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Effect of Step Rate on Foot Strike Pattern and Running Economy in Novice Runners

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by

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Effect of Step Rate on Foot Strike Pattern and Running Economy in Novice Runners

Abstract

Purpose—The objective was to examine if step rates ±5% or ±10% of a novice runner's preferred step rate (SR) is sufficient enough to shift a novice runner's foot strike pattern (FSP) (rear-foot, mid-foot, forefoot) and whether these SR changes produce changes in the rate of submaximal oxygen consumption (VO_2).

Methods—Foot strike angle (FSA) was recorded using sagittal plane video images and VO_2 was measured for novice runners while running on a treadmill at a constant speed during increased and decreased (±5% and ±10%) SR conditions. Foot strike angle was used to predict strike index (SI) (predicted strike index = [FSA – 27.4]/-0.39) and quantify FSP in each SR condition.

Results—Predicted SI was significantly different between preferred SR and the -5% ($p = .014$), -10% ($p = .001$), and the +10% ($p = .007$) SR conditions.

There was a shift to higher predicted SI measures in the increased SR conditions and lower predicted SI measures in the decreased SR conditions. Oxygen consumption was significantly increased in the -5% and -10% SR conditions ($p =.000$ and $p = .003$, respectively).

Conclusion-- Manipulations of SR produce shifts in FSP in novice runners and these changes cause small changes in submaximal VO_2.

Introduction

The average runner strikes the ground 600 times per kilometer, and the initial contact between the foot and the ground can occur in one of three ways: a rear-foot strike (RFS), a mid-foot strike (MFS), or a forefoot strike (FFS) (Lieberman et al., 2010). A RFS is characterized by the heel of the foot or the rear third of the sole making contact with the ground first (Altman & Davis, 2012; Hasegawa, Yamauchi & Kraemer, 2007). A MFS is characterized by the first contact of the foot being both the rear third of the foot and the mid-foot (Hasegawa et al., 2007). FFS is characterized by the ball of the foot or front half of the sole striking the ground first with no heel contact at foot strike (Altman & Davis, 2012; Hasegawa et al., 2007). How the foot makes contact with the ground, or a runner's foot strike pattern (FSP), can be determined through visual analysis of the foot at landing captured by a high speed video camera. While visual identification of FFS and RFS is highly reliable, accuracy in visually identifying MFS is more difficult (Altman & Davis, 2012). This is one of the reasons that strike index (SI) is considered the gold standard method used to quantify FSP's (Altman & Davis, 2012). Using force plate technology at the foot's initial contact with the ground, SI is a determination of the location of the center of pressure (COP) from the heel of the foot as a percentage of the length of the foot. An SI of 0-33% indicates a RFS, <33-67% indicates a MFS, and <67-100% indicates a FFS (Altman & Davis, 2012). It has been reported that 75-80% of distance runners use RFS and 20% use MFS or FFS patterns (Williams III, McClay, & Manal, 2000). Understanding how the foot makes contact with the ground has special importance because the foot is the only body segment that has direct interaction with the ground during running movement and is one of the anatomical structures of the human body most susceptible to injury (Hasegawa et al., 2007).

Runners, coaches, and health professionals are always searching for ways to reduce the risk of injury in runners and improve running economy (RE), which is defined as the aerobic demand (oxygen consumption) of running at a given submaximal speed (Morgan et al., 1994; Saunders, Pyne, Telford, & Hawley, 2004). In this regard, some have experimented with different FSPs. Research findings reveal that a RFS puts more demand on the ankle, knee, and hip joints and uses the cushioning structure of shoes and the skeletal structure of the lower leg to compensate for the collision of the heel to the ground (Lieberman et al., 2010; Perl, Daoud, & Lieberman, 2012; Williams & Cavanagh, 1987). A FFS puts increased demands on the forefoot, the arch of the foot, the Achilles tendon, and relies more on the elastic energy of the tendons, ligaments, and muscles to propel the body forward (Lieberman et al., 2010 Perl et al., 2012; Williams III et al. 2000). Decreased impact loading rates have been reported in MFS and FFS when compared to RFS (Altman & Davis, 2009; Lieberman et al., 2010; Williams III et al., 2000). Higher loading rates have been associated with stress fractures (Zadpoor & Nikooyan, 2011), patellofemoral pain (Davis, Bowser, & Hamill, 2010), and plantar fasciitis (Pohl, Hamill, & Davis, 2009). While FFS reduces loading rates, the increased demand on the plantarflexion musculature could cause runners to be more susceptible to Achilles tendonitis or metatarsal injuries (Altman & Davis, 2009). In a recent retrospective study, it was reported that runners who habitually RFS had twice the rate of repetitive stress injuries than those who habitually FFS (Daoud et al., 2012). Thus, while there seems to be advantages and disadvantages to different FSPs, changes to FSP may be important as they relate to injury prevention and treatment (Altman & Davis, 2009; Hasegawa et al., 2007; Lieberman et al., 2010; Williams III et al., 2000).

Step rate (SR), or the number of steps a runner takes per minute, has also been studied prominently as a possible means of improving RE and reducing the risk of injury (Clarke, Cooper, Hamill, & Clarke, 1985; Daniels, 2005; Heiderscheit, Chumanov, Michalski, Wille, & Ryan, 2011). Stride length (SL) and SR have been frequently studied as biomechanical measures in gait analysis. When speed is held constant, SR and SL have an inverse relationship. Therefore, when SR increases, a runner's stride shortens and when SR decreases their stride lengthens (Cavanagh & Williams, 1982; Clarke et al., 1985; Heiderscheit et al., 2011). Studies have shown a small increase in SR to a runner's preferred SR reduces forces at the ankle, knee, and hip and may reduce the risk of injury (Clarke et al., 1985; Heiderscheit et al., 2011).

