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Original Research

The Effects of Intermittent Sprint Training on Running Economy and Leg Stiffness in Highly Trained Runners

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Abstract

International Journal of Exercise Science 18(5): 290-305, 2025. https://doi.org/10.70252/SKPQ5840 The purpose of this study was to evaluate the impact of once-weekly sprint training on running economy (RE) and leg stiffness (LS) in highly trained athletes (12 M, 13 F, mean age 24.8 ± 7.1). Participants were recruited based on weekly exercise volume (minimum 4 hours) and athletic ability calculated by World Athletics score (minimum 500). RE and LS were evaluated at three velocities before and after 12 weeks of once-weekly sprint training. On average, participants experienced a non-statistically significant improvement in RE (average percent change -2.0 ± 5.6%, -1.2 ± 5.2%, -1.0 ± 4.6%, p = 0.389, 0.269, 0.272, Cohen's d = 0.21, 0.18, 0.17), and a statistically significant improvement in LS (12.59 ± 9.2%, 11.49 ± 10.9%, 15.67 ± 11.2%, p = 0.019, 0.027, 0.011, Cohen's d = 0.61, 0.56, 0.68) at the three running velocities. Interestingly, the improvement in LS was significantly influenced by a reduction in vertical displacement during the gait cycle (-17.7 ± 11.7%, -15.7 ± 12.2, -17.3 ± 13.4%, p < 0.001, = 0.001, = 0.001, Cohen's d = 1.10, 0.93, 0.91). Changes in RE and LS were significantly different when data were analyzed by exercise volume during the intervention period ($p < 0.05$). The present study demonstrates that LS, independently shown to improve performance and RE, can be improved by sprint training in highly trained athletes. Additionally, the average participant improvement in RE suggests that sprint training may lead to statistically significant improvement with an increase in participants and tighter participant training control.

Keywords: Running performance, elite runners, biomechanics

Introduction

For years, VO_2 max was considered one of, if not the sole major contributor to running performance. [1–3] While VO_2 max is still vital, running economy (RE) has been described to be a more accurate predictor of running performance.[4–6] RE is defined by Barnes et al. as the energy demand required to run at a constant submaximal velocity.[7] RE can be expressed in several different units (mL/kg/min, mL/kcal/min, L/min) and is impacted by many different variables. While many factors that impact RE are innate and cannot be changed, training quality and quantity can and do influence RE.[8] Changes in training can influence RE by modulating one or more of metabolic, cardiorespiratory, biomechanical, or neuromuscular efficiency. Of the many different training modalities, sprint training has been postulated to improve RE through improvements in biomechanical and neuromuscular efficiency.[9] Improvements in biomechanical efficiency can be due to more efficient kinetics of the gait cycle; however, optimization of gait style or pattern may also be observed.[7] Improvements in neuromuscular efficiency can be due to improved neural signaling and motor programming.[7] Several studies have investigated the relationship between sprint training or ability and RE, with several investigations showing positive performance results.[3,10–12] The discussion of the effects of sprint training on the RE of highly trained athletes remains understudied. While work has been done correlating sprint training with improved RE in moderately trained athletes,[9] no prospective study has demonstrated positive change in RE secondary to sprint training protocols in highly trained athletes.

Sprint training is hypothesized to impact RE by modulating biomechanical and neuromuscular efficiency. Biomechanical and neuromuscular efficiency are influenced by many variables, of which leg stiffness (LS) was of particular interest to the authors. LS is a measure of how rigid the plant leg is during the gait cycle, with higher stiffness shown to be correlated with improved RE.[13] While there are several ways to calculate LS, the present study elected to utilize the spring-mass model.[13–17] This model was first described by R. Blickhan in 1989 and is calculated with the leg portrayed as a spring during the gait cycle.[17] As a spring becomes stiffer, it is capable of storing more potential energy during the stance phase that can be converted to kinetic energy during the propulsive phase of the gait cycle.[17] Additionally, the stiffer the leg is during the stance phase, the less vertical displacement of the center of mass a runner will experience. This allows the lower limb musculature to utilize energy more efficiently in the propulsion of the body forward, rather than utilizing extraneous energy returning the center of mass to its necessary vertical position prior to forward propulsion.

The minimal number of peer-reviewed literature investigating the impact of sprint training on RE in highly trained athletes was instrumental in formulating the hypothesis for the present study. Additionally, the previously described relationship between LS and RE,[13] as well as the theoretical connection between LS and sprint training, further contributed to the formation of the hypothesis. The authors of the present study propose that once-weekly sprint training in highly trained athletes will result in an observable improvement in RE and LS at the conclusion of the 12-week intervention period.

Methods

Participants

Elite runners were recruited through social media advertisement and word of mouth. Eligible participants met the following criteria 1) between 15 and 40 years of age, 2) no current or past cardiopulmonary or cardiovascular disease, 3) free from acute illness, 4) exercised strenuously for more than four hours weekly for eight weeks prior to study initiation , 5) achieved a performance that earned a World Athletics score of greater than 500 in the last five years.[18]

Participants were deemed ineligible if the above criteria were not met. Sample size was calculated utilizing G*Power software (version 3.1.9.3, Universität Kiel, Germany). For a two-tailed paired *t-test*, a minimum sample size of 15 was determined given desired study power of 80%, and effect size of 0.80, and Type I error of 0.05.[19] For a single-tailed paired *t-test*, a minimum sample size of 12 was determined given desired study power of 80%, and effect size of 0.80, and Type I error of 0.05.[19] The effect size of 0.80 was chosen based on previous work examining the effects of intermittent sprint and plyometric training on running performance.[9]

This project was funded by Liberty University College of Osteopathic Medicine Center for Research and Scholarship (Index code MR2328). Subjects were compensated for their participation following the completion of their testing protocol.

