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Human Kinetics
ORIGINAL INVESTIGATION

Strength Training Improves Exercise Economy in Triathletes During a Simulated Triathlon

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Purpose: The completion of concurrent strength and endurance training can improve exercise economy in cyclists and runners; however, the efficacy of strength training (ST) implementation to improve economy in long-distance (LD) triathletes has not yet been investigated. The purpose of this study was to investigate physiological outcomes in LD triathletes when ST was completed concurrently to endurance training. ***Methods***: A total of 25 LD triathletes were randomly assigned to either 26 weeks of concurrent endurance and ST (n = 14) or endurance training only (n = 11). The ST program progressed from moderate (8–12 repetitions, ≤75% of 1-repetition maximum, weeks 0–12) to heavy loads (1–6 repetitions, ≥85% of 1-repetition maximum, weeks 14–26). Physiological and performance indicators (cycling and running economy, swim time, blood lactate, and heart rate) were measured during a simulated triathlon (1500-m swim, 60-min cycle, and 20-min run) at weeks 0, 14, and 26. Maximal strength and anthropometric measures (skinfolds and body mass) were also collected at these points. ***Results***: The endurance strength group significantly improved maximal strength measures at weeks 14 and 26 ($P < .05$), cycling economy from weeks 0 to 14 ($P < .05$), and running economy from weeks 14 to 26 ($P < .05$) with no change in body mass ($P > .05$). The endurance-only group did not significantly improve any economy measures. ***Conclusions***: The addition of progressive load ST to LD triathletes' training programs can significantly improve running and cycling economy without an increase in body mass.

Keywords: resistance, energy cost, cycling, running

Triathlon success is predominantly determined by the athletes' maximum sustained power or pace during competition and the energy cost associated with maintaining this movement.[1] The energy cost associated with this sustained power or pace is known as the athletes' economy, defined as the metabolic cost to cover a given distance at a constant velocity[1] and is considered to be a better indicator of performance than traditional measures, such as maximal oxygen consumption ($\dot{V}O_2max$).[2] In triathlon, specifically long distance (LD; >1500-m swim, 40-km cycle, and 10-km run), commonly referred to as "half iron" (1.9-km swim, 90-km cycle, and 21.1-km run) and "full iron" (3.8-km swim, 180-km cycle, and 42.2-km run) races the completion of each discipline has a negative influence on the economy of the subsequent discipline.[3] Traditionally, LD triathletes undertake large volumes of endurance training with the objective of improving economy; however, particularly in high-level athletes, improvements in cycling economy (CE) and running economy (RE) may be difficult to induce via endurance training alone. The identification of new training interventions to further improve the economy of endurance athletes, such as the addition of strength training (ST) to training programs, has therefore been extensively studied.[1,4–9]

The completion of concurrent endurance and ST can substantially load the neuromuscular system, resulting in improvements in musculotendinous stiffness, motor unit recruitment, rate of force development (RFD), and maximal strength.[1,4,5,8–11] This has been shown to lead to significant improvements in the economy of movement in both endurance cyclists[4,7,8,10] and runners.[1,6] While there is a large body of evidence supporting ST implementation for both cycling and RE improvements, there are only a limited number of studies examining its effects on triathlon physiological and performance variables[1,12,13] with 2 of these studies focusing on just one of the individual disciplines of triathlon in isolation and completed by participants who specialized in short-distance triathlons. Literature exploring the effects of ST in endurance cyclists and runners may also not be transferable to LD triathlon performance where athletes experience large volumes of accumulated fatigue throughout the competition (lasting anywhere between 3.5 and 17 h). The physical stress of completing 3 consecutive disciplines can induce ventilatory muscle fatigue, dehydration, metabolic changes, or biomechanical alterations which may negatively impact the economy of the succeeding discipline, and therefore is likely to negatively impact overall triathlon performance.[3] Due to the accumulative fatigue associated with performance in LD triathlon, to investigate the impact of ST on improving economy, the authors previously developed a LD triathlon simulation test, with high representative task design, which was demonstrated to have high reliability.[14] This performance test enables coaches and scientists to implement a valid method to accurately test training interventions and monitor athletes progress with confidence.[15]

Currently, no research has examined the performance and physiological improvements in LD triathletes from any form of ST implementation in all 3 disciplines of triathlon. Therefore, the purpose of the present study was to examine the effects of a 26-week progressive ST program in combination with preexisting endurance training on swim time, CE, and RE in LD triathletes. Furthermore, participants were tested in a simulated LD triathlon test to ensure that testing replicated race demands and fatigue.[14]

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It was hypothesized that the progressive ST program would significantly improve CE and RE during the simulated triathlon.

Methods

Experimental Approach to the Problem

A longitudinal experimental design was used to investigate the effect of a 26-week progressive load ST intervention on physiological (CE, RE, blood lactate [BLa], and heart rate [HR]) and performance (swim time and rating of perceived exertion [RPE]) indicators during a simulated triathlon. Anthropometric measures (skin folds and body mass) and maximal strength measures were also taken at baseline (week 0), mid (week 14), and post (week 26) intervention. Participants were tested using a validated simulated triathlon which replicated the demands of LD triathlon[14] at weeks 0, 14, and 26. Participants were randomized into either an endurance only (CON) group or an endurance strength (STR) group.

