The Effect of Strength Training on Performance Indicators in Distance Runners

Running head: Strength Training in Distance Runners

Authors: Kris Beattie¹, Brian P. Carson¹, Mark Lyons¹ Antonia Rossiter² and Ian C. Kenny¹

Institutional Affiliations:

¹Department of Physical Education and Sport Sciences, University of Limerick, Limerick, Ireland.
²Irish Institute of Sport, National Sports Campus, Abbotstown, Dublin 15, Ireland.

Corresponding Author:
Kris Beattie
Department of Physical Education and Sport Sciences, University of Limerick, Limerick, Ireland.
Email: kris.beattie@ul.ie
Fax: + 353 61 202814
Telephone: +353 61 234781

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Strength Training in Distance Runners

Abstract

Running economy (RE) and velocity at maximal oxygen uptake ($\dot{V}O_{2\text{max}}$) are considered to be the best physiological performance indicators in elite distance runners. In addition to cardiovascular function, RE and $\dot{V}O_{2\text{max}}$ are partly dictated by neuromuscular factors. One technique to improve neuromuscular function in athletes is through strength training. The aim of this study was to investigate the effect of a 40 week strength training intervention on strength (maximal- & reactive-strength), $\dot{V}O_{2\text{max}}$, economy and body composition (body mass, fat & lean mass) in competitive distance runners. Twenty competitive distance runners were divided into an intervention group (n = 11; 29.5 ± 10.0 years; 72.8 ± 6.6 kg; 1.83 ± 0.08 m) and a control group (n = 9; 27.4 ± 7.2 years; 70.2 ± 6.4 kg; 1.77 ± 0.04 m). During week 0, 20 and 40, each subject completed three assessments: physiology ($\dot{V}2\text{mmol/L BLa, }\dot{V}4\text{mmol/L BLa, RE, }\dot{V}O_{2\text{max}}, \dot{V}O_{2\text{max}}$), strength (1RM back squat; countermovement jump & 0.3m drop-jump) and body composition (body mass, fat mass, overall-lean & leg-lean). The intervention group showed significant improvements in maximal- and reactive-strength qualities, RE and $\dot{V}O_{2\text{max}}$, at weeks 20 (p < 0.05) and 40 (p < 0.05). The control group showed no significant changes at either time point. There were no significant changes in body composition variables between or within groups. This study demonstrates that forty weeks of strength training can significantly improve maximal- and reactive-strength qualities, RE and $\dot{V}O_{2\text{max}}$, without concomitant hypertrophy, in competitive distance runners.

Key Words: strength, running economy, $\dot{V}O_{2\text{max}}$, distance running.
INTRODUCTION

Performance in distance running is multi-faceted; relying on an intricate interaction of physiological, biomechanical and psychological factors. Even within the physiological domain, there is a complex synergy between the central and peripheral system’s role in facilitating adenosine triphosphate (ATP) regeneration for sustained running locomotion (4). Since the original work of Hill & Lupton (15), there has been an abundance of research studies investigating the role of maximal oxygen consumption ($\text{VO}_{2\text{max}}$) in distance running. Research has shown strong relationships between $\text{VO}_{2\text{max}}$ and middle- (800m, $r = 0.75$) and long-distance (marathon, $r = 0.78$) performance in heterogeneous groups (17, 37). Due to this, maximal oxygen uptake ($\text{VO}_{2\text{max}}$) protocols have been traditionally used in the laboratory to monitor and predict the performance potential of both middle- and long-distance runners. However, at elite long-distance level (marathon time < 2 h 30 min), the relationship between $\text{VO}_{2\text{max}}$ and performance is weak ($r = 0.01$), and it is likely that this relationship is negligible at ‘world-class’ standard (marathon time < 2 h 10 min) (37). A high $\text{VO}_{2\text{max}}$ (> 70 mL/kg/min) may be a pre-requisite to be an elite distance runner, but additional physical qualities are needed to succeed at this level. Key performance indicators such as running economy (RE), velocity at maximal oxygen uptake ($v\text{VO}_{2\text{max}}$) and anaerobic function (velocity during maximum anaerobic running test: $v\text{MART}$; & max-velocity sprinting) have been established as superior markers of success in these elite populations (5).