Protocol

Prior to initial testing, participants signed informed consent to establish eligibility for participation. All procedures were conducted in compliance with Institutional Review Board approval (Liberty University IRB-FY22-23-866). All research was completed in full agreement with the ethical standards of the *International Journal of Exercise Science*.[12] Eligible participants reported to Liberty University (Lynchburg, VA) to perform testing in the Human Performance and Biomechanics Laboratories. Participants underwent initial testing and returned twelve weeks later for follow-up testing.

After completion of informed consent, participants verbally reported their mean six-month volume of running as well as their personal best in various race events over the past five years. Participant then had their height (cm), and weight (kg) measured (Health-o-meter Professional, model 500KL, McCook, IL) and recorded in the Human Performance Laboratory. Participants then completed a ten-minute warm-up at a participant chosen pace that was slower than 70% of their reported 10 km pace.[13] Upon completion of the warm-up participants stepped off the treadmill and were fitted with a Hans Rudolph 7450 series 2 V2 mask and headgear (Lenexa, KS). Once the mask was fitted properly participants stepped back onto the treadmill and were connected to a Parvo Metabolic Cart 2400 calibrated to industry standards (ParvoMedic, Salt Lake, Utah). VO_2 was collected and reported throughout each stage. Participants completed three interval running stages: stage one consisted of running at 70% of current 10 km pace, stage two at 80% of current 10 km pace and stage three at 90% of current 10 km pace. Previous investigations have utilized 75%, 85%, and 95% speed at lactate threshold as velocities for RE evaluation;[20] however, lactate testing was unavailable and thus 70%, 80%, and 90% of 10 km pace was utilized as a substitute. If current 10 km pace was unknown, an approximate conversion was made using recent performance results and the World Athletics Scoring tables.[18] Steady state running was considered as achieved if the change in VO_2 was less than 10% different from one 30 second collection period to the next. In standard running economy measurement, data is typically recorded for one to two minutes following achievement of steady state oxygen consumption.[13,21,22] To further reduce error, in the present study, participants continued running for three minutes at steady state VO_2 after steady state oxygen consumption was achieved. Following the completion of each stage, participants performed two to three minutes of active recovery on the treadmill at a self-selected recovery pace and then entered the next stage.[11] After the final stage, subjects jogged at a self-selected pace for two to five minutes.

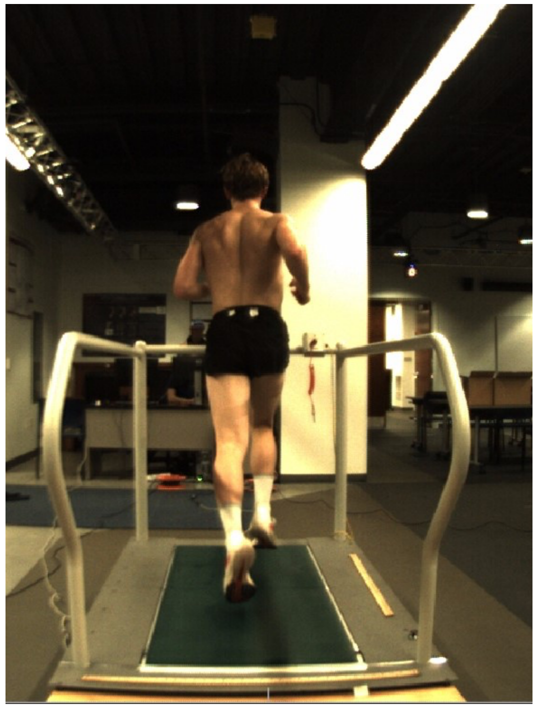

Figure 1. Participant with indicators placed on the posterior superior iliac spine bilaterally to indicate center of mass.

In the Biomechanics laboratory, participant leg length (cm) was measured from the floor to the greater trochanter; and center of mass was marked with athletic tape on the posterior superior iliac spine (Figure 1).[13] Subjects were then instructed to step onto an instrumented treadmill (AMTI, Model DBLEEWI-2, Watertown, MA). The treadmill was brought to a jogging speed slower than 70% of reported 10 km pace for one minute. To standardize speeds between the laboratories utilized in this study, participants ran at 70%, 80%, and 90% of their reported 10 km time while ground reaction force (sampling rate: 1000 Hz) and 2D video (sampling rate: 100 Hz) in both sagittal and frontal planes (Vicon, Model: Bonita 720c, Centennial, CO). Data were captured for eight seconds at each velocity to ensure that an adequate number of steps were recorded for analysis.[23,24] Following completion of the three stages, treadmill speed was slowed to a jogging pace and participants safely dismounted the treadmill. Maximum vertical ground reaction force as well as ground contact time were recorded for five randomly selected consecutive right steps that occurred during the 8-second data capture. Video data were transferred to a video analysis program (*Kinovea*, *Version 0.9.5*; Kinovea open-source project, www.kinovea.org) where vertical displacement using marked center of mass was measured and recorded for the same five steps analyzed previously. This process was repeated for each 70%, 80%, and 90% of 10 km pace trial. The spring-mass model for calculating LS calculations was completed utilizing the equations (Figure 2):[13,15–17]

1. $K_{leg} = F_{max} / \Delta L$
2. $\Delta L = \Delta y + L_0 (1 - \cos\theta)$

3. $\theta = \sin^{-1} [(v * Tc) / (2 * L_0)]$

where F_{max} is peak ground reaction force (vGRF); ΔL is change in leg length during stance phase of gait cycle; Δy is vertical displacement of center of mass during stance phase of gait cycle; L_0 is resting leg length; θ is the angle between the leg at initial ground contact and the vertical axis; v is the horizontal running velocity; Tc is ground contact time.

