89.

Table 3. Correlation values for natural log-transformed SF and SL vs. time.

Athlete	SF vs. time correlation	SL vs. time correlation
A1	-0.27	-0.38
A2	-0.57	-0.16
A3	-0.54	-0.31
A4	-0.39	-0.36
A5	0.11	-0.69
A6	-0.61	-0.65
A7	-0.12	-0.49
A8	-0.37	-0.58
A9	0.07	-0.80
A10	0.16	-0.89
A11	-0.79	-0.19

Paragraph Number 14 Figure 1 provides the difference between correlations for SF: time and SL: time, together with its 90% CI. Athlete A10 yielded the highest positive difference with a value of 1.05 (with the CI range from 0.50 to 1.53). The largest negative difference occurred for athlete A11 as -0.60 with the CI range of -1.20 to 0.03. The area of ±0.1 to indicate the smallest practically worthwhile difference between correlations is also shown in the Figure 1.

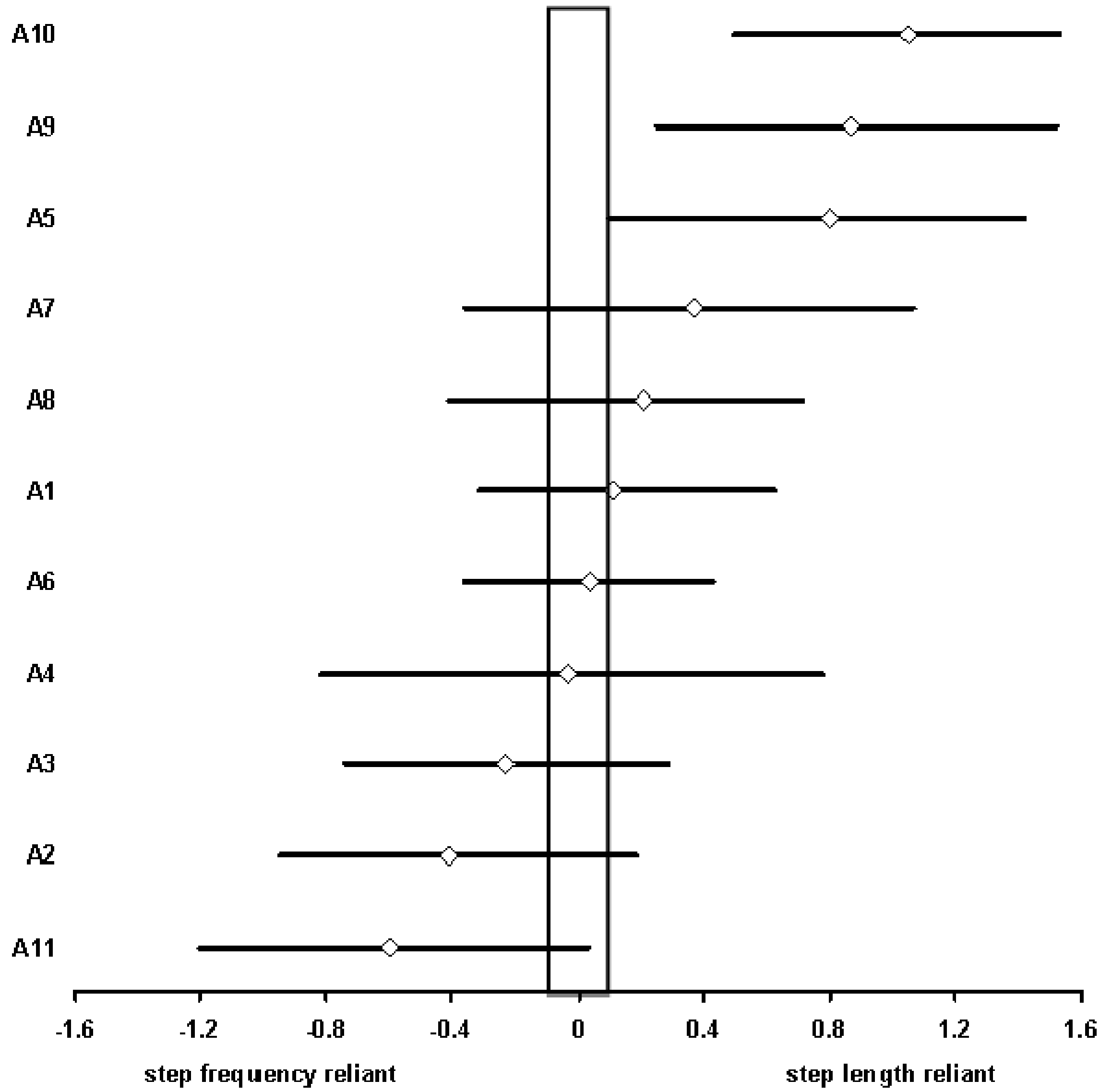

Figure 1. r-difference (diamonds) with 90% CI (bars) for each athlete A1 to A11. The area of ±0.1 from zero in the middle demonstrates the trivial (non-reliant) effect.