In addition to exploring FSPs and SRs in regards to possible injury implications, researchers have also looked at the possible effects of FSPs and SRs on RE. In studies where RE has been measured during different FSP conditions, submaximal oxygen consumption (VO_2) was not different between FFS and RFS (Ardigo, Lafortuna, Minetti, Mognoni, & Saibene, 1995; Cunningham, Schilling, Anders, & Carrier, 2010; Perl et al., 2012). Tartaruga et al. (2012) found that distance runners running at the same treadmill speed and the same physiological intensity had SR and internal ankle angles at foot strike (which relate to FSPs) that made up 23% and .6%, respectively, of the biomechanical factors affecting RE.

Increases and decreases in SR have been shown to have an effect on foot strike angle (FSA), which is the angle of the foot at initial contact with the ground (Clarke et al., 1985; Heiderscheit et al., 2011). A study by Heiderscheit et al. (2011) examined the effects of SR manipulations on energy absorption in the lower extremity joints, and one of the biomechanical components analyzed during each SR condition was FSA. Although FSA has been reported in previous gait analysis studies, the effect that SR has on specific FSPs (i.e., FFS, MFS, RFS) were not discussed, and it is unclear if a shift in FSP took place as a result of increases and decreases in SR from the participants' preferred SR. Many have used SR conditions or equivalent stride length conditions of ±5% and ±10% from preferred to examine the effects of increases and decreases on a runner's gait (Cavanagh & Williams, 1982; Clarke et al., 1985; Heiderscheit et al., 2011; Morgan et al., 1994). However, previous research seems to be lacking the specific SR parameters required to see a shift in FSP, as well as the coupled effects of SR and FSP on RE in a novice runner population.

In view of the previous research, the purposes of this study were: To examine if an increase or decrease in SR by ±5% or ±10% of a novice runner's preferred SR is sufficient enough to shift a novice runner's FSP and whether an increase or decrease in SR by ± 5% or ±10% of preferred SR produces changes in the rate of submaximal VO_2 (RE) for novice runners. Because we know different FSPs put different demands on the lower extremity, if SR is found to be a tool to shift FSP then SR manipulations could possibly be used for injury prevention, injury recovery, and for novice runners who want to safely transition from RFS to MFS/FFS in order to have a FSP that fits the design of barefoot or minimalist type shoes. Based on the shifts in FSA found by Clarke et al. (1985) and Heiderscheit et al. (2011), and the finding by Heiderscheit et al. (2011) that a significant change in FSA occurred only at +10% from preferred SR, it was hypothesized that increases and decreases in SR would cause a shift in FSP, but a significant change would occur only at a 10% increase in SR from a novice runner’s preferred SR. It was also hypothesized that during these stages of SR manipulation minimal changes in RE would occur based on the previous findings of Cavanagh and Williams (1982).

Methods

Participants: Eighteen novice runners (9 men, 9 women), with no running-related injury within the last 3 months, were asked to participate in the study. All participants were volunteers who had been running for less than 5 years with an average weekly mileage of 15.6 ± 6.2, and 6 mph (10 min mile pace or 2.68 m/s) was considered within a moderate intensity range for the participants’ current fitness level. Participants’ physical characteristics are reported in Table 1. At baseline, there were 10 RFS, 6 MFS, and 2 FFS with an average preferred SR of 168.8 ± 11.3 steps/min and an average RE measurement of 35.02 ± 1.8 mL/kg/min.

PHYSICAL AND TRAINING CHARACTERISTICS OF PARTICIPANTS												
Participant	**G**	**Age**	**Ht (cm)**	**Wt (kg)**	**LL (cm)**	**Shoe Type**	**FSP**	**SR (steps/min)**	**RE (mL/kg/min)**	**Run Exp. (yrs)**	**miles/ wk**	**days/wk**
1	M	31	184	69	97.6	lightweight/ neutral	RFS	164	31.8	1-2 years	5	2
2	F	42	162.5	59.7	87	stability	RFS	160	38.2	3-5 years	18	3
3	M	38	190.1	85.9	99.4	stability	MFS	158	34.0	<1	20	4
4	M	22	181	74.8	92.5	neutral	MFS	158	37.3	1-2 years	9.5	3
5	F	31	164.8	61.5	82.2	stability	RFS	168	36.5	<1 year	20	4
6	F	39	157.2	70.9	81.3	neutral	MFS	190	35.4	1-2 years	22.5	4
7	M	25	180.2	78.3	95.7	minimalist/ neutral	FFS	158	33.6	3-5 years	10	3
8	F	19	165.9	60.8	84.5	neutral	MFS	166	32.1	3-5 years	17.5	5
9	M	32	177.6	84.7	91.5	minimalist/ neutral	MFS	194	35.3	1-2 years	17.5	3
10	F	28	152.2	52	77.5	stability	RFS	184	33.8	3-5 years	13.5	4
11	F	29	162.1	53.8	82.9	neutral	RFS	174	34.2	1-2 years	25	4
12	F	32	159.2	66.4	84	neutral	RFS	166	37.9	1-2 years	17.5	3
13	M	21	179.1	92	89.3	stability	FFS	168	36.7	1-2 years	12.5	5
14	M	22	188.5	103	97.4	neutral	RFS	156	35.7	1-2 years	12.5	4
15	F	36	164.5	66.8	83.7	neutral	RFS	180	34.0	3-5 years	27.5	4
16	F	21	173.3	75.1	91.3	stability	MFS	164	33.6	3-5 years	5	1
17	M	44	166.3	60	86	stability	RFS	164	34.3	3-5 years	14	3
18	M	32	181.4	77.5	91	minimalist/ neutral	RFS	166	35.8	1-2 years	12.5	3
mean and SD:		**30.2 +/-7.57**	**171.7 +/-11.4**	**71.8 +/-13.6**	**88.6 +/-6.3**			**168.8 +/-11.3**	**35.02 +/-1.8**		**15.6 +/-6.2**	**3.4 +/-1.0**

TABLE 1. Physical and training characteristics of the participants. G = gender; Ht = height; Wt = weight; LL = leg length; Shoe type = type of shoe worn during training and during experiment, which was determined from manufacturers description of shoe type; FSP = foot strike pattern; SR = step rate; RE = running economy; Run Exp. = cumulative total number of years running; miles/wk = number of miles run per week; days/wk = number of days each participant runs per week.