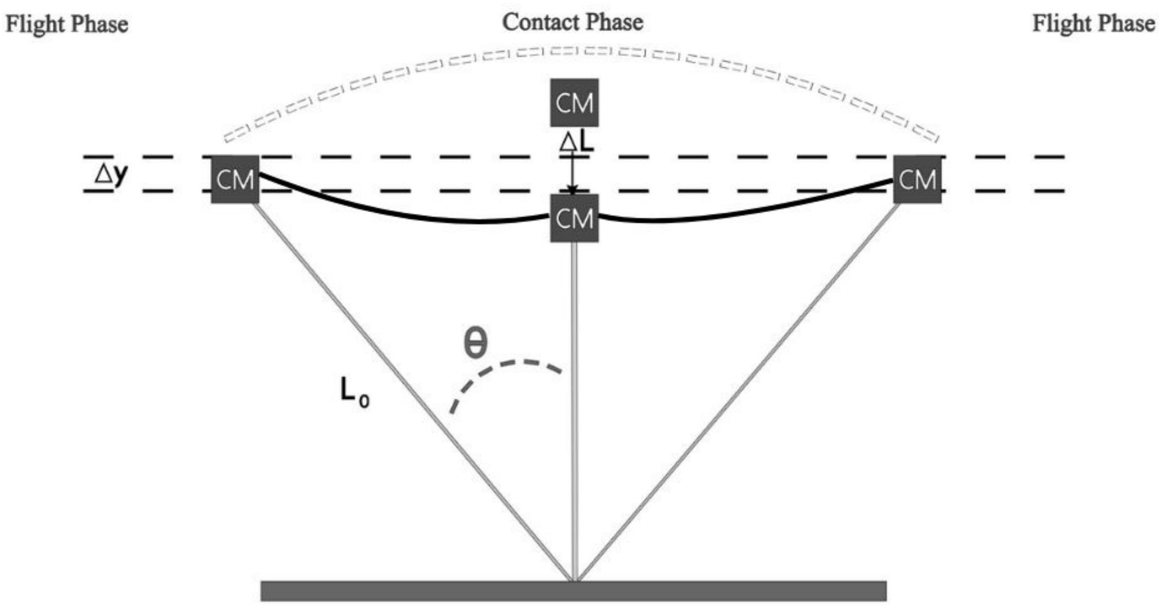

Figure 2. The spring-mass model utilized to determine the stiffness of the leg during the gait cycle. L_0 is resting leg length. ΔL depicts the maximal compression of leg during stance phase of the gait cycle. Δy depicts the vertical displacement of center of mass during the gait cycle. **θ** depicts half the angle traversed by the leg during the stance phase of the gait cycle. *Adapted from Figure 2, Li et al., 2019.* [13]

Table 1. Sprint workout regimen undergone by participants of the present study.

Week	Workout	Rest
1	2x(6x30m) sprints	2′ btw reps, 3-4′ btw sets
2	2x(8x30m) sprints	2′ btw reps, 3-4′ btw sets
3	3x(4x40m) sprints	2′ btw reps, 3-4′ btw sets
4	4x40m, 3x50m, 2x60m sprints	2′ btw 40m/50m reps, 3′ btw 60m reps, 3-4′ btw sets
5	3x(3x60m) sprints	2′ btw reps, 3-4′ btw sets
6	2x(5x50m) sprints	2′ btw reps, 3-4′ btw sets
7	8x60m sprints	3′ btw reps
8	3x50m, 3x60m, 2x80m sprints	2′ btw reps, 3-4′ btw sets
9	3x(3x80m) sprints	2′ btw reps, 3-4′ btw sets
10	8x80m sprints	2′ btw reps 1-4, 3-4′ btw reps 5-8
11	2x(3x90m) sprints	2′ btw reps, 4′ btw sets
12	2x60m, 2x80m, 2x100m sprints	3′ btw reps, 4′ btw sets

m = meter; btw = between; reps = repetitions

The intervention was a 12-week protocol of sprint workouts, developed by the authors, incorporated into each participant's own standard endurance exercise regimen (Table 1). Sprint workouts were to be completed on solid ground (*i.e.* not on a treadmill), however, the specific surface or location (indoors vs. outdoors) was up to the discretion of each participant. Throughout the course of the intervention period, the length of the sprints increased; however, the intensity of each sprint and week was to be equal. Participants were instructed to begin each sprint with a jogging start and to run as fast as possible without straining. Participants were considered to have completed the study protocol if they provided electronic documentation of completion of workouts.