Paragraph Number 15 Due to the large variation shown in r-difference values, three athletes' data are specifically shown in Figure 2 to illustrate athletes' times as a function of SL and SF. Based on data in Figure 1, Athlete A10 (Figure 2 a-b) had the largest SL reliance, Athlete A4 (figure 2 c-d) did not yield any reliance either on SF or SL, and Athlete A11 (figure 2 e-f) was the only athlete who was clearly SF reliant. The minimum, maximum and mean of average SL and SF values for each athlete are presented in table 4 showing that the lowest range for the average SL was 0.06 m, whilst the largest range was 0.14 m. The respective values for the average SF range were 0.07 and 0.30 Hz.

Table 4. Minimum (Min), Maximum (Max) and Mean of average step length and step frequency values for each individual athlete.

	Step Length [m]			Step Frequency [Hz]		
Athlete	Min	Max	Mean	Min	Max	Mean
A1	2.14	2.27	2.20	4.62	4.91	4.75
A2	2.18	2.28	2.23	4.50	4.77	4.66
A3	2.01	2.11	2.07	4.91	5.19	5.05
A4	2.07	2.21	2.14	4.64	4.94	4.83
A5	2.12	2.23	2.17	4.66	4.82	4.74
A6	2.20	2.28	2.24	4.54	4.73	4.63
A7	2.13	2.24	2.18	4.67	4.86	4.76
A8	2.28	2.34	2.30	4.43	4.54	4.47
A9	2.28	2.34	2.31	4.44	4.51	4.48
A10	2.13	2.24	2.19	4.65	4.76	4.71
A11	2.14	2.22	2.18	4.62	4.84	4.73
Mean	2.15	2.25	2.20	4.61	4.81	4.71