Subjects

A total of 30 triathletes comprising 29 trained[16] ($\dot{V}O_2$max run = 53.09 [8.18] $mL \cdot kg^{-1} \cdot min^{-1}$, $\dot{V}O_2$max cycle = 51.22 [8.62] $mL \cdot kg^{-1} \cdot min^{-1}$; males = 21, females = 8) and 1 professional male volunteered to participate in this study. All participants had completed at least one LD triathlon within 12 months of the study commencement. No participants had completed regular ST for 6 months prior to the study commencement. Participants were matched for years' experience in triathlon and average training hours per week and randomized into either the CON group (n = 15; males = 12, females = 3) or the STR group (n = 15; males = 10, females = 5). A total of 5 participants discontinued the study for the following reasons: one due to an injury, one moved to a new country, and 3 reported lack of time. Therefore, the final number of participants in each group were 14 (males = 10, females = 4) and 11 (males = 9, females = 2) in the STR and CON, respectively. Approval to conduct this study was granted by the University of Notre Dame, Australia, Human Research Ethics Committee (106101 F).

ST Intervention

In addition to endurance training, the STR group completed a 26-week progressive load ST program twice a week. The ST program was comprised of two 12-week periods with the initial 12-week period (weeks 0–12) consisting of a moderate load ST program (3–4 sets, 8–12 repetitions, ≥75% of 1 repetition maximum [RM]) and the second 12-week period (weeks 14–26) consisting of a heavy load ST program (1–6 repetitions, 3–5 sets, ≥85% of 1RM). There was a 2-week break between these 2 periods to allow for recovery from the ST. Endurance training continued as normal for both groups. The ST program consisted of 3 to 4 lower and one upper limb exercise per session. The lower limb exercises included a combination of 3 to 4 of the following per session; 90° knee angle squats, glute hamstring raises, weighted hip thrusts, single-leg (SL) leg press, SL seated calf raise, hip flexion, and hip abduction. The upper body exercise included one of the following per session; bent over row, latissimus dorsi (lat) pull down, or shoulder internal rotation. The exercises were selected to replicate movements and muscle groups utilized during triathlon. Participants were instructed to complete all exercises with a slow and controlled (3 s) eccentric phase, with their concentric phase completed as fast as possible. Participants warmed-up on a stationary bike for 5 to 10 minutes prior to each strength session, followed by 2 sets of 10 body weight squats. Each ST session was supervised by a qualified physiotherapist with strength and conditioning experience or a sport scientist.

General Training

Both groups maintained normal endurance training. As the participants were recruited from local clubs, it was not possible to control the participants' endurance training loads; however, all participants completed a weekly online training log which was monitored regularly by researchers. There were no significant differences between groups in training duration and intensity (RPE) at baseline or throughout the study (Table 1).

Testing Procedures

During weeks 0, 14, and 26, each participant completed a simulated triathlon, 4 maximal strength tests (1RM) and anthropometric testing. Anthropometric testing was completed on the same day prior to the maximal strength tests. All strength, physiological, and anthropometric testing were completed at the same time of day to avoid diurnal variation in performance and measurements.[17] Each participant was asked to consume the same diet and to complete the same training in the 24 hours prior to each test. Figure 1 outlines the timeline of testing completed.

Muscle Strength Assessments

All participants completed 1RM testing for 4 movements; 90° knee angle squat, independent arm lat pull down, SL (right) seated calf raise, and SL (right) leg press. Unilateral 1RM testing was completed to replicate the SL loading during running and cycling. All 1RM testing followed protocols as described in previous literature[8] after completing a minimum of a 5-minute self-paced "easy" cycle on a spin bike and 2 sets of 10 body weight squats.

Anthropometric Measures

Skinfolds were collected at baseline and postintervention by the same anthropometrist on the right side of the body. The sum of 8 skinfolds (using Harpenden skinfold calipers [Baty International Ltd, Burgess Hill, West Sussex, United Kingdom]) were taken from the bicep, tricep, subscapularis, supraspinale, iliac crest, abdominal, mid-thigh, and medial calf sites. All measures were

Table 1 Characteristics of Participants for STR and CON Groups

							Training hours (weekly)	
	Age, y	Height, cm	Body mass, kg	$\dot{V}O_2$max cycle, $mL \cdot kg^{-1} \cdot m^{-1}$	$\dot{V}O_2$max run, $mL \cdot kg^{-1} \cdot m^{-1}$	Triathlon experience, y	Weeks 0–14	Weeks 14–26
STR group (n = 14)	39 (6.2)	176.73 (9.87)	76.41 (17.08)	51.09 (9.09)	54.76 (8.25)	4.31 (3.25)	9.61 (4.09)	9.66 (4.14)
CON group (n = 11)	36 (10)	176.14 (8.27)	76.53 (12.42)	53.13 (9.05)	52.65 (8.82)	3.68 (2.39)	8.60 (4.28)	10.32 (5.04)

Abbreviations: CON, endurance only; STR, endurance strength. Note: Values are presented as mean (SD).