Statistical Analysis

Intervention-related change for the study population was analyzed on both an individual and population level. Statistical analyses were conducted via JMP Pro 17 (JMP®, Version *17*. SAS Institute Inc., Cary, NC, 1989–2023). Measurements of both RE and biomechanical data (leg stiffness (k), ground contact time (Tc), ground reaction force (vGRF/kg), and pelvic height change (Δy)) at 70%, 80%, and 90% 10k pace were recorded pre- and post-intervention and compared for each participant at each pace. The intervention would be considered successful only when a decrease in RE was measured. Only increases in k and vGRF/kg would allow for a successful intervention; similarly, only decreases in Tc and Δy were considered successful outcomes. Therefore, paired, single-tailed t tests were conducted comparing pre- and post-intervention RE data within both the male and female cohorts. To further assess the effects of the studied intervention, the study population was analyzed statistically for *any* predictable changes in RE and biomechanical data pre- and post-intervention using dependent, two-tailed *t test* analysis. Independent, two-tailed t tests were conducted comparing post-intervention RE and biomechanical data between males and females, participants in the top vs. bottom half of the population's intra-study weekly training volume, participants in the top vs. bottom half of the study's pre-intervention weekly training volume, participants with top vs. bottom half World Athletic score, and participants aged greater than or equal to 30 years old vs. those aged less than 30 years old. To standardize the difference between mean values, all appropriate *t-test* analyses were accompanied by Cohen d analysis, with values ≤ 0.50 indicating small effect size, values between 0.51 – 0.80 indicating medium effect size, and values ≥ 0.81 indicating large effect size.[25]

Results

Twenty-nine participants were recruited for the study and completed initial testing. Of these, four participants failed to complete the intervention due to injury or other circumstances. In total, twenty-five participants (12 males, 13 females) completed the study and were used for statistical analysis. Partial participant demographics is presented in Table 2.

On average, participants improved their RE at all three evaluation velocities (70%, 80%, 90% of 10 km pace) across two definitions of RE (mL/kg/min, kcal/kg/min) (Tables 3, 4, 5). Biomechanical data also indicated gross mean improvement with LS (k), ground contact time (Tc), vertical displacement (Δy) improving across all three evaluation velocities (Tables 3, 4, 5). Maximal ground reaction force vGRF/kg improved at 90% of 10 km pace (Table 5).

Table 2. Participant demographics, including participant: ID, age, sex, maximal World Athletic score (WAS), exercise volume in the 8 weeks preceding intervention period in hours per week, exercise volume during the intervention period in hours per week, and actual, estimated, or calculated 10km time used for pace calculation. Participants 1, 5, 6, and 11 were unable to complete the study.

Participant	Age	Sex	WAS	Pre-I Volume	Intra-I Volume	10km Time
2	18	M	808	13.5	16.1	32:12
3	23	F	787	7	7.0	40:15
4	23	M	739	7	7.2	32:42
7	21	M	800	7	4.6	34:37
8	21	F	769	7	6.4	39:40
9	20	F	690	7	4.2	42:00
10	18	M	632	7	6.9	35:05
12	18	M	666	8	7.0	34:35
13	35	F	867	5	5.7	40:45
14	36	M	762	7	5.5	34:00
15	20	M	710	7	7.4	34:00
16	20	M	741	7	5.0	34:30
17	21	F	894	7	4.7	43:39
18	31	F	809	7	7.8	39:00
19	35	F	688	7	5.5	43:47
20	18	F	752	7	6.4	41:30
21	36	M	510	7.5	5.4	37:00
22	39	M	786	6	5.6	37:30
23	36	F	714	9	7.4	43:00
24	19	F	772	11	9.6	43:30
25	23	F	863	10	8.1	43:00
26	22	M	660	10	8.0	36:00
27	24	F	871	4.5	4.0	39:00
28	24	F	824	4.5	4.5	39:00
29	19	M	769	10	10.7	36:30

The average participant percent improvement or lack thereof was variable with 17 participants experiencing improvement (Range: -0.22% – -13.75%) and eight participants experiencing a worsening of RE (Range: 1.02% – 15.25%) (Figure 3). While still variable, the improvement of LS was observed in more participants, with 20 of 25 subjects experiencing improvement across all three evaluation velocities (Figure 4).

Table 3. Mean pre- and post-intervention values with standard deviation at 70% of 10km pace (mean ± SD).

	Mean Pre-Intervention	Mean Post-Intervention	Mean Percent Change	*p*	*d*
RE (mL/kg/min)	36.0 ± 4.1	35.3 ± 3.1	-2.0 ± 5.6%	0.389	0.21
RE (kcal/kg/min)	0.96 ± 0.07	0.94 ± 0.07	-1.9 ± 6.2%	0.231	0.21
Leg Stiffness (kN/m)	11.2 ± 2.1	12.7 ± 2.6	14.5 ± 8.7%	0.019*	0.61
vGRF (N/kg)	24.6 ± 2.4	24.4 ± 2.5	-0.90 ± 4.2%	< 0.001*	0.07
Tc (s)	0.22 ± 0.02	0.22 ± 0.02	-0.56 ± 4.5%	0.395	0.08
Δy (cm)	0.088 ± 0.02	0.072 ± 0.01	-17.7 ± 11.7%	< 0.001*	1.10

*SD, Standard deviation; RE, Running economy; vGRF, maximal vertical ground reaction force; Tc, ground contact time; Δy, vertical displacement; *, p < 0.05; d, Cohen's d.*

Table 4. Mean pre- and post-intervention values with standard deviation at 80% of 10km pace (mean ± SD).