Procedures:

After filling out a consent form, age, height, weight, and leg length were measured, shoe type was recorded, and maximum heart rate was predicted (220-age = maximum heart rate). A brief questionnaire was also collected on general information about running background, shoe type, and history of injury (see Appendix). Participants were asked to run on a level treadmill (ICON, Logan, UT) for 6 min at a treadmill speed of 6.0 mph (10 min mile pace or 2.68 m/s). This bout of exercise served as a warm up and treadmill familiarization period during which the participant's preferred SR was calculated during the 3rd min and the 6th min by visually counting the number of left foot strikes for 30 s and multiplying the number by four. The average of the two SR measures was used as the participant's preferred SR. This technique of visually determining SR was based on procedures of previous research done by Heiderscheit et al. (2011). A rest period of 5-10 min followed the warm up/familiarization session, during which ±5% and ±10% of preferred SR were calculated, and the researcher put the heart rate monitor and the equipment required to measure VO_2 on the participant. VO_2 measurements were based on expired air analysis using a metabolic cart (TrueOne, ParvoMedics Inc, Sandy, UT). Participants were asked to run on the treadmill at a speed of 6.0 mph under the following five SR conditions: preferred SR, ±5% and ±10% of preferred SR. The order of SR conditions was randomized for each participant. The participant matched each footstep to a digital audio metronome created in MatLab (Natick, MA) to facilitate each condition's desired SR. Each condition was 6 min long separated by 5 min rest periods to facilitate recovery. The participant was instructed to focus on matching his/her footsteps to the desired SR facilitated by the metronome tone for each condition, but no mention of FSP was discussed. A researcher was visually and audibly able to tell for the most part if the participant was matching their steps to the metronome and gave the participant feedback if adjustments needed to be made. Submaximal VO_2 was recorded that last two min of each SR condition and rate of perceived exertion (RPE) was recorded at the completion of each condition.

FSA was captured via a high speed digital camera (Casio, Exilim EX-F1, Tokyo Japan) positioned in the sagittal plane of motion at a distance of 8.5 m from the participant. The camera height was set up to record the lower left leg, with the focus being the left foot, to improve the accuracy of digitizing markers placed on the foot. To assist in digitizing FSA, two athletic tape markers were placed on the participants left shoe; one at the 5th metatarsal head and the other was slightly lateral to the most posterior bony prominence on the calcaneus. Before the treadmill warm up period, 5 s of video was recorded to capture each participant's standing FSA.

Data Analysis: FSA was computed from video images recorded during min 4:50-5:00 during each 6 min SR condition. As shown at the bottom of Figure 2, FSA is defined as the angle of the foot in the sagittal plane with respect to the ground at initial foot contact while running, minus the foot angle at standing. FSA was computed using Kinovea (Kinovea, www.kinovea.org), which is a video analysis software that uses a digital goniometer positioned on the shoe markers to compute angles with a precision of 1° increments (see Figure 1). The reliability of methods used for measuring foot strike angle in our study has been reported previously and are reliable (intraclass correlation coefficients, ICC 0.98-0.99) (Miller & Callister, 2009; Norris & Olson, 2011). To insure our methods were reliable between assessments, only one researcher analyzed the angle data. Averages of five FSAs for each SR condition were used for further analysis. The five FSAs on average produced standard deviations of 0.71. With force plate technology unavailable, SI index was predicted using FSA and a regression equation developed by Altman and Davis (2012) (predicted SI = (FSA-27.4)/-0.39). Altman and Davis' (2012) research revealed a strong correlation between SI and FSA, R = 0.92 ($p < 0.01$).

FIGURE 1. The foot angle at footstrike measured using the Kinovea angle-tracking tool. This is during the -10% from preferred SR condition for participant #17.

As shown in Figure 2, SI, which is determined with force plate technology, is a measure of the location of the center of pressure (COP) from the heel of the foot as a percentage of total foot length at initial foot contact with the ground (Altman & Davis, 2012). A SI of 0-33% indicates RFS, >33-67% a MFS, and >67-100% a FFS (Altman & Davis, 2012).

Measures of submaximal VO_2 (mL/kg/min) and heart rate (bpm) were computed between min 3:30-5:30 of each 6 min condition. All VO_2 and heart rate measures were averaged within each condition. Submaximal VO_2 was used to determine RE, and heart rate was used to determine the physiological intensity for each participant running at the treadmill speed of 6.0 mph.

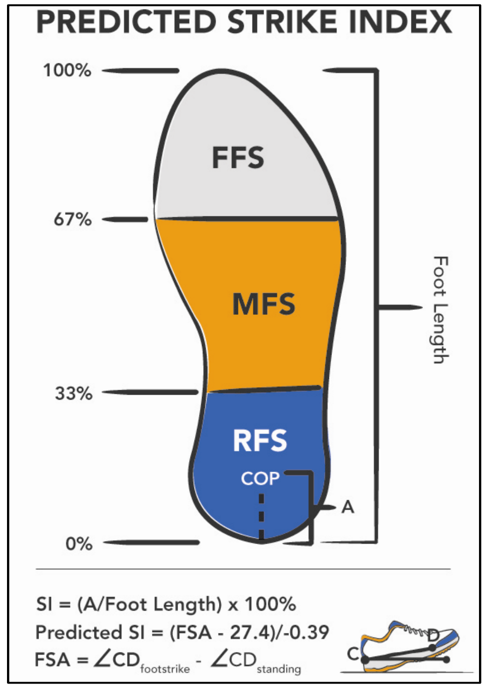

FIGURE 2. Strike Index (SI) is a measure of the location of the center of pressure (COP) from the heel of the foot, as a percentage of total foot length at foot strike. SI is categorized into rear-foot strike (RFS), mid-foot strike (MFS), and forefoot strike (FFS). Foot strike angle (FSA) can be used to predict SI.