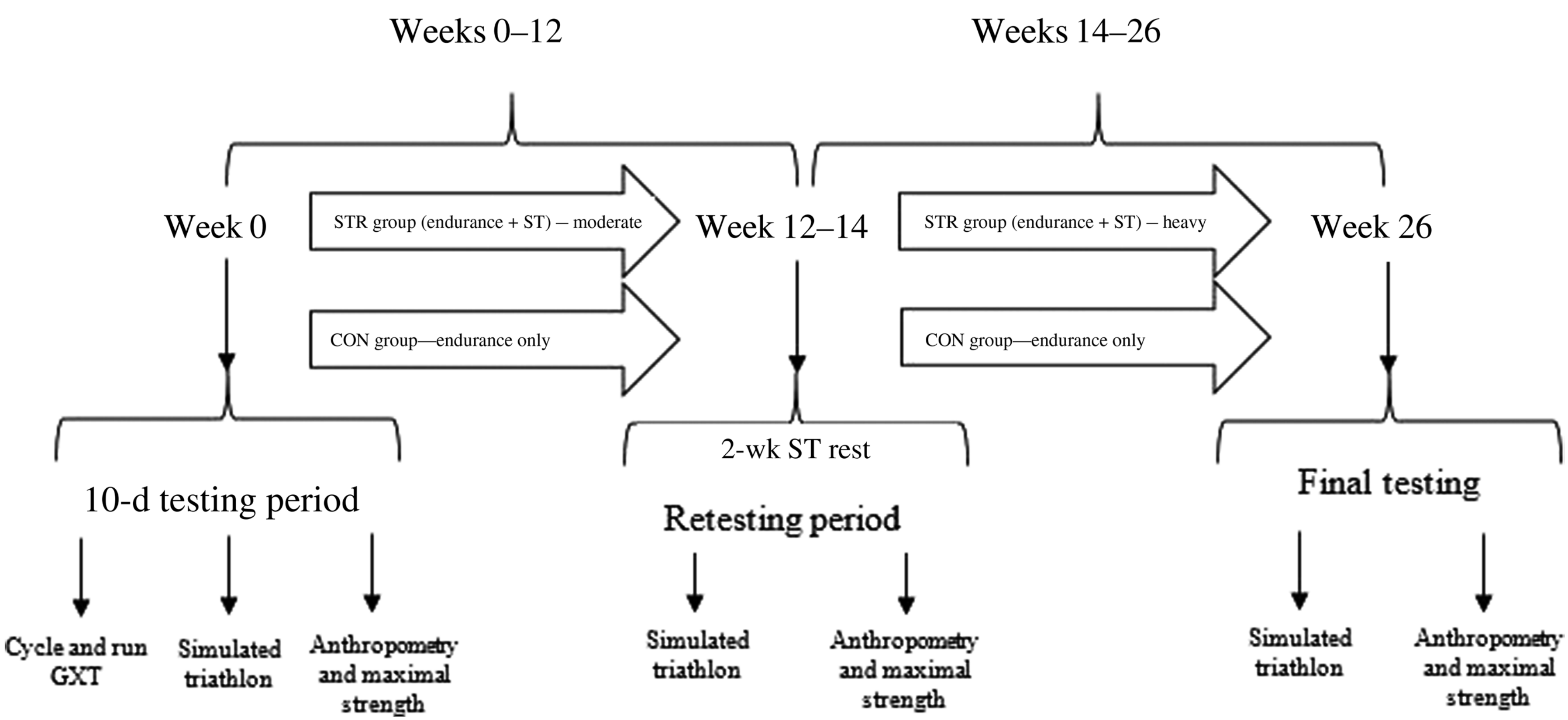

Figure 1 — Timeline of testing and intervention. Anthropometry testing indicates skinfolds and body mass; CON, endurance-only group; GXT, graded exercise test; heavy, heavy load ST (1–6 repetitions, ≥85% of 1RM); maximal strength, 1RM testing of back squat, SL leg press, SL seated calf raise, lat pull-down; moderate, moderate load ST (8–12, repetitions, ≤75% of 1RM); 1RM, 1-repetition maximum; simulated triathlon, 1500-m swim, 60-minute cycle, and 20-minute run; SL, single leg; ST, strength training; STR, endurance strength group.

taken in duplicate with a triplicate measure being taken if the difference in measures exceeded 1 mm. Body mass (in kilograms) was also measured at baseline postintervention using scales (model UC-321; A&D, Kitamoto-shi, Saitama, Japan).

Graded Exercise Testing and Simulated Triathlon Testing

All participants completed both a running and cycling graded exercise test (GXT) prior to the start of the study to determine their velocity at $\dot{V}O_2$max (v$\dot{V}O_2$ max) and power at $\dot{V}O_2$max (w$\dot{V}O_2$ max) respectively, which was used to set the power and pace in the simulated triathlon. A SportsArt treadmill (SportsArt, Mukilteo, WA) and WattBike Pro (WattBike Ltd, Nottingham, United Kingdom) was used to complete the run and cycle GXTs, respectively, with protocols following those outlined in previous research.[18,19] A participant's $\dot{V}O_2$max was defined as the highest 60-second value reached during the GXT. The v$\dot{V}O_2$ max and w$\dot{V}O_2$ max were determined as the velocity or power sustained for at least 60 seconds at which $\dot{V}O_2$max was reached.[1] At weeks 0, 14, and 26, all participants completed a validated simulated triathlon using procedures as described in previous research.[14] In summary, the simulated triathlon consisted of a 1500-m swim at 85% of the participants perceived maximum effort, a 60-minute cycle at 60% of w$\dot{V}O_2$ max, and a 20-minute run at 70% of v$\dot{V}O_2$ max, completed consecutively with breath by breath and HR data being taken throughout the duration of each test using a Moxus Modular $\dot{V}O_2$ system (AEI Technologies, Pittsburgh, PA). Participants wore the same attire during each of the simulated triathlons. A training and food questionnaire were completed by each participant 48 hours prior to their initial simulated triathlon with all participants required to replicate training, food, and fluid intake prior to their subsequent simulated triathlon tests. Participants were only allowed to consume water ad libitum during the simulated triathlon.

