International Journal of EXERCISE SCIENCE

Original Research

Is the Relationship Between Stride Length, Frequency, and Velocity Influenced by Running on a Treadmill or Overground?

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ABSTRACT

International Journal of Exercise Science 10(7): 1067-1075, 2017. The purpose of the study was to compare the relationship between stride length (SL), stride frequency (SF), and velocity while running on a treadmill and overground. Participants (n=10; 22.3±2.6 yrs; 1.71±.08 m; 71.4±15.5 kg) completed a total of 14 runs (7 treadmill, 7 overground) with each run at a different velocity. SL, SF, and velocity data were recorded using wearable technology (Garmin, Fenix2). The outdoor trials occurred first. The treadmill velocities were selected to match the range of velocities used overgroud. SL vs. velocity plots were generated for treadmill and overground data for each participant and fit with a 2nd order polynomial in the form of $SL=Av^2+Bv+C$. Each equation coefficient (i.e., A, B, C) was averaged across participants and compared between treadmill and overground using paired t-tests. The A coefficient (v^2 term) was different treadmill vs. overground ($p=0.031$). Neither B ($p=0.136$) nor C ($p=0.260$) coefficients were different treadmill vs. overground. It was concluded that the A coefficient (v^2 term) for SL vs. velocity was larger during overground vs. treadmill running. This is an indication that the strategy of changing SL across velocities was different when on the treadmill vs. overground. Specifically, while running on a treadmill, SL continued to increase in a more linear manner than when running overground.

KEY WORDS: Step frequency, running economy, energetic cost of locomotion

INTRODUCTION

The basic kinematic descriptors of running include stride length (SL), stride frequency (SF), and running velocity. The relationship between these three parameters is generally thought to be well understood. Specifically, it is often described that SL increases as velocity increases across submaximal running velocities. Further increases in velocity towards maximal velocity are achieved by increases in SF while SL plateaus (e.g., 3, 8). In reviewing published literature (Figure 1), it is clear that there is general support for the hypothesis that SL plateaus at higher velocities.