Statistical analysis: The effect of changing SR (±5% and ±10%) on SI and VO_2 were examined using a one-way repeated measures ANOVA. Alpha level was set at an adjusted 0.05 level using the Bonferroni technique. A post hoc multiple comparison (LSD) test was used to identify any significant differences among the five SR conditions. Our main focus was a comparison of any changes that occurred in SI and submaximal VO_2 during increased and decreased SR conditions from preferred SR; therefore, with the exception of a comparison between -10% SR and +10% SR, only those pair-wise comparisons in which preferred SR was involved are reported. Pearson correlations were also utilized to determine if there was a relationship between submaximal VO_2 and SI or submaximal VO_2 and FSA.

Results

The ANOVA indicated that predicted SI was statistically different between SR conditions ($F(4, 68) = 14.039$, $p < 0.001$). Follow-up comparisons revealed significant changes between SI at preferred SR and at -5% ($p = .014$), -10% ($p = .001$) and +10% ($p = .007$) from preferred SR. However, no significant shifts in SI were found between preferred SR and +5% from preferred SR. Predicted SI for preferred SR showed that 56% of participants were RFS, 33% were MFS, and 11% were FFS. Because of the wide range of preferred FSPs (and thus SIs) among the participants, the standard deviations were the following for each SR condition's predicted SIs: -10% SR = 22.50, -5% SR = 19.87, preferred SR = 19.71, +5% SR = 20.84, and +10% SR = 23.10.

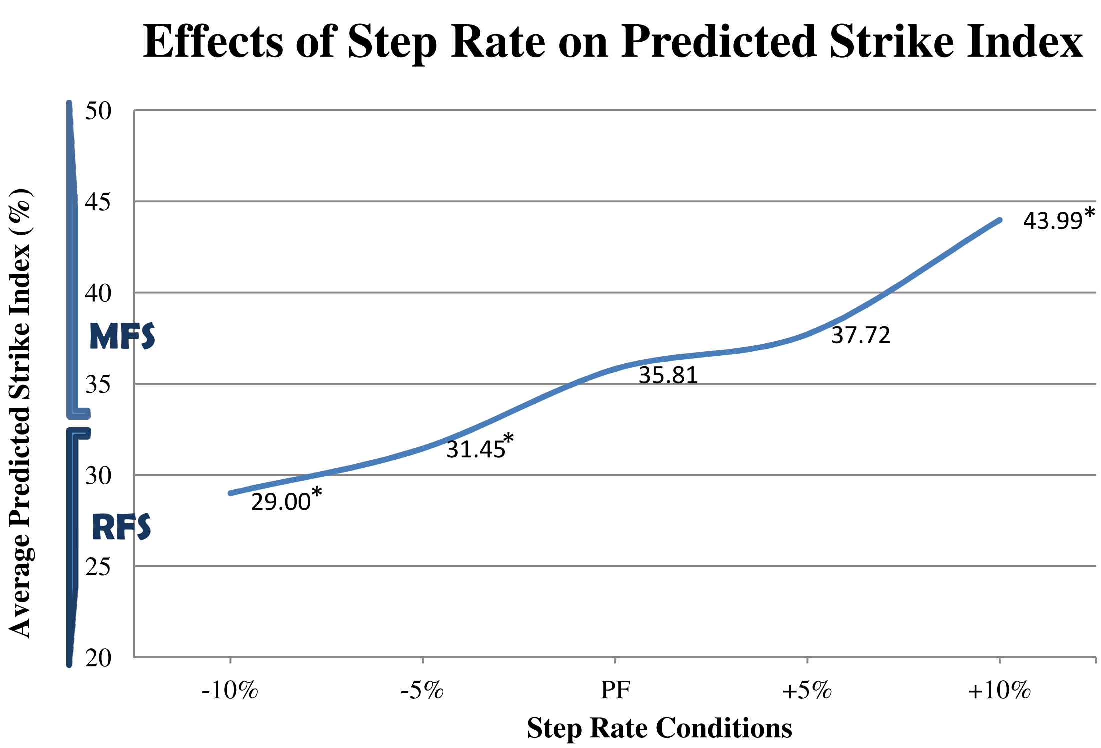

FIGURE 3. Average predicted strike index (SI) for each step rate (SR) condition. A SI of 0-33% = rear-foot strike (RFS), >33-67% = mid-foot strike (MFS), and >67-100% = forefoot strike (FFS). Note the increased SI in the increased SR conditions (center of pressure moving in the direction of the fore-foot) and the decreased SI in the decreased SR conditions (center of pressure moving in the direction of the rear-foot). * Significantly different from preferred $p < 0.05$

When looking at overall trends, there was a shift to higher predicted SI measures in the increased SR conditions and lower predicted SI measures in the decreased SR conditions (see Figure 3). Therefore, when increasing SR from preferred, participants tended to move more toward the anterior end of the foot at initial contact with the ground and more toward the heel of the foot when decreasing SR. Figure 4 shows the amount of change in SI, from preferred SI, during each SR condition. There was a 5.33% and a 22.84% increase in SI from preferred SI at +5% and +10% from preferred SR, respectively. At a -5% and -10% change in SR from preferred there was a 12.18% and 19.02% decrease, respectively, in SI from preferred SI.