Economy Calculations

Gas exchange measurements during the final minute of each measuring sample time period were analyzed to determine $\dot{V}O_2$ in mL·kg$^{-0.75}$·km^{-1} and mL·km^{-1}. Appropriate allometric scaling exponent (0.75) was used to account for the nonlinearity associated with oxygen uptake response to differences in body mass.[20] $\dot{V}O_2$ and $\dot{V}CO_2$ were used to calculate energy cost (E_C) and RE. Nonprotein respiratory quotient equations[21] were used to estimate substrate utilization (g·min^{-1}). The energy derived from each substrate was then calculated by multiplying fat and carbohydrate usage by 9.75 kcal and 4.07 kcal, respectively, reflecting the mean energy content of the metabolized substrates during moderate-intensity exercise to high-intensity exercise.[22] The E_C was quantified as the sum of these values expressed in kcal·kg$^{-0.75}$·km^{-1} (E_C relative [E_CRel]) and kcal·km^{-1} (E_C absolute [E_CAbs]). During cycling, economy was measured as the power produced in watts (W) divided by the volume of oxygen used to produce the power in liters per minute per kilogram (W·L·min^{-1}·kg^{-1}). RE was measured as the $\dot{V}O_2$ consumed relative to body mass (kg$^{-0.75}$) per minute (mL·kg$^{-0.75}$·min^{-1}).[23]

Data Analysis

Physiological and performance data were analyzed using linear mixed models with Bonferroni correction to accommodate for the multiple testing periods. Means and SD were calculated for all measures across the 2 simulated triathlon trials. Effect sizes (ES) for the key data were calculated as Cohen *d* to compare the practical significance of the performance improvements among the 2 groups from preintervention to postintervention. The criteria to interpret the magnitude of the ES were the following: 0.0 to 0.19 trivial, 0.2 to 0.59 small, 0.6 to 1.19 moderate, 1.2 to 1.99 large, and >2.0 very large.[24] Statistical significance was set at $P < .05$. Statistical analyses were performed using Stata statistical software (release 14; StataCorp LP, College Station, TX).

Results

There were no significant differences between groups in age, height, body mass, years of experience, and $\dot{V}O_2$max values at baseline ($P > .05$). The main characteristics of participants are displayed on Table 1.

Anthropometric Measures

There were no significant differences between the STR and CON groups in body mass or skinfolds at week 0 (body mass, $P = .91$ and skinfolds, $P = .27$); 14 (body mass, $P = .98$ and skinfolds, $P = .52$); or 26 (body mass, $P = .91$ and skinfolds, $P = .56$). Neither group displayed within-group significant changes in body mass or skinfolds throughout the duration of the study ($P > .05$) (Table 2).

Maximal Strength Measures

There were no significant differences between the STR and CON groups in 1RM values at week 0 (lat pull down, $P = .72$; squat, $P = .46$; SL leg press, $P = .31$; and SL calf raise, $P = .15$) or 14 (lat pull down, $P = .83$; squat, $P = .87$; SL leg press, $P = .31$; and SL calf raise, $P = .32$). However, there was a significant difference in squat 1RM between groups at week 26 ($P = .04$). There were no other significant between-group differences at week 26 (lat pull down, $P = .41$; SL leg press, $P = .87$; and SL calf raise, $P = .35$). The STR group had a significant within-group improvement in all 1RM measures from weeks 0 to 14 ($P < .05$), while the CON group displayed only a significant within-group improvement in the squat 1RM ($P < .05$) (Table 3). The change in both the STR and CON within-group 1RM improvements at week 14 had a moderate effect (Cohen $d > 0.6$). From weeks 14 to 26, the STR group showed within-group significant improvements in all 1RM values ($P < .05$, ES = 0.31 to 1.13) (Table 3).

Economy Measures

There were no significant differences between the STR and CON groups for any RE or CE measures during the simulated triathlon tests at week 0 (RE, $P = .17$; E_CAbs, $P = .62$; E_CRel, $P = .15$; and CE, $P = .48$) or 14 (RE, $P = .35$; E_CAbs, $P = .81$; E_CRel, $P = .41$; and CE, $P = .46$). The STR group had a significant within-group improvement in CE from weeks 0 to 14 ($P < .05$) with a moderate effect (Cohen's $d = 0.76$) (Table 4). The CON group did not have any within-group significant improvements in any measurements from weeks 0 to 14 (Table 4). At week 26, there was a significant difference between the STR and CON groups for 2 of the running physiological measurements; RE, $P = .049$ and E_CAbs, $P = .049$; however, E_CRel was not significantly different between groups ($P = .31$). The STR group also had significant within-group improvements in all running physiological measurements from weeks 14 to 26 ($P < .05$, ES = −0.21 to −0.56) with the CON group having

Table 2 Anthropometric Measures of Participants Obtained at Weeks 0, 14, and 26

	Anthropometric measures, mean (SD)						*P*, percentage difference, and Cohen *d*					
	Week 0		Week 14		Week 26		Weeks 0–14 (moderate-load ST)		Weeks 14–26 (heavy-load ST)		Weeks 0–26	
Anthropometric measure	STR group	CON group	STR group	CON group	STR group	CON group	STR group	CON group	STR group	CON group	STR group	CON group
Sum of skinfolds, mm	96.85 (38.81)	78.39 (27.98)	97.72 (44.14)	83.86 (39.88)	91.43 (44.12)	78.53 (42.42)	$P=.999$, 0.9%, $d=0.02$	$P=.999$, 6.98%, $d=0.66$	$P=.999$, 6.44%, $d=-0.14$	$P=.999$, 6.36%, $d=-0.27$	$P=.999$, 5.60%, $d=-0.13$	$P=.999$, 0.18%, $d=0.003$
Body mass, kg	76.38 (16.92)	76.42 (42)	75.85 (12.92)	76.42 (12.36)	75.45 (17.43)	74.68 (12.55)	$P=.999$, 0.70%, $d=-0.03$	$P=.999$, 0%, $d=0.00$	$P=.87$, 0.53%, $d=-0.03$	$P=.81$, 2.28%, $d=-0.14$	$P=.999$, 1.22%, $d=-0.05$	$P=.06$, 2.28%, $d=-0.06$

Abbreviations: CON, endurance only; ST, strength training; STR, endurance strength.