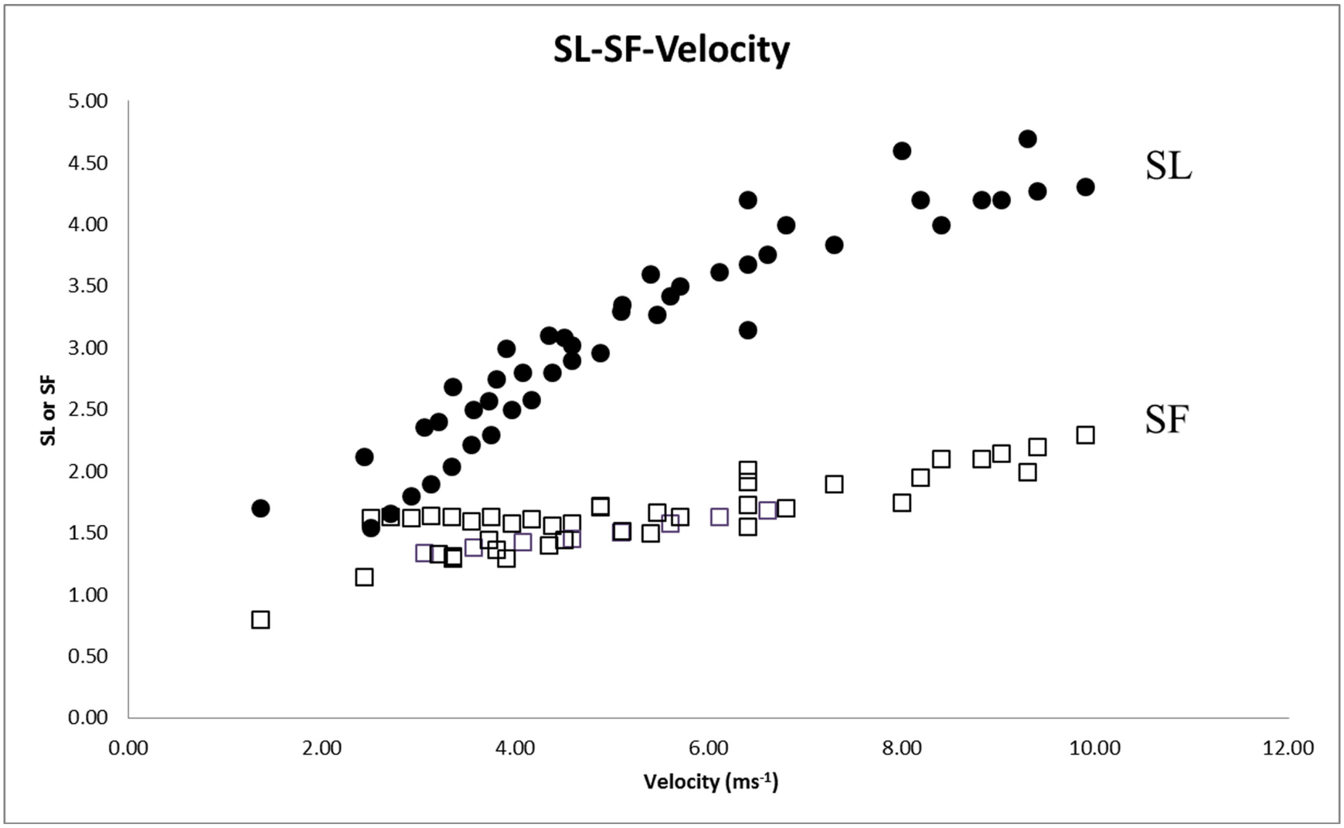

Figure 1. Aggregate data illustrating relationships between stride frequency (SF) and stride length (SL) with running velocity. The y-axis units are strides/s (Hz) for SF and m/stride for SL. Data points represent a variety of published data sets (1, 7, 8, 9, 10, 12, 13, 14).

Given the focus of the present manuscript, it is important to operationally define stride, SL, and SF to avoid confusion between studies. A stride is defined as the movements from a discrete event on one side to the very next same discrete event of the same side. For example, the movements between the time of a right foot contact to the time of the very next right foot contact. Stride frequency represents how quickly a stride is completed and is typically represented using units of strides/s (or Hz). Stride length is the distance covered during a stride and is typically represented as m/stride. The product of SF and SL is running velocity (v = SF · SL); performing a unit analysis: v = (strides/s) · (m/stride) = $m \cdot s^{-1}$.

Interestingly, not all studies reported a plateau of SL (1, 2, 8, 10, 14). For example, Mercer et al. (9) had participants run between 50% and 100% of their maximal velocity and reported that SL did not plateau as the 100% velocity condition was reached. The authors hypothesized that a SL plateau may only be observed at faster absolute velocities studied by Luhtanen and Komi (9) (which included up to 9.3 $m \cdot s^{-1}$) since the relative 100% velocity was on average 6.4±0.5 $m \cdot s^{-1}$. However, it is also interesting to note that Mercer et al. (10) had participants run on a treadmill whereas Luhtanen and Komi (9) had participants run overground. It may be that the strategy to achieve faster velocities is influenced by running on a treadmill vs. overground.

Although running on a treadmill is mechanically similar to running overground, kinematic differences have been reported (4, 6, 11, 12). For example, Elliott and Blanksby (5) reported that participants tended to use a shorter stride length while running at faster velocities on a treadmill vs. overground. In contrast, Nelson and colleagues (11) reported that SL was greater while running at a faster velocity on a treadmill vs. overground. However, they did not compare SL between treadmill and overground over a range of submaximal velocities (11). Nevertheless, despite the wealth of research on running characteristics, the relationships between SL, SF, and velocity have not been directly compared between overground and treadmill running. Therefore, the purpose of this study was to determine if the manipulation of SL and SF combinations across different velocities was similar while running overground and on a treadmill. It was hypothesized that the relationships would be different while running overground and on a treadmill. Since the product of SL and SF is velocity, analyzing the relationships of SL-velocity and SF-velocity is redundant and we analyzed only the SL-velocity relationship.

METHODS

Participants

Participants (n=10; 8 male, 2 female; 22.3±2.6 yrs; 1.71±0.08 m; 71.4±15.5 kg) were physically active and free from any injury that would interfere from running. Participants were recruited from the general university population; they were not specifically runners, but all comfortable running at a variety of speeds. All participants gave written informed consent prior to participating with the study approved by the Institutional Review Board in accordance with the ethical standards of the Helsinki Declaration.