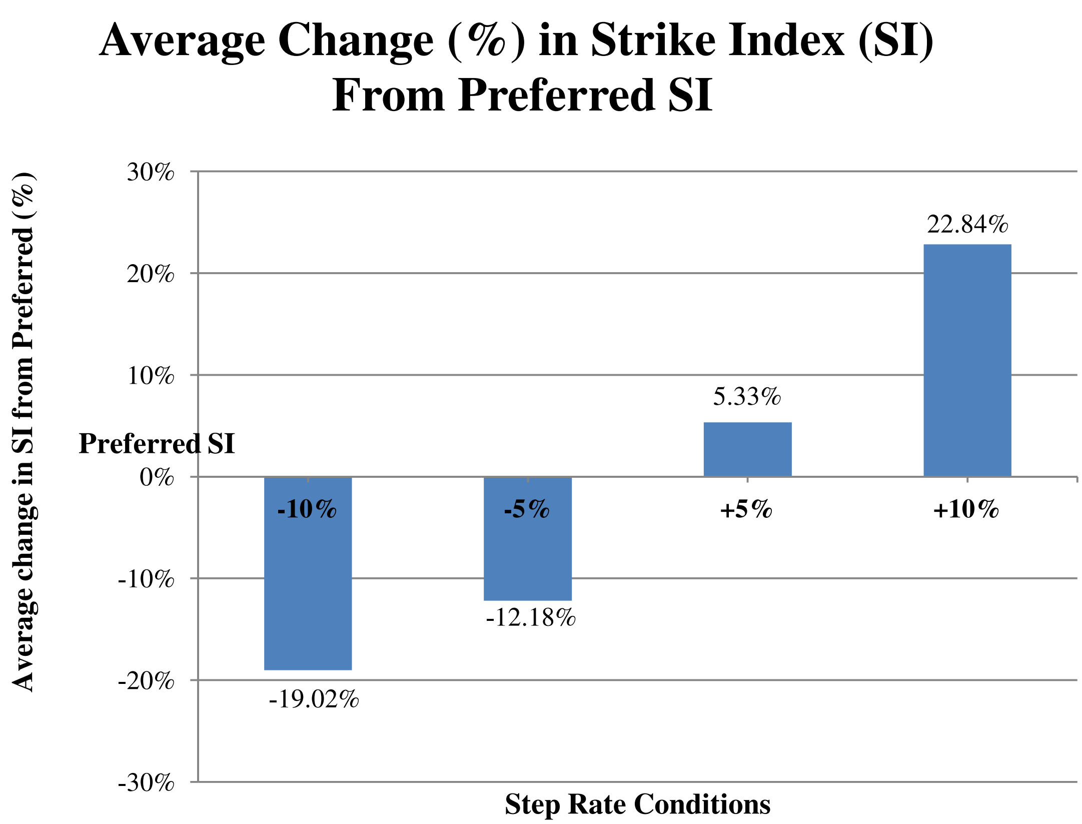

FIGURE 4. Average change (percentages) in strike index (SI) from preferred SI during each step rate (SR) condition. 0% represents preferred SI, positive percentages indicate increased SIs from preferred, and negative percentages indicate decreased SIs from preferred.

Among the participants, eight out of eighteen participants (44%) demonstrated a shift from their preferred FSP to a new FSP (i.e., RFS to MFS or MFS to RFS). The frequency of change in FSP was greatest at the 10% increase and 5% decrease from preferred SR. Three out of the eighteen participants (16.7%) changed from RFS to MFS when their SR was increased by 10% and three (16.7%) and two (11.1%) of the participants changed from MFS to RFS when SR was decreased by 5% and 10%, respectively.

Oxygen consumption at -5% and -10% SR conditions resulted in statistically significant differences from VO_2 measurements recorded during preferred SR ($p = .000$, $p = .003$), but no significant differences were found between preferred SR VO_2 and the increased SR conditions (see Figure 5).