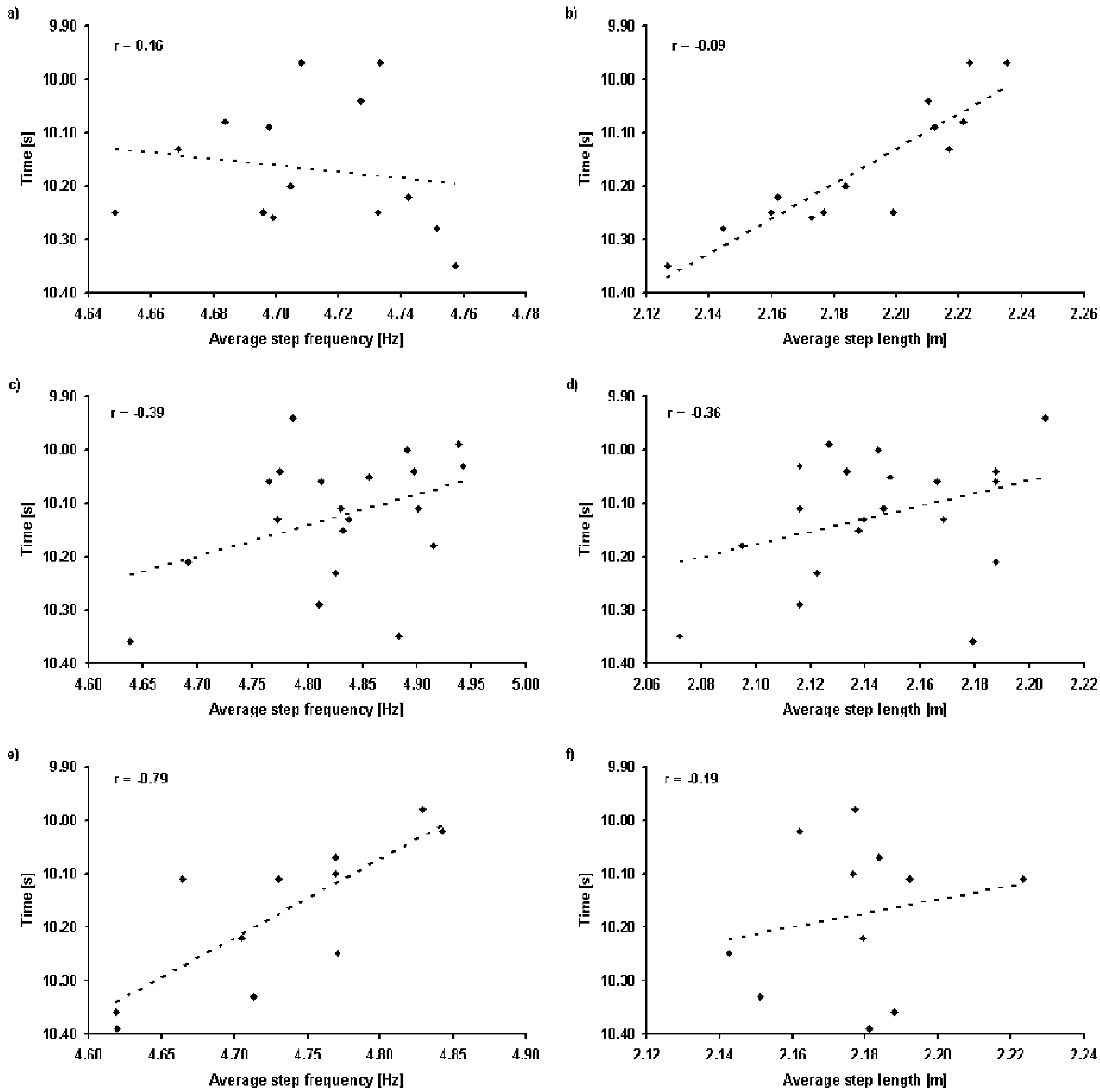

Figure 2. Three athletes race times as a function of SF and SL: Athlete A10 (a &b) showed step length reliance, Athlete A4 (c & d) did not yield either reliance, and Athlete A11 (e & f) was step frequency reliant. Please note that y-axes have been inverted as quicker times demonstrate improved performance. Points on the figures with trend lines are from the original data; r-values are from the log-transformed data (table 3). Due to inverted y-axes the signs of r-values do not match the visual impression.

Paragraph Number 16 The SF-SL reliance (as correlation difference) did not show a meaningful relationship with athletes' mean race time (CI for *r*, -0.27 to 0.71), the personal best times (-0.63 to 0.40) or with height of the athletes (-0.13 to 0.77).

DISCUSSION:

Paragraph Number 17 This study was designed to increase our understanding of the SF and SL characteristics of elite athletes in major competitions. The main results showed that these characteristics vary considerably between the athletes. Previous studies have generally identified only one of these variables to be the main reason for faster running velocities, and the results have given a somewhat confusing picture. Kuitunen et al. (15) showed that SF was the dominant factor when running velocity increased from 70 to 100%. Higher SF seemed also be the major difference between three Olympic 200 m finalists (17). On the other hand, Gajer et al. (8) found that better 100 m sprinters in their study had longer SL than slower athletes, and Hunter et al. (11) showed that the SL was significantly related to running velocity at the group level (whilst SF was not). The results of Hunter et al. (11), though, showed that within individuals SF was higher in the fastest trials. None of these studies, however, have looked at elite athletes across different races to determine how an individual athlete performs. From an elite athlete point of view, the group level data does not provide appropriate information to improve individual performance. For example, by executing an average performance of 100 m Olympic finalists the athlete would not win the race. In fact, often if an athlete were to achieve the average performance of all the finalists that would not be sufficient to even place that athlete on the podium. Thus, it is important to look at each elite athlete individually. To the best of our knowledge, this is the first study which has looked at step characteristics of elite athletes individually and longitudinally across multiple competitive races. In addition, a novel aspect of the current study is the use of a criterion bootstrapping method, together with a criterion for practical significance, to elucidate the within-athlete differences between SF and SL.

Paragraph Number 18 Average SF multiplied by average SL provides the average running velocity, which in turn has an inverse relationship with the race time. This means that both SF and SL are inversely linked with the race time and strongly related to each other. This collinearity between SF and SL makes it impossible to properly separate the independent influence of these predictors on race time, if both are entered together as predictors in a multiple regression model. Therefore, a novel approach was sought to understand any reliance on particular step characteristics by athletes. Consequently, it was decided that the most appropriate approach was to adopt a bootstrapping technique to calculate the 90% CI for the difference between SF: time vs. SL: time correlations to inform how practically meaningful this effect was. The interpretation of the results in Figure 1 follows the recommendations by Batterham and Hopkins (2). The effect is considered reliant if the 90% CI is fully on either the SF or SL side or if one end reaches only to the area of a trivial effect in the middle. If the CI extends to include both frequency and length reliance, then the effect is considered unclear.