Protocol

Each participant wore a Global Positioning System (GPS) watch (Garmin Fenix2 GPX) and had a footpod (Garmin) attached to one shoe. The GPS watch sampling rate was set to capture a sample every 0.1 s (i.e., 10 Hz). The watch records velocity and SF (as well as other measures not used in this study) with data being downloaded to a user's profile on a website interface (Garmin Connect).

All participants completed overground and treadmill running conditions on the same day. Treadmill running conditions were completed on the same treadmill (Bertec FIT) for all participants. Overground running conditions were completed outdoors with data collected over a 100 m flat section of pavement. Seven trials per condition were completed with overground condition preceding treadmill condition. Overground trials preceded treadmill trials in order to match running velocities between modes.

Each overground running trial lasted about one minute. Participants were instructed to select a velocity and maintain that velocity as they ran through a 100 m test area. The instructions for each overground run were either to run slower or faster than the previous run, creating a range of running velocities across the seven trials. The GPS watch was manually triggered by the participant at the start and end of each run.

Each treadmill condition (indoors) lasted about 1-min and consisted of completing seven trials at different velocities. The velocities of these trials were evenly spaced within the range of velocities used during overground trials. At this stage of the experiment, the average velocity of about the middle 40 m section of the outdoor run was used to determine treadmill velocities. Prior to the start of each trial, the GPS watch was triggered manually and stopped at the end. Since the treadmill was indoors, no GPS data were recorded while the footpod measured stride characteristics.

Data Reduction: At the end of each data collection session, all data files (14 trials in total per participant) were uploaded via the internet to Garmin Connect (Version 3.8.1.1). Using the proprietary software, the *.fit file was exported and downloaded. That file was then processed via a custom program to convert the *.fit file format to ASCII format. The ASCII file was saved and then imported into Microsoft Excel (2013) for curve fitting analysis. SL was calculated using velocity and SF data columns (SL = velocity / SF) for overground conditions. For treadmill conditions, the treadmill velocity setting was used in combination with SF data to calculate SL (SL = treadmill velocity setting / SF). Further processing was focused on SL and velocity and not SF. The reason for that is that SF would simply be the reciprocal of SL (i.e., velocity = SF · SL) and therefore the analysis of SF would be redundant to the analysis of SL.

For each participant, SL vs. velocity data were graphed and fit with a 2nd order polynomial ($SL=Av^2+Bv+C$). This was done for the treadmill and overground conditions (i.e., two equations per participant). The coefficients (i.e., A, B, C) were recorded for statistical analysis.

Statistical Analysis

The dependent variables were the coefficients of the 2nd order polynomial equations (A, B, C) with the independent variable being condition (treadmill, overground). Each coefficient was compared between conditions using paired t-tests (□=0.05). 95% Confidence Intervals of the Difference were calculated and effect sizes (Cohen's d) calculated when a difference was observed.

RESULTS

The SL vs. velocity relationships for treadmill and overground are presented in Figure 2. Group means and standard deviations for each coefficient presented in Table 1. The A coefficient (v^2 term) was different treadmill vs. overground ($p=0.031$; 95% Confidence Interval of the Difference (CI): lower -0.14, upper -0.01; Effect Size: 1.4432). Neither the B coefficient (v term) ($p=0.136$; 95% CI -0.08, 0.49) nor the constant C ($p=0.260$; 95% CI -0.049, 0.15) were different between treadmill vs. overground.