	Mean Pre-Intervention	Mean Post-Intervention	Mean Percent Change	*p*	*d*
RE (mL/kg/min)	41.2 ± 4.5	40.5 ± 3.7	-1.2 ± 5.2%	0.269	0.18
RE (kcal/kg/min)	0.97 ± 0.06	0.96 ± 0.07	-0.55 ± 5.6%	0.363	0.50
Leg Stiffness (kN/m)	11.7 ± 2.1	13.0 ± 2.5	14.1 ± 10.5%	0.027*	0.56
vGRF (N/kg)	25.2 ± 2.5	25.1 ± 2.7	2.2 ± 6.0%	0.556	0.04
Tc (s)	0.208 ± 0.02	0.205 ± 0.02	-2.8 ± 3.0%	0.327	0.13
Δy (cm)	0.079 ± 0.02	0.066 ± 0.01	-15.7 ± 12.2%	0.001*	0.93

*SD = Standard deviation; RE = Running economy; vGRF = maximal vertical ground reaction force; Tc = ground contact time; Δy = vertical displacement; * = p < 0.05; d = Cohen's d.*

Table 5. Mean pre- and post-intervention values with standard deviation at 90% of 10km pace (mean ± SD).

	Mean Pre-Intervention	Mean Post-Intervention	Mean Percent Change	*p*	*d*
RE (mL/kg/min)	47.0 ± 5.0	46.1 ± 4.8	-1.0 ± 4.6%	0.272	0.17
RE (kcal/kg/min)	0.99 ± 0.06	0.98 ± 0.07	-0.2 ± 5.8%	0.332	0.13
Leg Stiffness (kN/m)	12.0 ± 2.5	13.9 ± 2.9	17.0 ± 10.5%	0.011*	0.68
vGRF (N/kg)	25.8 ± 2.4	26.2 ± 2.8	2.2 ± 6.0%	0.301	0.14
Tc (s)	0.197 ± 0.02	0.192 ± 0.02	-2.8 ± 3.0%	0.133	0.32
Δy (cm)	0.070 ± 0.02	0.057 ± 0.01	-17.3 ± 13.4%	0.001*	0.91

*SD = Standard deviation; RE = Running economy; vGRF = maximal vertical ground reaction force; Tc = ground contact time; Δy = vertical displacement; * = p < 0.05; d = Cohen's d.*