Table 3 Maximal Strength (1-Repetition Maximum) Measures Obtained at Weeks 0, 14, and 26

	Maximal strength values, kg, mean (SD)						*P*, percentage difference, and Cohen *d*					
	Week 0		Week 14		Week 26		Weeks 0–14 (moderate-load ST)		Weeks 14–26 (heavy-load ST)		Weeks 0–26	
Movement tested	STR group	CON group	STR group	CON group	STR group	CON group	STR group	CON group	STR group	CON group	STR group	CON group
Squat	92.31 (21.47)	99 (20.52)	111.73 (26.80)*	113.5 (23.61)*	143.65 (29.59)*,**	119.5 (21.14)*	$P=.001$, 21.04%, $d=0.80$	$P=.05$, 14.65%, $d=0.66$	$P=.001$, 21.04%, $d=1.13$	$P=.999$, 5.28%, $d=0.27$	$P=.0001$, 55.62%, $d=1.99$	$P=.001$, 20.71%, $d=0.98$
LP	77.88 (24.17)	81.22 (19.00)	82.71 (24.99)*	81.25 (20.18)	90.96 (24.95)*	83.00 (19.18)	$P=.001$, 6.20%, $d=0.22$	$P=.999$, 0.04%, $d=0.001$	$P=.001$, 6.20%, $d=0.31$	$P=.999$, 2.15%, $d=0.09$	$P=.0001$, 16.79%, $d=0.53$	$P=.999$, 2.2%, $d=0.09$
SLLP	91.53 (28.60)	103.5 (25.9)	101.25 (29.16)*	102.5 (24.64)	115.21 (29.43)*	109 (28.65)	$P=.03$, 10.62%, $d=0.34$	$P=.999$, 0.97%, $d=-0.04$	$P=.001$, 10.62%, $d=0.48$	$P=.999$, 6.34%, $d=-0.24$	$P=.0001$, 25.87%, $d=0.82$	$P=.999$, 5.31%, $d=0.20$
SLSCR	38.37 (11.94)	45 (8.33)	45.48 (10.67)*	49.63 (7.95)	52.80 (12.16)*	48.37 (9.75)	$P=.001$, 18.53%, $d=0.63$	$P=.26$, 10.29%, $d=0.57$	$P=.001$, 18.53%, $d=0.64$	$P=.26$, 2.54%, $d=-0.13$	$P=.0001$, 37.61%, $d=1.20$	$P=.999$, 7.49%, $d=1.00$

Abbreviations: CON, endurance only; LP, latissimus pull-down; SLLP, single-legged leg press; SLSCR, single-legged seated calf raise; ST, strength training; STR, endurance strength.
*Significantly different from week 0 value, $P \leq .05$. **Significantly different from control group, $P \leq .05$.

Table 4 Economy Variables and Swim Time During a Simulated Long-Distance Triathlon at Weeks 0, 14, and 26

	Economy measures and swim time, mean (SD)						*P*, percentage difference, and Cohen *d*					
	Week 0		Week 14		Week 26		Weeks 0–14 (moderate-load ST)		Weeks 14–26 (heavy-load ST)		Weeks 0–26	
Economy variable	STR	CON	STR	CON	STR	CON	STR	CON	STR	CON	STR	CON
RE ($mL\cdot kg^{-0.75}\cdot km^{-1}$)	665.48 (53.81)	685.84 (45.18)	664.63 (47.52)	678.83 (59.07)	633.14 (59.37)*,**	670.42 (65.78)	$P=.999$, 0.13%, $d=-0.30$	$P=.999$, 1.02%, $d=-0.13$	$P=.005$, 4.74%, $d=-0.56$	$P=.999$, 1.24%, $d=-0.13$	$P=.004$, 4.86%, $d=-0.57$	$P=.999$, 2.25%, $d=0.27$
EC ($kcal\cdot km^{-1}$)	69.38 (15.32)	71.24 (9.00)	69.21 (15.14)	70.41 (10.23)	65.83 (16.00)*,**	70.41 (11.35)	$P=.999$, 0.25%, $d=-0.005$	$P=.999$, 1.17%, $d=-0.09$	$P=.004$, 4.88%, $d=-0.21$	$P=.999$, 0.0%, $d=0.00$	$P=.003$, 5.12%, $d=-0.23$	$P=.999$, 1.16%, $d=-0.08$
EC ($kcal\cdot kg^{-0.75}\cdot km^{-1}$)	2.68 (0.22)	2.76 (0.19)	2.67 (0.21)	2.73 (0.24)	2.55 (0.24)*	2.70 (0.27)	$P=.999$, 0.37%, $d=-0.04$	$P=.999$, 1.09%, $d=-0.14$	$P=.002$, 4.49%, $d=-0.51$	$P=.999$, 1.10%, $d=-0.12$	$P=.001$, 4.85%, $d=-0.56$	$P=.999$, 2.17%, $d=-0.26$
CE ($W\cdot L\cdot min^{-1}\cdot kg^{-1}$)	67.50 (5.43)	68.38 (5.34)	71.22 (4.33)*	70.51 (3.58)	72.58 (5.05)*	71.70 (4.64)	$P=.001$, 5.51%, $d=0.76$	$P=.11$, 3.11%, $d=0.48$	$P=.80$, 1.91%, $d=0.47$	$P=.999$, 1.69%, $d=0.29$	$P=.001$, 7.53%, $d=0.97$	$P=.999$, 4.86%, $d=0.66$
Swim time (min:s)	28:45 (4:10)	29:08 (2:43)	28:30 (4:10)	29:03 (2:50)	28:25 (4:17)	28:32 (2:43)	$P=.999$, 0.89%, $d=0.05$	$P=.999$, 0.27%, $d=-0.03$	$P=.999$, 1.21%, $d=-0.04$	$P=.999$, 1.81%, $d=-0.44$	$P=.999$, 1.15%, $d=-0.06$	$P=.001$, 1.42%, $d=-0.22$