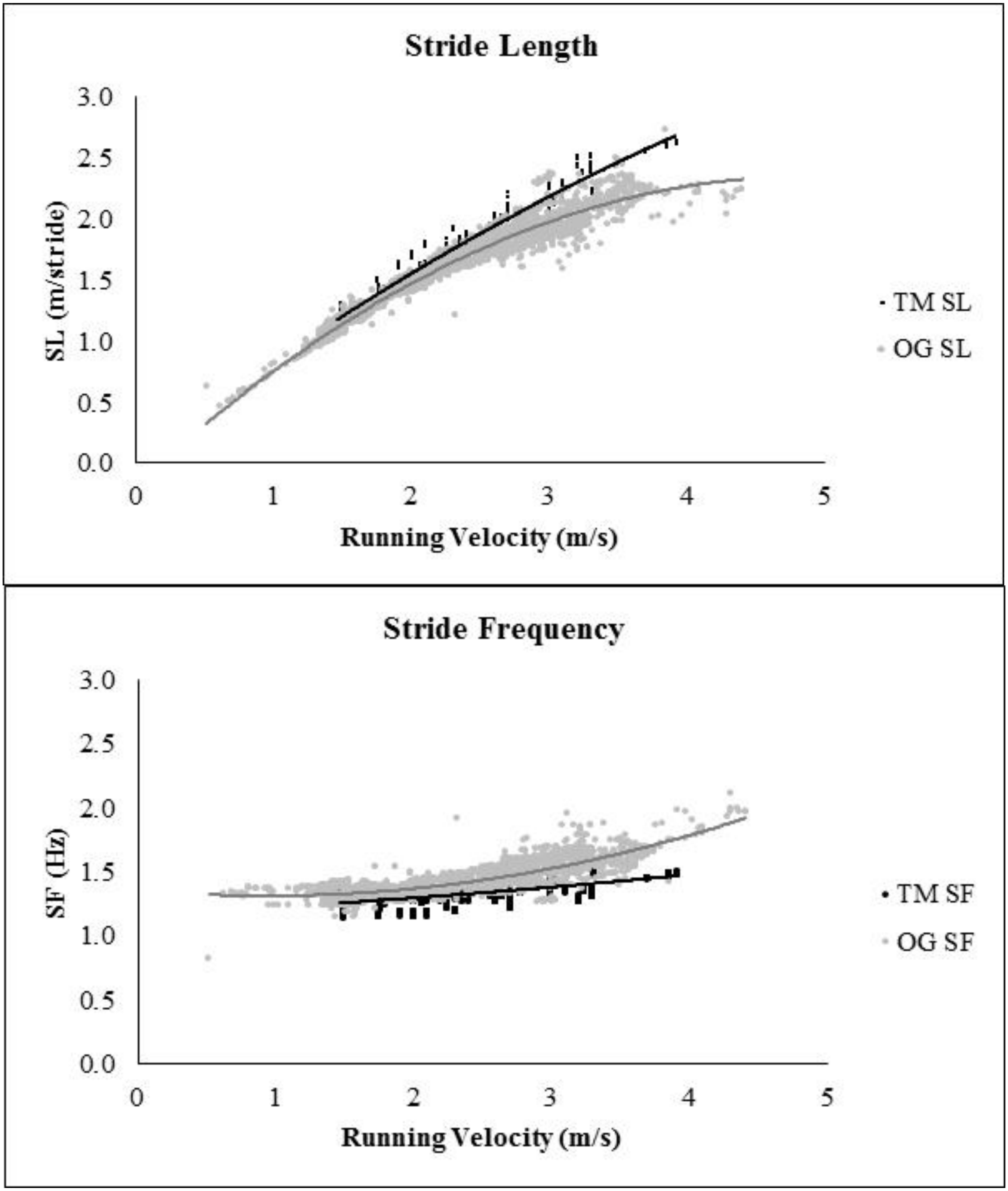

Figure 2. Illustration of all data from all participants as well as the average 2nd order polynomial equation for stride length (SL) vs. velocity (top) and stride frequency (SF) vs. velocity (bottom) while running on a treadmill (TM, black) and overground (OG, grey).

Table 1. Group mean and standard deviation of coefficients for 2nd order polynomial fit to the stride length (SL) vs. velocity data (SL = Av² + Bv + C, where 'v' represents run velocity). Note: * 'A' coefficient (i.e., Av²) was different between running overground and on a treadmill (p=0.031).

	2nd Order Polynomial Coefficients			
	A	B	C	R^2
Overground	-0.128±0.063*	1.130±0.233	-0.275±0.229	0.976
Treadmill	-0.052±0.039	0.923±0.201	-0.103±0.270	0.993
	p=0.031	p=0.136	p=0.260	

DISCUSSION

The most important observation of this study was that the strategy used to achieve a faster running velocity was dependent on whether the participant was running on a treadmill or overground. In this study, the strategy used being defined by the SL and SF combination chosen to achieve each velocity. Specifically, the 2nd order polynomial coefficients differed only for the non-linear component (i.e., A coefficient for the v^2 term) when running overground vs. on a treadmill. This observation seems to indicate a more curvilinear response between SL and velocity when running overground vs. on a treadmill (Figure 2), which suggests a plateau of SL at faster velocities. Thus, the hypothesis that the relationships between SL, SF, and velocity would be different during running overground and on a treadmill remains tenable.