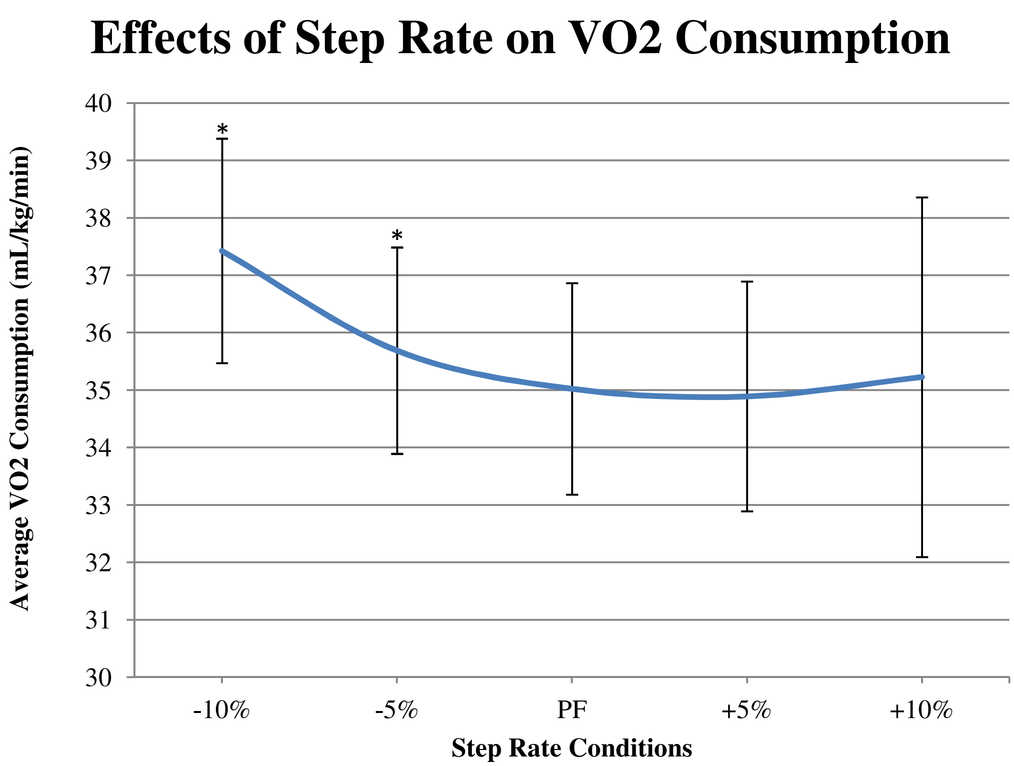

FIGURE 5. Average oxygen consumption and standard deviations during each step rate (SR) condition. Note the greater increase in VO_2 consumption when decreasing SR and the similar VO_2 measurement to preferred when increasing SR.

However, as portrayed in Figure 6, 67% of participants had their lowest VO_2 measurement when their SR was increased by 5% or 10%. The average absolute changes in VO_2 from preferred SR were the following (with positive values representing less economical running and negative values representing improved RE): -10% SR = +2.4 mL/kg/min; -5% SR = +0.67 mL/kg/min; +5% SR = -0.13 mL/kg/min; +10% SR = +0.21 mL/kg/min. Pearson correlations showed little relationship between RE and FSA or SI during each of the SR conditions.

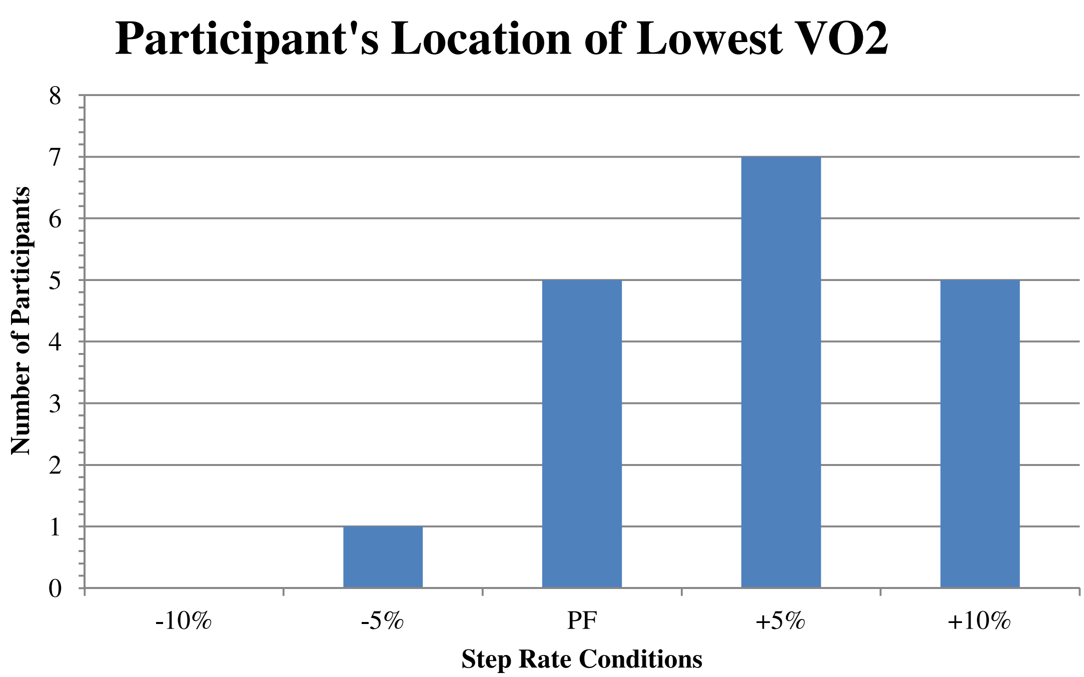

FIGURE 6. Illustration of the number of participants and the particular step rate condition where participant's lowest VO_2 consumption measurement occurred.

Discussion

The main objectives of this study were to examine if an increase or decrease in SR by ±5% or ±10% of a novice runner's preferred SR was sufficient enough to shift a novice runner's FSP and whether an increase or decrease in SR by ± 5% or ±10% of preferred SR produced changes in the rate of submaximal VO_2 (RE) for novice runners. Our findings partially support our first hypothesis because we observed significant shifts in SI, and thus FSP, at the +10% from preferred SR condition. However, we did not predict that we would also observe significant shifts in SI at -5% and -10% from preferred SR. This is in contrast to the findings observed by Clarke et al. (1985) where no significant changes in FSA were found during each of the same SR conditions and findings of Heidersheit et al. (2011) where significant differences in FSA were found only in the +10% from preferred SR condition. Differences in results may possibly be due to differences in using FSAs versus predicted SI measurements to locate changes that occurred due to SR manipulation. Additionally, based on our predicted SI measurements, there was an overall tendency for runners to shift forward on their feet during increased SR conditions and backward during decreased SR conditions, which indicates that manipulating SR is a possible tool for manipulating FSP. This was supported especially during SRs at +10%, -5%, and -10% from preferred SR where we saw a 22.84% increase in SI and a 12.18% and 19.02% decrease in SI, respectively, from preferred SI (see Figure 4). These findings are similar with Heiderscheit et al. (2011) and Clarke et al. (1985) that reported a decrease in FSA during increased SR conditions (implying the participants moved more forward on their feet at initial contact with the ground) and an increased FSA during decreased SR conditions (implying the participants moved more towards their heels at initial contact). In addition to the aforementioned studies, we were able to identify, and quantify through a predicted SI measurement, the runner's specific FSP during each of the SR conditions. Because of this approach, we were able to identify how many participants and under which SR conditions a distinct shift in FSP occurred (i.e., RFS to MFS or MFS to RFS). As mentioned previously in the results, eight out of eighteen participants (44%) demonstrated a shift from their preferred FSP to a new FSP. The frequency of change in FSP was greatest at the 10% increase and 5% decrease from preferred SR. We also observed that the magnitude of change in FSP occurred more quickly in the decreased SR conditions and required a more drastic SR manipulation (+10%) to see the same magnitude of change in the increased

SR conditions. Therefore, if a change in FSP is desired, a more drastic SR manipulation may be required to shift a novice runner's FSP more forward on their feet and a less drastic change in SR may be required to move a runner's FSP more toward the heels of their feet.