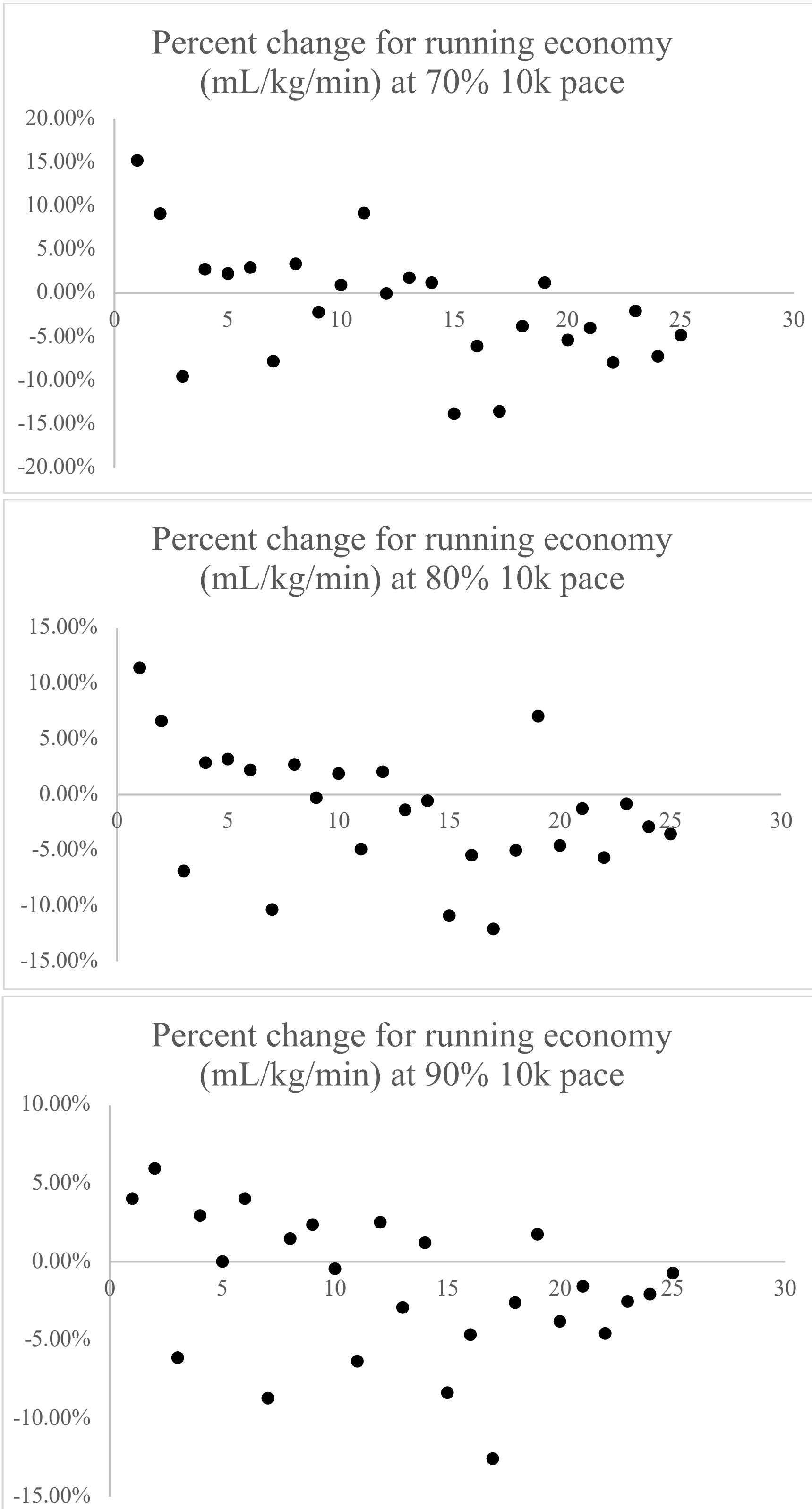

Figure 3. Participant percent change between pre- and post-intervention for running economy (mL/kg/min) at 70%, 80%, and 90% of 10k pace.

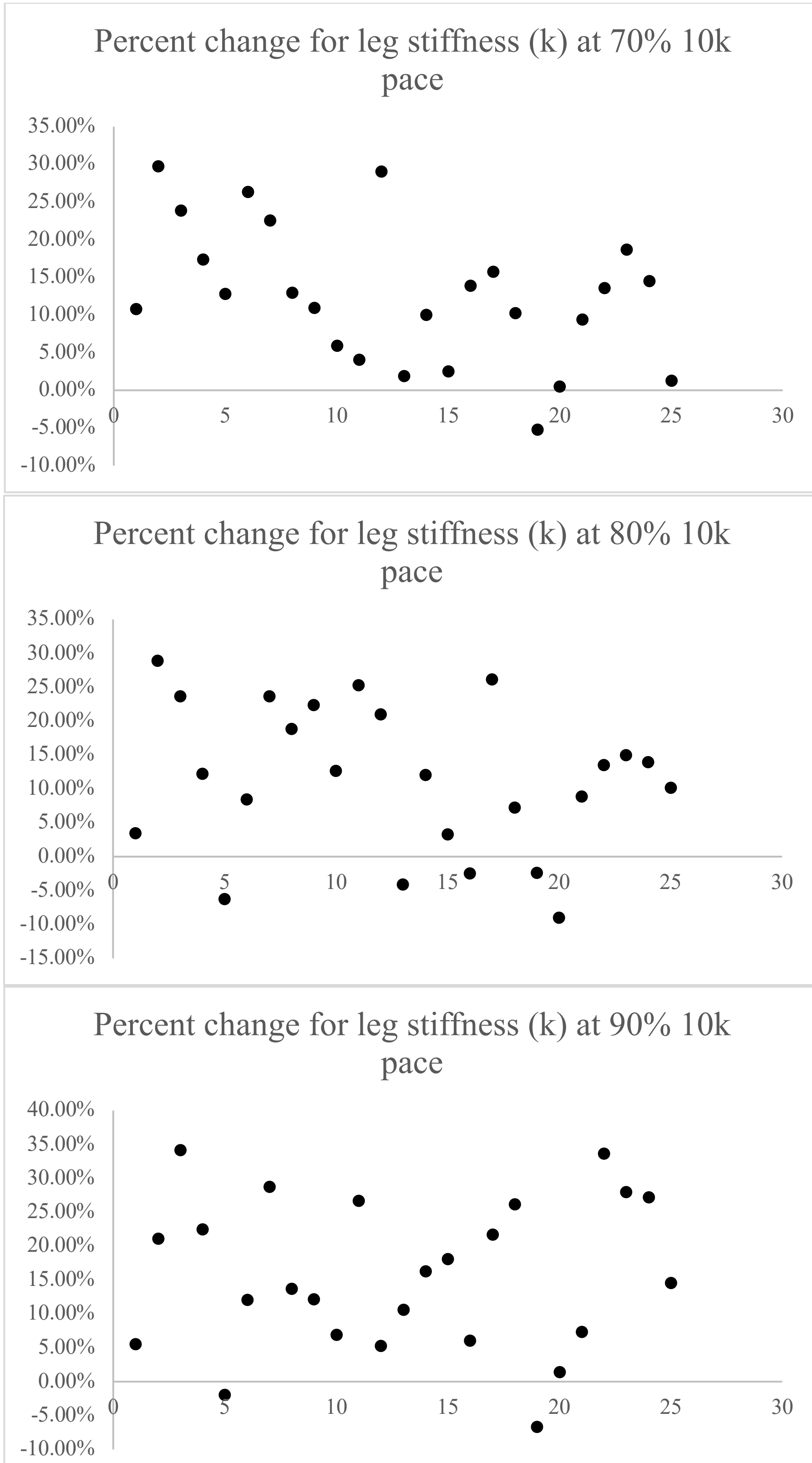

Figure 4. Participant percent change between pre- and post-intervention for leg stiffness (k) at 70%, 80%, and 90% of 10k pace.