RE is defined as the metabolic cost to cover a given distance at a constant velocity (36). RE represents the ability of a runner to translate cellular energy production into running locomotion and is normally expressed as the volume of oxygen consumption per unit of body mass required to run a kilometer (mL/kg/km) (36). RE has been shown to be a stronger indicator of performance than $\text{VO}_{2\text{max}}$ alone within elite homogenous populations, with inter-individual variability ranging between 20-30% (27). The east African dominance in distance...
running has been partly attributed to their superior economy (36). RE is determined by the athlete’s physiology, anthropometrics, biomechanics and environment; however improvements in RE may be difficult to obtain in trained runners, and therefore any novel training modality that results in marginal improvements may be crucial for success (2).

The velocity attained at $\dot{\text{VO}}_{2\text{max}}$ ($v\dot{\text{VO}}_{2\text{max}}$) is a ‘functional’ expression of maximal oxygen consumption in velocity units (km/h). $v\dot{\text{VO}}_{2\text{max}}$ is a composite of both maximal oxygen consumption and economy. Due to this, the variable has shown to be strongly associated with elite middle- ($r = 0.71$) (17) and long-distance ($r = 0.89–0.94$) (27) running performance. Even though $\dot{\text{VO}}_{2\text{max}}$ may remain stable throughout an elite distance runner’s career, research has shown that the velocity at $\dot{\text{VO}}_{2\text{max}}$ can improve by approximately 14% (19). This demonstrates that elite distance runners can improve their ability to translate maximal aerobic energy production into faster running velocities. During middle-distance events (800m & 1500m), or sprint finishes in long-distance events where velocities exceed $v\dot{\text{VO}}_{2\text{max}}$, the contribution of the anaerobic energy system is increased (27). Endurance-specific ‘muscle power’ is the ability of the neuromuscular system to rapidly produce force following a sustained period of high-intensity exercise (high glycolytic and/or oxidative energy demand) (28). This ability may be the differentiating factor for succeeding in elite distance running (i.e. sprint finish). Therefore, rate of force development (RFD) is essential not only in short-distance events (i.e. 100m, 200m & 400m), but also in middle- and long-distance running. Consequently, in addition to cardiovascular capacity, limitations to elite distance running performance may be dictated by peripheral neuromuscular force production ability.

One training technique for improving rate of force production in athletes is strength training. Early work from Paavolainen et al (29, 30) demonstrated that the neuromuscular adaptations from strength training (i.e. musculotendinous stiffness, motor unit recruitment and synchronization, rate coding, intra- and intermuscular coordination & neural inhibition)
(10, 45) have the potential to improve performance in distance runners (44) by improving RE (2), \(\dot{V}O_{2\text{max}}\) and/or anaerobic function (24). However, strength training is generally still an uncommon physical preparation modality in the distance running community. This is most likely due to the ‘hypertrophic’ connotations associated with lifting weights, with distance runners inadvertently linking strength adaptations to increased musculature and body mass - which would potentially negatively affect relative physiological performance parameters (i.e. \(\dot{V}O_{2\text{max}}, \text{RE}\)). Nonetheless, a recent systematic review by Beattie et al (5) in competitive distance runners reported that strength training can improve 3 km (2.7%, ES = 0.13) (38) and 5 km time-trial performance (3.1%) (30), economy (4.0 – 8.1%, ES: 0.3 – 1.03) (6, 21, 24, 30, 32, 38, 40), \(\dot{V}O_{2\text{max}}\) (1.2%, ES: 0.43 – 0.49) (6, 24) and maximum anaerobic running velocity (\(v_{\text{MART}}\) (3%) (24, 30). However, Beattie et al.’s (5) review showed that the strength interventions in these studies were relatively short-term (~ 8 weeks), and used inadequate exercises (i.e. machine-based, isolated exercises) that may have limited optimal strength development of the leg musculature for distance running performance (41). Therefore, the current study addressed for the strength and conditioning community, the uncertainty surrounding long term adaptations to strength training in trained distance runners (1500 m – 10 000 m).

To our knowledge, the effects of a strength training intervention longer than 10 weeks, on \(\dot{V}O_{2\text{max}}\) and RE in distance runners, is unknown. Therefore, the aim of the current study was to investigate the effect of a 40 week (20 week pre-season & 20 week in-season) strength training intervention on strength qualities (maximal- & reactive-strength), key physiology performance indicators (\(\dot{V}O_{2\text{max}}\) and RE) and body composition in collegiate and national-level distance runners (1500 m – 10 000 m). The experimental approach to answer this research question was to conduct a 40 week longitudinal strength intervention study with a parallel control group, measuring physiological, strength and body composition variables at

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weeks 0, 20 and 40. We hypothesised that a 40 week strength intervention in distance
runners would result in significant changes in strength qualities (maximal- & reactive-
strength), key physiology performance indicators ($\dot{V}O_{2max}$ & RE) and body composition.