The classic relationship between SL, SF, and velocity is historically described by Luhtanen and Komi (9) which is a landmark study for description of the relationships between these parameters. The results from the present study largely agree with Luhtanen and Komi (9) in that there was a strong relationship between SL and velocity given the large R^2 values while running either on a treadmill (R^2=0.993) or overground (R^2=0.976). However, the lack of clear plateau in SL as faster velocities were ran on the treadmill is the most striking difference between the present study and Luhtanen and Komi (9).

Interestingly, in a review of published studies that measured SL and SF at different velocities while participants ran on a treadmill, the plateau phenomena of SL is typically not evident (1, 8, 10, 14) or SF observed to not change as higher velocities are reached (6). Instead, SL is typically observed to increase in a linear fashion across running velocities while on a treadmill. This observation agrees with the present study of continued increase in SL as faster velocities are achieved during treadmill running.

Whether or not SL plateaus at faster velocities may be related to absolute maximum velocity achieved vs. whether that velocity is achieved while running on a treadmill or overground. In Luhtanen and Komi's (9) study, participants (n=6) ran at a maximum velocity of 9.3±0.3 $m \cdot s^{-1}$. In our study, the maximum velocities reached by any participant was 3.92 $m \cdot s^{-1}$ and 4.41 $m \cdot s^{-1}$ (treadmill and overground, respectively). Interestingly, even at these velocities, the SL-velocity relationship was different when running on a treadmill or overground. Nevertheless, we did not consider subjects having reached their individual maximum velocity since our methods required them to run 1-min on a treadmill and 100 m overground. Further testing could be done by having subjects run shorter periods of time and distance to yield individual maximum running velocities.

It is not clear why the relationship between SL, SF, and velocity would differ while running on a treadmill or overground. It is conjectured that participants learned to achieve faster velocities while running on a treadmill by increasing the vertical displacement during flight. This strategy would have the effect of allowing the treadmill to move underneath the participant during flight, thus causing an increase in SL. While running overground, it may be that the mechanical demand of propelling the body horizontally is better achieved by increasing SF vs. flight time (and therefore SL). This hypothesis would seem to be testable in future studies by comparing the vertical displacement of the center of mass of the runner while running on a treadmill and overground.

We also considered that participant familiarization with treadmill running may be a factor influencing the results. In our study, the treadmill did not have support rails and it may be that participants adopted a running strategy that optimized safety (or comfort) as each velocity was achieved. Nevertheless, the observation that SL did not plateau at faster velocities is consistent with other studies (1, 8, 10, 14).

It is recognized that using a GPS watch as the primary instrument to collect data is limited by the sampling rate of the instrument as well as the accuracy of determining position at a given time. However, any error present in the device would be similar between conditions. To increase accuracy of the GPS watch, run distance was 100 m and sample rate was set to 10 Hz (vs. 'smart sample' which could yield a variable sample rate) (3).

It is also recognized that SL, SF, nor velocity are constant throughout a short duration run. For example, during running overground, velocity of the center of mass will slow down and speed up with each stance phase. Likewise, velocity may not be constant over a short duration run nor is it expected that SL is the same with each consecutive stride. Even on a treadmill, the velocity of the belt changes with each footstrike. Our approach was to use as much of the data per run as possible to build a 2nd order line of best fit. The outcome of this study would be further understood if subsequent studies test the same relationships using other instruments. It is also important to recognize that the measurement of velocity was different while running overground (using GPS position data) and on a treadmill (using treadmill belt speed). This problem is unavoidable since the person does not move forward while running on a treadmill. In any case, the 2nd order polynomials seem to overlap well at submaximal velocities and only seem different as faster velocities were achieved (Figure 2).

The basic kinematic descriptors of a running stride are SL and SF. Runners select a particular SL and SF combination to achieve a given velocity. Understanding the relationship between SL, SF, and velocity gives some insight as to preferred running style. By having participants run at different velocities on a treadmill as well as overground, it was determined that the SL – SF combination selected was dependent on whether the participant was running on a treadmill or overground. Specifically, it was observed that SL-velocity relationship had more curvature indicative of a plateau while achieving faster velocities overgound, but not so on a treadmill. Therefore, it is concluded that participants behaved differently when attempting to achieve faster running velocities overground versus running on a treadmill.

ACKNOWLEDGEMENTS

This study was partially supported by the NIH/NIDDK grant 5R25DK078382 Short Term Research Experience for Underrepresented Persons (STEP-UP).

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