Pre-intervention and post-intervention data were also analyzed on an entire cohort basis, indicating significant change in LS (p = 0.019, 0.027, 0.01, Cohen's d = 0.61, 0.56, 3.91) and change in vertical displacement (p < 0.001, = 0.001, = 0.01, Cohen's d = 1.10, 0.93, 0.91) at all three velocities and vGRF/kg at 70% of 10 km pace (p < 0.001, Cohen's d = 1.05).

To evaluate if the study outcome was influenced by participant sex assigned at birth, results were compared between males and females using Cohen's d calculation for effect size. Analyses indicate a medium effect size for mL/kg/min at 70% of 10k pace (Cohen's d = 0.55), kcal/kg/min at 70% and 80% of 10k pace (Cohen's d = 0.58, 0.63), vGRF/kg at 80% and 90% of 10k pace (Cohen's d = 0.62, 0.75), and Tc at 80% of 10k pace (Cohen's d = 0.75). There were no calculations that indicated a large effect size.

Male and female participant results were isolated and compared within each sex. Statistical analyses for the male cohort indicate a significantly different response to the intervention in Δy across all three evaluation velocities (p = 0.007, 0.032, 0.031, Cohen's d = 1.12, 0.80, 0.81). While not significant, mL/kg/min (p = 0.113, 0.169, 0.266) and kcal/kg/min (p = 0.066, 0.188, 0.295) in males appear to be trending towards significance. Statistical analyses for the female cohort indicate a significantly different response to the intervention in LS at 70% and 90% of 10k pace (p = 0.049, 0.046, Cohen's d = 0.68, 0.69) and Δy across all three evaluation velocities (p = 0.005, 0.006, 0.006, Cohen's d = 1.10, 1.07. 1.10).

To evaluate if the study outcome was influenced by weekly exercise volume during the intervention period, participants were divided into an upper and lower half by intra-intervention volume. Statistical analyses indicate a significantly different response to the intervention in mL/kg/min at all three evaluation velocities (p = 0.008, 0.047, 0.044, Cohen's d = 1.20, 0.85, 0.87), kcal/kg/min at 70% of 10k pace (p = 0.028, Cohen's d = 0.94), and LS at 70% and 80% of 10k pace (p = 0.013, 0.033, Cohen's d = 0.82, 0.91).

Data were analyzed by participant ability, with subjects divided into an upper and lower half by best performance World Athletic Score.[18] Statistical analyses indicate no significantly different response to the intervention.

To evaluate if the study outcome was influenced by weekly exercise volume before the intervention period, participants were divided into an upper and lower half by pre-intervention volume. Statistical analyses indicate no significantly different response to the intervention across all data points.

To evaluate if the study outcome was influenced by participant age, results were compared between participants of age greater than 30 and participants of age less than 30. Statistical analyses indicate a significantly different response to the intervention in Tc at 70% of 10k pace (p = 0.011, Cohen's d = 0.83).

Discussion

Several previous studies have investigated the influence of sprint training, or similar explosive, power-based workouts, on RE.[3,10,11,26] These investigations have demonstrated mixed results, with two showing an improvement of RE or performance,[11,26] and two studies showing no change in RE.[5,10] Additionally, studies most similar to the present study either recruited moderately trained participants,[9] or observed no change in RE following sprint training.[10] The present study expands the relationship between sprint training and RE to highly trained athletes. Limited research outside of the present study have investigated the impact of sprint training on LS, which has been shown to independently improve RE.[13]

The results of the present study indicate that a once-weekly sprint training regimen may improve RE in highly trained runners; however, the relationship is unclear (Table 3). Previous research has utilized high-quality athletes to investigate the static relationship between RE and explosive characteristics, such as sprinting ability and peak force production.[2,12] Additionally, other studies have recruited moderately trained athletes or have not observed an improvement in RE following a sprinting regimen intervention.[10,11] To the knowledge of the authors, this study is the first to observe an improvement in RE by average participant percent change following a sprint training regimen while recruiting highly trained athletes. Importantly, this improvement in RE was observed across both definitions of RE utilized (mL/kg/min, kcal/kg/min). These results support previous literature that demonstrated high intensity, short duration activity, specifically weight and explosive training, leads to an improvement of RE.[2,26] Training of untrained or moderately trained athletes may be undifferentiated and may respond positively to any endurance or strength-based regimens. This could cause a false conclusion to be made regarding the impact of sprint training on RE. Lum et al. investigated the impact of sprint training on RE in moderately trained athletes;[9] however, the present study supports that RE can be improved by sprint training in highly trained athletes as well. The results of our study demonstrate this generalizability even further, as there was no difference in the response to the intervention between the top and bottom half of performers based on participant's maximal World Athletics score. Additionally, based on the results of the present study, sex, age (between 15-40 years), and pre-intervention weekly exercise volume may not influence a response of RE to the study intervention. Our findings suggest that improved RE as a result of a 12-week once-weekly sprint training regimen can be generalized to a wide range of individuals.

While a mean improvement in RE was seen by percent change over the course of this study, the standard deviation indicate that the effect may be highly variable. This may also explain why *t*-tests did not yield significant results when RE was analyzed with an alpha value set at 0.05. While these results do not suggest that RE is strongly influenced by sprint training, the average participant improved and there is a trend towards statistical significance. It is likely that with a larger sample size of participants, and potentially with tighter control over participant training, the standard deviation will narrow and RE results will become significant by statistical analyses.