In support of our second hypothesis, we observed that negligible to moderate changes (2.4 mL/kg/min or less) in submaximal VO_2 occurred when increasing and decreasing SR. The increased SR conditions did not substantially improve RE or make the runner less economical, but rather they produced similar measurements in VO_2 to preferred SR (See Figure 5). On the other hand, the slower SRs made the runners less economical, particularly at the -10% SR condition which resulted in a 2.4 mL/kg/min increase in VO_2. So if changes in SR and FSP are desired, increasing SR is preferred to decreasing SR. Also, these findings may have implications in regards to fatigue and performance in the final stages of a distance race. Runners have the tendency to lengthen their stride, decrease SR, and

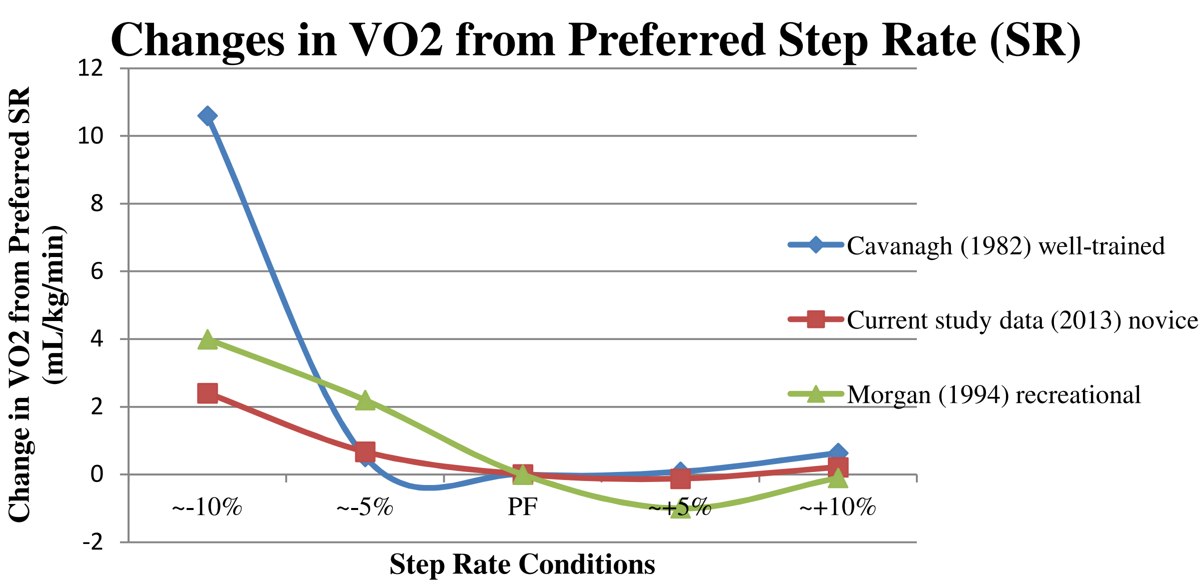

FIGURE 7. A comparison of the changes in average VO_2 consumption from preferred step rate for recreational, novice, and well-trained runners exposed to similar increases and decreases in step rate. Measurements below zero indicate improved running economy and measurements above zero indicate less economical running conditions. Data for Cavanagh (1982) was determined by our visual inspection and estimation of graphed individual data they reported.

adopt more of a RFS FSP in the later stages of a race (Larson et al., 2011). Therefore, increased focus on producing a quicker SR as fatigue sets in may help the runner avoid increasing the amount of oxygen needed to perform the running movement, help to maintain RE, and result in better performance. Our novice runners' VO_2 response to each SR condition mirrors previous research by Morgan et al. (1994) when observing uneconomical recreational runners and it also compares to research done in 1982 by Cavanagh and Williams utilizing well-trained distance runners (see Figure 7). However, Cavanagh and Williams (1982) showed much higher changes from preferred SR in submaximal VO_2 at approximately the -10% SR condition compared to our research and research done by Morgan et al. (1994). Possible reasons for this may have something to do with specificity of training and the amount of time spent training. Well-trained runners have spent a greater amount of time training at their preferred SR compared to novice or recreational runners and have most likely adopted a SR and SL combination that is very close to their predicted optimal SL (Cavanagh & Williams, 1982). On the other hand, novice and recreational runners have most likely not yet adopted their optimal SR (Cavanagh & Williams, 1982; Dallam, Wilber, Jadelis, Fletcher, & Romanov, 2005). Because of this, a 10% decrease in SR was possibly a more novel SR condition or more of a "shock" to well-trained runners' already established running biomechanics compared to the evolving running mechanics of novice or recreational runners who have spent less time training at a specific preferred SR.