**METHODS**

*Experimental approach to the problem*

To investigate the hypothesis of the study, a longitudinal and controlled experimental
design was used to investigate the effect of a 40 week (20 week pre-season & 20 week in-
season) strength training intervention on strength qualities (maximal- & reactive-strength),
key physiology performance indicators ($\dot{V}O_{2max}$ and economy) and body composition in
collegiate and national-level distance runners (1500 m – 10 000 m). A two group, repeated
measures (pre-, mid- and post-testing) design was used. After an 8-week off-season, subjects
were divided into the two groups based on their ability to adhere to the study conditions (i.e.
time commitments and location relative to training facility). The two groups consisted of an
intervention group (endurance training AND strength training: n = 11; 29.5 ± 10.0 years; 72.8
± 6.6 kg; 1.83 ± 0.08 m) and a control group (endurance training ONLY: n = 9; 27.4 ± 7.2
years; 70.2 ± 6.4 kg; 1.77 ± 0.04 m). There were no significant differences between groups at
baseline for all measures. All athletes and coaches were instructed not to deviate from their
normal 1500 m – 10 000 m endurance training. It is known that the control group did not
employ any strength training as part of their normal training programme. Due to the extensive
longitudinal nature of the study, endurance training (volume & intensity) was not controlled.

In addition to their endurance training, the intervention group strength trained twice a
week during the pre-season period (weeks 1-20, December – March, winter months), and
once a week during the in-season ‘racing’ period (weeks 20-40, April – July, summer
months) (see Figure 1). All strength sessions were coached by an experienced UK Strength
& Conditioning Association (UKSCA) accredited coach (the lead author). Each strength
session lasted approximately sixty minutes (see Table 1).

Subjects

Thirty competitive collegiate and national-level distance runners (1500 m – 10 000 m)
participated in the study, however due to unrelated injury and time commitment, twenty
subjects (n = 20; 28.2 ± 8.6 years; 71.6 ± 6.6 kg; 1.80 ± 0.07 m) completed the study. The
subjects had a mean maximum oxygen uptake (VO$_{2\max}$) of 61.3 ± 3.2 mL/kg/min, which is
close to the BASES ‘national-level’ physiological standard (65-75 mL/kg/min) for male
distance runners (Jones, 2006). It is also important to note that all subjects had no strength
training experience. All subjects were recruited through poster and email. After being
informed of the benefits and potential risks of the investigation, each subject completed a
health-screening questionnaire and provided written informed consent prior to participation in
the study. All experimental procedures were ratified by the University of Limerick Research
Ethics Committee in accordance with the provisions of the most recent Declaration of
Helsinki.

Insert Figure 1 here

Strength, Physiology & Body Composition Assessment

During week 0, 20 and 40, each subject completed three assessment days: physiology,
strength and a body composition assessment day. All strength, physiology and body
composition assessments were undertaken at the same time of day to avoid diurnal variation
in performance. There were 48 hours between each testing day. To control the effect of diet
and physical readiness, each subject was asked to consume a habitual diet and avoid alcohol
(< 48 hours), limit caffeine ingestion (< 4 hours), and avoid vigorous exercise (< 24 hours)
prior to assessments. For body composition assessment, participants reported to the
laboratory following a 3h fast, having consumed 500ml of water, one hour prior to
measurement.