Abbreviations: CE, cycling economy; CON, endurance only; EC, energy cost; RE, running economy; ST, strength training; STR, endurance strength.
*Significantly different from week 0 value, $P\leq.05$. **Significantly different from control group, $P\leq.05$.

no within-group improvements for any running measurements in this time (Table 4). Neither group significantly improved CE from weeks 14 to 26 (Table 4), and there were no significant differences in CE between groups at week 26 ($P = .44$). Over the duration of the whole study, the STR group significantly improved all RE and CE measures (weeks 0–26, $P < .05$), while the CON group did not significantly improve any economy measures (Table 4).

Swim Time

There were no significant differences between the STR and CON groups in swim times at week 0 ($P = .89$), 14 ($P = .82$), or 26 ($P = .44$). Neither the STR nor CON group had significant within-group improvements in their swim time at any stage of testing ($P > .05$) (Table 5).

Other Variables

The HR, BLa, and RPE measured during the simulated triathlons are displayed in Table 5. In the CON group, HR during the cycle significantly decreased from weeks 0 to 14 ($P < .05$) (Table 5). The HR in the CON group was also significantly lower than the STR group at week 14 ($P < .05$); however, at baseline, the CON group had a significantly lower cycle HR than the STR group ($P = .01$). Both the CON and STR group significantly decreased cycle HR from weeks 0 to 26 ($P < .05$) (Table 5). The CON also significantly increased their running RPE from weeks 0 to 26 ($P < .05$). There were no other significant between- or within-group changes in any other performance variables at week 0, 14, or 26 (Table 5).

Discussion

The current study demonstrates that a 26-week progressive load ST program in addition to regular endurance training can significantly improve CE, RE, and maximal strength values in LD triathletes. Furthermore, the improvements in RE are greater than both the smallest worthwhile change and typical error associated with measuring RE variables (~2.4%).[25] These changes occurred without an increase in body mass. The results of this study demonstrate the complexity of prescribing ST for optimal performance improvements in all 3 disciplines of LD triathlon as different load ST protocols were needed to induce improvements in cycling and RE while neither protocol improved swim time.

In the current study, the STR group saw no significant improvements in RE from the moderate load ST intervention (weeks 0–14); however, after 12 weeks of heavy load ST (weeks 14–26), all measures of RE improved significantly, while the CON group had no changes throughout the study, aligning with other similar studies.[1,6,26] RE is a strong determinant of performance as the more economical an athlete becomes through training adaptations; the less energy will be used at the same velocity when compared with an athlete with inferior RE.[2] It is proposed that skeletal muscle energy cost accounts for the majority of the total metabolic cost of running,[27] with studies emphasizing the importance of improving "muscle power" (the neuromuscular system's ability to produce power).[1,26] ST can improve these neuromuscular factors through several proposed mechanisms. The significant increases in maximal strength seen in the current study occurred without changes to body mass, suggesting that these strength improvements are likely from neural changes rather than muscular hypertrophy.[6,26] Since the mechanisms behind how ST improved RE were not explicitly tested in the current study, this remains relatively unknown; however, previous literature has highlighted some possible mechanisms.[1,6,28,29]

It is estimated that approximately half of the mechanical work performed during running is from the storage and return of elastic energy due to the impact nature of running on the ground.[30] During the contact phase of running, elastic energy is stored in the muscles, tendons, and ligaments and then partially returned during the second part of the contact phase. By improving musculotendinous stiffness, particularly in the Achilles tendon, the athlete can improve the utilization of elastic energy and decrease the muscle contraction required during running, thereby decreasing energy consumption during running. ST has been shown to be an effective training method utilized to increase musculotendinous stiffness.[1,31] Endurance runners who possess the highest RE have greater strength of the triceps surae muscles (gastrocnemius and soleus)[32] which is unsurprising given these muscles account for up to 40% of the total metabolic cost of running in recreational athletes.[27] In the current study, only the STR group significantly improved their SL seated calf raise maximal strength values which may have also been associated with a concomitant increase in stiffness of the Achilles tendon and therefore contributed to the significant improvements in RE observed. While tendons are highly adaptable and respond to mechanical loading, the current study suggests that a moderate load ST program may not provide enough mechanical loading to sufficiently elicit changes in musculotendinous stiffness. In addition, studies comparing submaximal, heavy, or explosive ST protocols demonstrate superior RE improvements with heavy or plyometric ST protocols when compared with submaximal load protocols similar to the initial 12-week moderate load ST program implemented in the current study.[33] Another potential mechanism contributing to the improvements in RE may be from RFD enhancements. Increases in the RFD are primarily a result of increases in neural activation from ST programs which emphasize the maximal velocity of the concentric phase of exercises,[29] which was replicated in the current study. In addition, eccentric strength is highly correlated to RE in distance runners[28] which may have also contributed to improvements in RE seen in the current study as each exercise was completed with a 3-second eccentric control (however, eccentric strength was not directly measured within the current study). The results of the current study demonstrate the importance of sufficiently loading the neuromuscular system with heavy load ST to induce the previously mentioned proposed mechanisms which are essential for improvements in RE.[1,6,26]