To ensure our results were not simply due to one subgroup experiencing significantly higher levels of improvement, data were analyzed to isolate several different variables which showed no difference in RE or LS response with regards to age (between 15-40 years) or pre-intervention weekly exercise volume. However, a difference was observed when participants were separated based on intra-intervention weekly exercise volume. Participants who recorded more weekly exercise volume during the intervention period experienced a greater improvement in RE, consistent with previous studies showing increased running volume being correlated with an improvement in RE.[1,23,27,28] Participants in the present study who recorded more hours of exercise during the intervention period may have provided additional stimulus for this improvement in economy. This theory suggests that a percentage of the improvement in RE can be attributed to overall exercise volume and not to the sprint intervention alone. Additionally, the mean percentage change for men and women for each variable was analyzed by Cohen's d calculation. This showed a medium effect size for several biomechanic and RE data. This could indicate a difference in response to sprint training between men and women; however, since no instances of large effect size were appreciated and instances of medium effect size were not consistent across measured variables, this difference is expected to normalize as sample size and more study control is achieved.

The majority of participants (68%) experienced an improvement in RE; however, the improvement in LS was far greater. Across all three velocities of evaluation, mean LS improved drastically, influenced by a reduction in vertical displacement (Δy) during the gait cycle (Table 3). In the calculation of LS, the less vertical displacement the spring (leg) undergoes during the stance phase of the gait cycle, the stiffer and more efficient the spring. Between the pre- and post-intervention testing, the mean Δy decreased by a large margin while other variables in LS improved slightly (Tc), or variably (vGRF and vGRF/kg) (Table 3). It appears that as participants completed the sprint workouts, the primary adaptation was a decrease in Δy which greatly contributed to an improvement in LS and may also help explain the improvement in RE. The more the center of mass of a runner descends vertically during the gait cycle, the more energy the musculoskeletal system must expend to raise the center of mass back to the height of the gait cycle for the next step. If the runner's center of mass descends less during that cycle, less energy is required for each step, leading to improved economy at the same velocity.[29,30]

Not only was mean improvement in LS much higher than in RE, but 80% of participants experienced an improvement in LS at all three evaluation velocities, and 96% experienced an improvement in LS at one or more evaluation velocities (Figure 4). It is possible that while sprint training improved the LS of almost every athlete, the impact of LS on RE is variable between participants. As RE is impacted by a large number of variables,[5,7] it is probable that an individual's RE is influenced by each variable to different degrees. Therefore, it is recommended that further studies investigate this topic to formulate a method for predicting which athletes are likely to obtain a beneficial RE response to sprint training.

Limitations of this study exist, most prominently the inability to maintain a tighter control on participant training. Although the majority of participants (68%) experienced an improvement in RE, the response to the intervention was highly variable (Figure 3) and likely influenced by the study's non-control of physical activity levels outside of the intervention. Participants were instructed to include the assigned sprint workouts into their weekly training without changing any other training variables in their training; however, it was unlikely each participant's training during the intervention period was identical to their pre-intervention regimen. This presents both a limitation and an opportunity for future studies, as more rigorous control of participant training would allow for more concrete conclusions to be drawn from study data. Additionally, while testing was completed on a treadmill in an indoor setting, participant sprint workouts were to be completed on a surface other than a treadmill. While challenging logistically, future studies should attempt to test participants in a setting more similar to the intervention setting. Another limitation was the participant number. Although twenty-five participants is consistent with similar studies in scope and size;[3,10,11] a larger number of participants would have enhanced the current study's statistical power and generalization of results. While data was meticulously analyzed, the potential for human and machine error exists. It is recommended that future research build on the present study, such as implementing a randomized trial to compare changes in training volume to sprint training; or performing a cross-over study, in which participants complete the intervention and transition to a standard training regimen. Lastly, future research should investigate how the impact of sprint training on running performance directly translates to specific long-distance running event (*i.e.* 1500 meters, 5000 meters, etc.) performance.

The results of the present study indicate that a 12-week protocol of once-weekly sprint training improves LS in highly trained athletes. Additionally, the results of this study indicate that the investigated intervention is associated with a non-statistically significant improvement in RE. This fills a literature gap as there is limited research investigating this relationship in elite or sub-elite athletes. While the impact of sprint training on running performance was not evaluated in the present study, the improvement in running performance due to improved RE is well documented.[7] As RE improves for the average participant following once-weekly sprint training, running performance is expected to improve; however, the degree of performance improvement is currently unknown. Furthermore, LS has been shown to independently improve RE and is positively correlated with running performance.[13,27,31] This suggest that an improvement in LS may lead to an improvement in running performance even in the absence of an improvement in RE. While the specifics of RE and LS may not be directly important to some athletes, improved performance following sprint training should be of interest to athletes of all ability levels. Lastly, the results of this study demonstrated that the data outcomes are generalizable. While the sprint training schedule implemented in this study can certainly be utilized, the authors encourage athletes to seek the advice of highly qualified coaches trained in these areas prior to the introduction of such training. Athletes of all levels who are seeking to improve running performance should evaluate whether sprint training is a necessary inclusion in their training regimen. Inclusion of sprint training may additionally be a fruitful means of performance improvement for lifelong runners who feel their performance has stagnated under typical training regimens. Based on the results of this study, along with results of existing literature, athletes of all types and ability levels can utilize sprint workouts to supplement training as a means to improve running performance.

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