Paragraph Number 19 Overall, the results in Figure 1 revealed that there is a large variation of performance patterns amongst the elite athletes. There were clearly athletes at the highest elite level of 100 m sprinting who were SL reliant (Athletes A10, A9 and A5) while only athlete A11 was clearly SF reliant. All other athletes did not have clear reliance on either side, although there were trends implying that, for example, athlete A7 was most likely to be SL reliant and athlete A2 SF reliant. When looking at the results in further detail, Athlete A10 yielded a 90% CI (0.50 to 1.53) which did not even cross over the ±0.1 trivial effect region (Figure 1). Thus, athlete A10 performed best when he was able to produce long steps (within his own range) (Figure 2b). Such reliance of SL meant that if the athlete was not able to produce long steps, he could not compensate the performance enough with high SF to produce fast 100 m times. On the contrary, Athlete A11 performed his best times when he was capable of producing high step frequencies (within his own range) (Figure 2e). The 90% CI (-1.20 to 0.03) crosses over into the trivial effect region from the SF reliance, but does not reach to a SL reliant effect (Figure 1). This meant that if the athlete could not produce high step frequencies (for example, if the nervous system was not ready to fire quickly enough to have a fast turnover of the steps), the SLs had not compensated the running velocity enough. The athletes whose 90% CI reached over all three different zones in Figure 1 were such that they produced best times sometimes with slightly higher SL (and lower SF) and sometimes with slightly higher SF (and lower SL) (see an example of Athlete A4 in Figure 2c-d).

Paragraph number 20 When looking at the individual SL and SF values within athletes and across the races, the three examples in Figure 2 provided a very similar range of values. Step length range was 0.08 m for A11, 0.11 m for A10 and 0.13 m for A4. The respective SF ranges were 0.22 Hz, 0.11 Hz and 0.30 Hz. The Athlete A4 had the largest range in both SL and SF from all athletes (Table 4). As the range of values on SF and SL were quite similar for all athletes, it reinforced that SF or SL reliance occurred within the normal range of that variable in individual athletes, and it was not due to some clear outliers in occasional runs.

Paragraph Number 21 The average within-athlete SF in this study ranged from 4.43 Hz to 5.19 Hz, whilst the average SL ranged from 2.01 m to 2.34 m (Table 4). It is clear that the average SLs over the full 100 m in this study were less than those found in the maximum velocity phase in the literature, as data in the current study contains also steps at the start of the run, which are shorter than later in the run. Ae et al. (1) reported SLs from 2.29 m up to 2.71 m for the World Championships' finalists in the maximum velocity phase. Step length values reported by Gajer et al. (8) fell within the range provided by Ae et al. (1). Step frequency values in the current study match more closely to those at maximum velocity, as step frequency does not alter largely during the race. This is due to the fact that when early contact phases are generally longer, the flight phases are shorter. This ratio gradually changes - however, the total step time (and thus frequency) does not drastically change, as visible in the data of the first four steps out of the blocks in a study by Salo et al. (21). Step frequencies in the maximum velocity phase provided by Ae et al. (1) and Gajer et al. (8) generally matched the range seen in the current study.

Paragraph Number 22 At the group level SF-SL reliance did not yield meaningful relationships with athletes' mean race times (CI for *r*, -0.27 to 0.71) nor the personal best times (-0.63 to 0.40). This means that, for example, SL reliant athletes were not any faster than SF reliant athletes. Thus, it is possible to reach the absolute top level of sprinting in the world (run under 10.00 s) with widely varying pattern of SF and SL reliance. The results also showed an unclear (trivial) effect (i.e. there was no relationship) between the height of athletes and SF-SL reliance (CI for *r*, -0.13 to 0.77). This means that taller athletes within this group were not SL reliant (against the general perception), nor were shorter athletes SF reliant, and vice versa. Overall, these three results support the idea that either SF or SL reliance is a highly individual occurrence.

Paragraph Number 23 The wind has been shown to influence the finishing time in sprinting. For example, the theoretical calculation by Ward-Smith (24) showed that a 2 $m \cdot s^{-1}$ following wind improves a 100 m result at the elite level (10.00 s runner) by 0.10 s, while the same head wind would slow the runner down by 0.13 s. However, the situation in the current study was different to that of an individual race as data were collected over a long period of time and across numerous races. It is clear that athletes train and target some major competitions and thus they potentially run faster in these races regardless of the wind speed in comparison to races perhaps earlier in a season. There were no clear trends that the faster times were set with better wind conditions. Additionally, regardless of the wind, the race time was performed with that specific SF and SL combination found in the analysis, and it is this specific SF - SL pattern (reliance), which is the interest in the current study.