**Strength Assessment**

Prior to the strength assessment day, each subject carried out a familiarisation day to
ensure habituation with the back squat, countermovement jump and drop-jump tests. The
familiarisation day included the same protocol as the strength assessment day (see below).
Also, all subjects were familiarised with the physiological measurement equipment during the
warm-up period before physiological measurements (\(\dot{V}O_2\)mmol/L BLa, \(\dot{V}4\)mmol/L BLa, RE,
\(\dot{V}O_{2\text{max}}\), \(\dot{V}O_{2\text{max}}\)) were taken. Before back squat 1 repetition maximum (RM) testing, each
subject completed a five minute warm-up (self-myofascial release, stretching and dynamic
mobility exercises). Following completion of the warm-up, subjects started the back squat 1
RM testing protocol to assess maximal-strength (25). This protocol consisted of a warm-up of
10 repetitions at 50% of their [estimated] 1RM load, 5 x 70% 1RM, 3 x 80% 1RM, and 1 x
90% 1RM. Each participant’s 1RM was estimated by the researcher based on the athlete’s
body mass, age and gender (25). Following the warm-up protocol, each subject had three
attempts to determine their actual 1RM (with 3 minutes in between sets). To ensure safe
conditions during testing, a box was set at the lowest depth the athlete could squat while
keeping optimal lumbar spinal position. Therefore, squat depth was specific to each subject
and knee angles ranged from 90° - 120° flexion. Only trials in which the subject touched the
box were considered successful lifts. The knee flexion angle was recorded to ensure the same
squat depth during week 0, 20 and 40 assessments.
Approximately ten minutes after the 1RM back squat, subjects started the reactive-strength assessment. Reactive-strength movements are categorised depending on their slow or fast stretch-shortening cycle (SSC) characteristics (34). Slow SSC function was assessed through a countermovement jump (CMJ), and fast SSC function was assessed through a 0.3m drop-jump. Both jumps were performed on a force platform (AMTI OR6-5; AMTI, Watertown, MA, USA) operating at a sampling rate of 1000Hz. Each subject addressed the CMJ in a standing position while keeping their hands on their hips in order to restrict arm movement. After instruction, subjects initiated the jump via a downward countermovement. All subjects were instructed to choose a depth that they felt would maximise jump height. For each trial the subject was told to “jump as high as possible”. Two minutes recovery was given between jumps. Three jumps were performed with the highest value used for analysis. Following CMJs, subjects performed three individual drop-jumps from a 0.3 m box onto a force platform. Each jump was separated by two minutes of recovery. Prior to each drop-jump, the subject was instructed to step forward off the box, and on contact with the platform to immediately jump as high as possible. They were also instructed to keep their hands on their hips in order to restrict arm movement. Three drop-jumps were performed with the highest reactive-strength index [RSI = jump height (m) / contact time (s)] used for analysis.

Physiology Assessment

All physiological variables (\(\bar{VO}_{2\text{max}}\), \(\dot{\bar{VO}}_{2\text{max}}\), RE, \(\dot{v}2\text{mmol/L} \& \dot{v}4\text{mmol/L BLa}\)) were determined during a two-part treadmill protocol (H/P/Cosmos Pulsar treadmill, H/P/Cosmos Sports & Medical gmbh, Germany). The treadmill was set at 1% gradient throughout the protocol. Oxygen consumption was determined continuously using a gas analyser (MOXUS, Model DC-3A, AEI Technologies, Naperville, IL, USA). Before each test, the metabolic cart was calibrated for air flow, and the gas analyser was calibrated against a certified gas
mixture. Prior to the protocol, each subject warmed-up on the treadmill for ten minutes. The first five minutes was completed at a velocity that was 7 km/h slower than their estimated 4 mmol/L blood lactate velocity (4mmol/L BLa), and the second five minutes at a speed that was 6 km/h slower than 4mmol/L. Following the warm-up, a resting BLa sample was taken using a Lactate Pro Analyser (Lactate Pro, ARKAY Europe, Amstelveen, Netherlands).

The first part of the treadmill protocol consisted of a twenty minute sub-maximal 'step' test. The step test consisted of five, four minute stages. Each stage was four minutes in length to allow for steady-state oxygen consumption, heart rate and BLa levels. The first stage was performed at a velocity 5 km/h slower than the subject’s estimated 4mmol/L. Each stage increased by 1 km/h every four minutes so the final stage was at estimated 4mmol/L BLa. Heart rate (Polar s610 HR Monitor, Kempele, Finland) and VO₂ values used for analysis were the mean values from the last minute of each sub-maximal stage. RE, the oxygen cost of running a kilometer at a specific velocity was calculated using the following formula: \( \frac{\text{VO}_2 (\text{mL/kg/min})}{[\text{speed (km/h)/60}]} \). After every stage the subject stepped off the treadmill for 15–20 s to allow ear-lobe blood samples to be taken for determination of BLa concentration. The velocity at 2mmol/L & 4mmol/L of blood lactate were calculated using Lactate-E 2.0 Software (26). The subjects rested for ten minutes following the sub-maximal treadmill protocol.