CE significantly improved in the STR group from 12 weeks of moderate load ST (weeks 0–14); however, it did not improve further from an additional 12-week heavy ST program. Most studies demonstrating improvements in CE from ST generally incorporate heavier ST loads (1–6 repetitions, ≥85% of 1RM)[4,5,8–10] when compared with those completed in the moderate load ST period utilized in the current study. In contrast to the recent literature, the authors have demonstrated here that the implementation of a moderate rather that heavy ST program was sufficient to improve CE in LD triathletes. As the STR group significantly improved CE by 5.5% in the first 12 weeks of moderate load ST, this may have resulted in a plateau in CE, potentially contributing to the lack of improvements observed from the following 12 weeks of heavy ST. While the potential mechanisms attributing to the improvement in CE in the current study were not directly measured, previous literature has highlighted some possible mechanisms.[4,7,10]

Research has shown that type I muscle fibers are more efficient than type II muscle fibers at a given submaximal intensity.[34]

Table 5 Physiological and Performance Variables Measured During a Long-Distance Simulated Triathlon at Weeks 0, 14, and 26

Performance or physiological variable	Physiological and performance variables, mean (SD)						*P*, percentage difference, and Cohen *d*					
	Week 0		Week 14		Week 26		Weeks 0–14 (moderate-load ST)		Weeks 14–26 (heavy-load ST)		Weeks 0–26	
	STR	CON	STR	CON	STR	CON	STR	CON	STR	CON	STR	CON
Swim												
RPE	4.25 (1.29)	4.92 (1.38)	4.42 (1.24)	4.84 (1.57)	4.33 (1.30)	4.85 (1.46)	$P=.999$, 4%, $d=-0.13$	$P=.999$, 1.62%, $d=-0.05$	$P=.999$, 2.04%, $d=-0.07$	$P=.999$, 0.21%, $d=0.01$	$P=.999$, 1.88%, $d=0.06$	$P=.50$, 1.42%, $d=0.5$
Cycle												
HR	152.45 (11.94)	144.12 (16.76)	148.52 (12.64)	137.48 (20.25) *,**	147.95 (13.03)*	137.48 (20.25)*	$P=.06$, 2.58%, $d=-0.32$	$P=.003$, 4.61%, $d=-0.36$	$P=.999$, 0.38%, $d=0.04$	$P=.999$, 0.59%, $d=0.00$	$P=.016$, 2.95%, $d=-0.36$	$P=.001$, 4.61%, $d=-0.36$
BLa	3.42 (1.66)	3.85 (2.13)	3.60 (2.06)	3.84 (1.61)	3.36 (1.73)	3.74 (2.17)	$P=.999$, 5.26%, $d=0.10$	$P=.999$, 0.26%, $d=-0.005$	$P=.999$, 6.67%, $d=-0.13$	$P=.999$, 2.6%, $d=-0.05$	$P=.999$, 1.75%, $d=-0.04$	$P=.999$, 2.86%, $d=-0.05$
RPE	3.81 (1.02)	4.18 (1.28)	3.64 (1.12)	3.97 (1.33)	3.93 (1.35)	4.06 (1.37)	$P=.999$, 4.46%, $d=-0.16$	$P=.999$, 5.02%, $d=-0.16$	$P=.999$, 7.97%, $d=-0.23$	$P=.999$, 2.60%, $d=-0.07$	$P=.999$, 3.15%, $d=0.10$	$P=.999$, 2.87%, $d=0.09$
Run												
HR	159.92 (9.89)	152.82 (16.73)	163.63 (13.01)	153.72 (16.94)	158.00 (10.66)	148.73 (19.78)	$P=.999$, 2.32%, $d=0.32$	$P=.999$, 0.59%, $d=0.05$	$P=.10$, 2.08%, $d=-0.47$	$P=.45$, 2.32%, $d=-0.27$	$P=.999$, 1.2%, $d=-0.19$	$P=.999$, 2.68%, $d=-0.22$
BLa	3.46 (1.33)	3.85 (2.33)	4.09 (2.11)	4.6 (1.56)	3.38 (1.67)	3.98 (2.46)	$P=.999$, 18.21%, $d=0.36$	$P=.999$, 19.48%, $d=0.38$	$P=.999$, 17.36%, $d=0.37$	$P=.999$, 13.48%, $d=-0.30$	$P=.999$, 2.31%, $d=0.05$	$P=.999$, 3.38%, $d=0.05$
RPE	3.86 (0.95)	3.64 (1.29)	4.28 (1.64)	4.36 (1.29)	4.14 (1.61)	4.54 (1.37)*	$P=.999$, 10.88%, $d=0.31$	$P=.999$, 19.78%, $d=0.56$	$P=.999$, 3.5%, $d=0.21$	$P=.999$, 4.13%, $d=0.13$	$P=.999$, 7.25%, $d=-0.09$	$P=.014$, 24.72%, $d=0.68$

Abbreviations: BLa, blood lactate; CON, endurance only; HR, heart rate; RPE, rating of perceived exertion (scale 0–10); ST, strength training; STR, endurance strength.
*Significantly different from week 0 value, $P \leq .05$. **Significant between-group difference, $P \leq .05$.