Paragraph Number 24 As the SF or SL reliance varied considerably between the athletes, it is proposed here that this should be taken into account in their training, especially in the preparations for the most important competitions. The effect of different types of training on athletes' performance is difficult to prove due to two factors: firstly, there is an inherent problem in getting elite athletes to participate in training studies (14), and secondly, it is practically impossible to isolate the training influence of one specific type of exercise or mode of exercise. However, some indirect conclusions can be drawn from the literature and theory of specificity in training.

Paragraph Number 25 Based on animal research, Heglund and Taylor (9) concluded that the increased stride length in various animals primarily required higher average muscle force production pointing towards the association between muscle strength and stride (step) length. Studying humans' sprinting performance, Weyand et al. (25) concluded that the faster running speeds were achieved by greater vertical ground reaction forces rather than more rapid leg movements. The higher average force production during the contact (i.e. strength) resulted in considerably higher stride lengths. The regression analysis showed that 1.8-fold increase in top running speed was achieved with 1.69 times longer strides (and with an average vertical force production which was 0.5 times body weight larger). It is acknowledged that in the same study, higher stride frequency was also associated with increased force production. This was due to the fact that higher vertical force production allowed athletes to produce the required impulse in shorter contact time. However, the regression analysis showed only a 1.16 times increase in stride frequency across the same range of top speeds as above. On the other hand, Mero and Komi (18) found that only well trained athletes (as opposed to less trained athletes) were able to increase SF when towed to supra-maximal velocities. Ross et al. (20) concluded that this ability to increase SF may have been due to neural adaptations of training. Furthermore, Heglund and Taylor (9) stated that higher stride frequencies in animals require faster production of cross-bridges due to faster force generation demands pointing towards the association between SF and neural conditioning.

Paragraph Number 26 Hunter et al. (11) hypothesised, based on their results and the literature, that developing longer SLs requires long term development of strength and power, especially to increase horizontal ground reaction impulse. Cronin et al. (5) studied how two types of resistive training (sled towing and weighted vest) acutely influenced step characteristics over the first 30 metres in comparison to unresisted sprinting. As relative strength due to additional weights was reduced, the decrease in performance was mainly due to lower SLs with only small decreases in SF. Moir et al. (19) had a slightly different approach when the authors studied the influence of eight weeks resistance training on step characteristics. Despite the fact that these were analysed only over the first three steps after the start, and thus may not be fully applicable to the current paper, the results gave indications of how such training affects these step variables. Increased maximum and explosive strength was associated with increased SL and reduced SF over these first three steps (19).

Paragraph Number 27 Thus, overall it is reasonable to conclude that SL is related more to increased force production, and SF is associated with faster force production during the contact and quick leg turnover requiring neural adaptations. Higher SF requires cross-bridges within the muscles to be built at high rates, and thus these need a high rate of neural activation. Consequently, it is proposed that the SF reliant athletes are required to concentrate on neural activation in their final preparations for the major races and have a nervous system ready such that they can produce the quick turnover of the legs. On the other hand, the SL reliant athletes need to keep their strength levels up throughout the season and have the required flexibility in the hip area to produce long steps. Naturally, athletes cannot totally forget the non-reliant variable, as any disproportionate reductions in one variable cannot be generally compensated for by the other variable. The athletes who cross-over the ±0.1 trivial effect region, should perhaps focus equally on SL and SF in their training. It is also good to remember that the current study was based on the average step variables over the whole 100 metres, while SL, especially, varies throughout the race. It is estimated that the accuracy of our measurements is about 0.01 m for the SL and 0.06 Hz for the SF. The final caution is that this paper was able to provide only results based on how people have performed, not how an ideal performance could be created. Thus, to further understand how SF and SL influence each other and interact to produce the velocity of the individual athlete, these same variables should be analysed individually at the maximum velocity phase and longitudinally in training. Some questions about the SF, SL and velocity relationships could probably be best answered by adopting a modelling approach.

CONCLUSIONS:

Paragraph Number 28 This study analysed step lengths and step frequencies of world elite male 100 metre sprinters over multiple competitions. As group level analysis could mask personal differences, this study concentrated on analysing each athlete separately. Individually some athletes' performances were more reliant on step length, one athlete was clearly step frequency reliant and some athletes used combinations which showed a reliance on neither. It is proposed that athletes should take this reliance into account in their training with step frequency reliant athletes needing to keep their neural system ready for fast leg turnover and step length reliant athletes requiring more concentration on maintaining strength levels.

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Paragraph Number 30 The authors declare that they have no conflict of interest and that the results of the present study do not constitute endorsement by the American College of Sports Medicine.

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