In previous studies where RE has been measured during different FSP conditions, submaximal VO_2 hasn't differed significantly between FFS and RFS (Ardigo et al., 1995; Cunningham et al., 2010; Perl et al., 2012). In contrast, we found that SI changes in each SR condition showed substantial shifts in FSP and when comparing the difference in VO_2 under the two SR conditions (±10% from preferred) that on average produced the greatest alteration and gap in FSP, we did find significant differences in VO_2 between the -10% SR condition and the +10% condition. Furthermore, the average predicted SI indicated a RFS at -10% SR from preferred and a MFS at +10% SR from preferred, so the significant differences in VO_2 may lead one to assume the differences had something to do with the change in FSP. However, based on the little relationship we found between SI and RE, the differences in VO_2 were most likely due mainly to the effects of SR (and other biomechanical factors) on RE rather than FSP on RE. The disparity in VO_2 results between studies may be due to different experimental procedures for manipulating FSPs. In the previous studies, SR was held constant, which is most likely the majority of the reason for the disparity in results. According to Tartaruga et al. (2012) a runner's FSP does play a small role in the percentage of biomechanical factors affecting RE (.06%), but a larger contribution comes from SR (23%). Therefore, the differences in RE for our study are mostly likely due to the effects of SR (and other biomechanical factors) on RE, with a very small contribution from FSP.

One should consider the limitations to our study when interpreting the results. Because preferred SR was measured through visual inspection there is a possibility for slight measurement error. Also, visual observation and audible feedback as the runner's feet struck the treadmill was used to determine if each participant was adhering to the adjusted SR desired for each SR condition, but exact verification of whether or not a participant was running at the desired SR for each condition is lacking. Although the system used in this study to determine adherence seemed to be effective and determining if there was a discrepancy between a runner's SR and the desired SR was relatively obvious, for future studies it may be useful to use additional verification for determining adherence. If anything, visual feedback in addition to the audible feedback of the metronome may be useful for the participant to adopt the desired SR more quickly and, in some cases, with less instruction from the experimenter. As researchers, we realize that a runner's FSP and SR are only a piece of what encompasses a runner's overall biomechanics. Foot strike angle and thus FSP were captured through a high speed camera, but we did not capture overall body kinematics. There were individuals that produced less pronounced shifts in

FSP as a result of changes to SR, and we were unable to directly determine what other adaptations (besides shifts in SI) were taking place in order for them to match the desired SR. It would be interesting to observe vertical oscillation of the center of mass, knee angles, hip angles, etc. and compare the differences in these factors as a result of changes to SR in novice runners.

Are changes to FSP beneficial for novice runners? We know that different FSPs put different demands on the body, thus a change in FSP and SR may be beneficial in regards to the prevention or treatment of injury. A change in FSP through SR manipulations may be helpful if novice runners are predisposed to a certain running injury due to their running technique or to areas of weakness (joints, ligaments, tendons, muscles) possibly due to past injuries (sport related or not). Training errors (i.e. increases in mileage and/or intensity of training by too much or in too short of a time period) may occur, especially in the case of novice runners, and an injury could develop as a result. Under this circumstance, manipulation of SR in a way that alters their FSP and decreases the demand on the injured area may allow the novice runner to recover more quickly and/or continue participating in the sport (Heiderscheit et al., 2012). This desired change in SR and FSP could be facilitated by having a novice runner listen to a metronome during training runs and focus on matching their SR to the beat of the metronome. Furthermore, if and when continued research of FSPs determines if one FSP is clearly more advantageous, our findings demonstrate that SR is a way to shift FSP.

In regards to a novice runner's RE, a manipulation of SR may be warranted if, based on their measurements of VO_2 during each condition of SR, the runner appears to be uneconomical at their preferred SR and a shift in SR would improve their RE enough to produce significant changes in performance. Morgan et al. (1994) defined uneconomical VO_2 measurements as a deviation in VO_2 between optimal stride length and freely chosen stride length that was greater than or equal to 0.5 mL/kg/min. Because changes in SR can alter overall running biomechanics and the possible repercussions of doing so are not completely understood, this standard may be too conservative and a larger difference in VO_2 may be required for a change in SR to be justified.

Another implication from our findings may be the use of SR as a way for a RFS runner to transition into running in barefoot/minimalist type shoes, which has recently become a popular trend (McDougall, 2011). Barefoot/minimalist type shoes are designed for a MFS or FFS FSPs, and most are lacking the additional cushioning and structure of traditional running shoes (Lieberman et al., 2010), which is necessary for RFS (Cavanagh & Williams, 1987). Increasing SR while running in traditional shoes may be a safer way to transition to MFS or FFS and into barefoot/minimalist type shoes because the transition takes place with the safety of the cushioning/structure of the traditional shoe as a protection. In summary, there may be some valid situations for using SR to change a runner's FSP, but considerations to do so would need to be evaluated on a case by case basis. The approach to prevent or reduce injury, improve RE, or the decision to transition to barefoot/minimalist type footwear should be unique to the characteristics that make up an individual's running technique.

In conclusion, manipulations of SR can cause shifts in FSP in novice runners, and these SR changes within ±10% of preferred SR cause trivial to modest changes in VO_2 consumption.

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APPENDIX:

Name: ______________________________ Age:______

RUNNING HISTORY QUESTIONNAIRE

1. Approximately how many years of total cumulative running have you participated in?
    a. < 1 year
    b. 1-2 years
    c. 3-5 years

2. Are you currently involved in a consistent running program? If yes, how many weeks or months have you been involved?

3. How many days a week are you currently running?

4. How many miles do you currently run during the week?

5. Do you have any treadmill running experience? YES or NO
   If so, how would you rate the amount of time you spend running on a treadmill?
    a. Hardly ever
    b. occasionally
    c. sometimes
    d. frequently
    e. almost always

6. Please list any lower extremity injuries you have had and how long ago they occurred.

7. What type of shoes do you currently run in? List brand, model, and type (neutral/cushion, stability, or motion control). (Example: Nike Pegasus – neutral/cushion)