The current study displays significant improvements in maximal strength measures in the STR group throughout the study, suggesting that the muscle fiber tension developed for each pedal stroke at the same absolute power will decrease to a lower percentage of the athlete's maximal values. Following the size principle of muscle fiber recruitment, this would result in postponing the activation of the less efficient type II muscle fibers and therefore potentially contribute to the improvements in economy.[34] To consider the delay in activation of the less economical type II muscle fibers as a likely contributing mechanism to improved CE, it is essential for athletes to be tested at an intensity and duration long enough to induce fatigue in the type I muscle fibers to assess a change.[9] The simulated triathlon in the current study was completed at the participants' race pace intensity and may have been of adequate duration to potentially assess these muscle fiber changes. Furthermore, research examining concurrent strength and endurance training has proposed increases in the proportion of the less fatigable and more economical type IIa muscle fibers at the expense of a reduction in the less efficient type IIx muscle fibers and improvements in RFD to be likely mechanisms contributing to improvements in cycling performance.[7,8,10] These changes in muscle fiber recruitment may also have contributed to the improvements in RE seen in the current study.

No improvements in swim time were seen in either group throughout the duration of the current study. Despite the lack of research examining ST implementation on open-water swimming performance, it is still recommended that open-water swimmers include ST to optimize performance.[35] The current ST program primarily focused on lower limb muscles which are used during cycling and running rather than those used by the upper body during swimming which may have contributed to the lack of swim time improvement. In addition, it may be argued that a focus on swim technique and biomechanics which was not addressed in the current study may be a more beneficial means of improving swim performance.

The absence of increased body mass from combined strength and endurance training as seen in the current study has also been observed in similar ST studies.[1,6,7] Endurance exercise may negatively affect intracellular pathways important for myofibrillar protein synthesis, inhibiting the promotion of activation of pathways responsible for muscle hypertrophy which may contribute to the lack of muscle hypertrophy observed in the current study.[36] The absence of increased body mass for endurance sports is generally considered desirable for improved performance.

The STR group significantly improved all maximal strength measurements at weeks 14 and 26, while the CON group significantly improved only the 90° squat at week 14 after the moderate load ST period. This improvement in the CON group contrasts with previous research where the control groups displayed no changes in maximal strength.[1,4–7,13] This change may be a result of a learning effect and increased confidence with the squat from the initial testing period. As such, these results may not reflect accurate improvements in maximal strength as the CON group did not significantly improve SL leg press maximal strength.

Neither group displayed significant changes in any other performance or physiological measures except for cycle HR in the STR and CON group and run RPE in the CON group. Cycle HR in the CON group significantly decreased from weeks 0 to 14 and was also significantly lower than the STR group. At week 0, however, the CON groups HR was significantly lower during the cycle than the STR group, which may have contributed to this finding. Both groups significantly decreased cycle HR from weeks 0 to 26. While the CON group significantly increased run RPE at week 26, the STR group did not significantly decrease run RPE showing equivocal findings as to whether ST may change LD triathletes RPE during the run as a result of ST. The lack of significant changes in any other performance measures aligns with previous literature which also observed no changes in BLa measures and HR post ST interventions.[1,6,7,13,29]

It should be noted that while there were no significant differences in endurance training loads completed between groups, endurance training loads and race scheduling were not controlled in either group. In addition, future studies should consider nutritional intake of athletes to determine the influence nutrition may have on strength adaptations and endurance performance from ST interventions. The current study had a mixed population of both males and females. While recent literature examining ST in female duathletes has shown similar significant improvements in CE as that seen in the current study,[8,9] the same improvements were not seen in RE, potentially due to lower tendon connective tissue formation rates in females when compared with males.[37] Future research should examine gender-specific responses to ST in LD triathletes. Furthermore, participants in the current study were classified as "trained" triathletes and included only 1 professional triathlete. Future research is required to determine if similar results can be obtained in professional triathletes and the potential mechanisms contributing to the improvements in economy displayed. It should also be noted that the simulated LD triathlon utilized in the current study measured changes in CE and RE, rather than direct measures of performance improvements.

Practical Application

The results of the current study emphasize the importance of designing a ST program for LD triathletes to address the varying factors contributing to both cycling and RE. The present study shows that the neuromuscular system must be sufficiently loaded through heavy ST to induce significant and meaningful changes in RE, which are not seen when compared with moderate load ST. In contrast, a 12-week moderate load ST program can significantly improve CE in LD triathletes while a lower limb focused ST program does not appear to result in improvements in swim time. A 26-week ST program transitioning from moderate to heavy loads is recommended to improve both RE and CE in LD triathletes.

Conclusions

This is the first study to examine the effects of concurrent strength and endurance training on physiological and performance parameters in LD triathletes. A 12-week moderate load ST program can significantly improve CE and may be an effective training method to elicit improvements in CE in LD triathletes; however, it appears the moderate load may not be adequate to generate significant changes in RE or swimming performance. A 12-week heavy ST program can significantly improve RE and maximal strength in LD triathletes without an increase in body mass. Coaches and sport scientists can be confident when interpreting results from the current study as all physiological changes were assessed in a reliable simulated triathlon test with high representative task design.

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