The second part of the treadmill protocol consisted of a maximal ‘ramp’ test until exhaustion. The initial velocity of the treadmill was set at 2 km/h slower than the subjects’s estimated 4 mmol/L BLa stage velocity, and increased by 0.5 km/h every 30s until exhaustion. To ensure that \( \text{VO}_2_{\text{max}} \) was reached, each subject had to meet the following criteria: respiratory exchange ratio (RER) > 1.00; heart rate within 5% of their age-predicted maximum; and/or BLa of 8–10 mM. Maximal oxygen uptake was taken as the highest 60s VO₂ value. Velocity at \( \text{VO}_2_{\text{max}} \) was taken as the minimum velocity that elicited \( \text{VO}_2_{\text{max}} \).
Following the maximal ramp test, the subject cooled-down for ten minutes at a velocity that was 7 km/h slower than their estimated $\dot{v}4$ mmol/L velocity.

**Body Composition Assessment**

A Lunar iDXA™ (dual energy X-ray absorptiometry) scanner (GE Healthcare, Chalfont St Giles, Bucks., UK) with enCORE™ 2007 v.11 software was used to perform total body scans. Each subject was instructed to refrain from exercise for 12 h, to refrain from eating for 3 h and to consume 500 ml of water 1 h prior to testing. Each subject emptied their bladder immediately prior to the measurement. Participants were positioned on the scanner bed according to the manufacturer’s recommendations and instructed to remain as still as possible for the duration of the scan.

**Strength Programme**

The lead author, an experienced UKSCA accredited S&C coach, designed and coached the strength programme over the 40 weeks. The subcategories for strength training in this programme included (1) maximal-strength that targets maximal force development through high-load, low-velocity movements (e.g. back squats); (2) explosive-strength (strength-speed and speed-strength) that improves RFD and maximal power output through medium to high-load, high-velocity movements (e.g. jump-squats); and (iii) reactive-strength that targets musculotendinous stiffness and stretch-shortening cycle (SSC) function through low-load, high-velocity exercises (e.g. pogo-jumps, drop jumps) (12).

The programme’s aim can simplistically be described as to “increase the athlete’s motor potential, and gradually improve their capacity to use [this] motor potential during the performance of specific competition exercises” (41). Reactive-strength is the most important strength quality for short-, middle- and long-distance running events (42).
kinetic characteristics of ‘fast’ SSC reactive-strength exercises (i.e. knee & hip joint displacement, elastic musculotendinous force production) are similar to that of running. However, during the first twenty weeks (pre-season, December - March), the primary focus of the programme was maximal-strength development, with a secondary focus on developmental reactive-strength training (see Table 1). There were two strength sessions per week with at least 48 hours of recovery between sessions during the pre-season period. The rationale for a ‘general’ maximal-strength emphasis is that (i) there is a positive correlation between relative maximum-strength and reactive-strength levels in athletes (r = 0.63) (11), (ii) a maximum-strength programme can concurrently improve maximal-strength, explosive- and sSSC reactive-strength qualities in relatively ‘weak’ athletes (7), (iii) maximum-strength training improves stiffness (K_{leg}) in relatively ‘weak’ athletes (8), and (iv) relatively ‘strong’ athletes adapt quicker to power training when compared to the ‘weaker’ athletes (9).

During the in-season ‘racing’ period (weeks 20 to 40, April - July), after an increased level of maximum-strength had been attained, the primary emphasis of the programme changed to reactive- and explosive-strength development, with the secondary focus on maintenance of maximal-strength adaptations. The frequency of strength sessions decreased to one per week during the in-season ‘racing’ period.

Assistance work throughout the forty weeks consisted of either single-leg squat (e.g. split-squat, reverse-lunge & single-leg squat) or single-leg deadlift variations (e.g. single-leg Romanian deadlift) in the 5-12 repetition range to target (i) additional strength development through the ‘sub-maximal effort’ method (45) and (ii) gluteal strength and femoral control for knee stability (43). Supplementary gluteal and abdominal strength work was performed during the warm-up and ‘core-circuit’ at the end of each session. The strength programme was designed and developed from the works of Haff & Nimphius (12), Rippetoe & Baker (31), Verkhoshanky & Verkhoshanky (41) and Zatsiorsky & Kraemer (45).
Statistical Analyses

Independent variables were defined in terms of the different interventions (strength vs. control) and the three measurement points (pre-test vs. mid-test vs. post-test). The dependent variables were strength (maximum-strength: 1RM back squat; slow SSC reactive-strength: CMJ; fast SSC reactive-strength: 0.3m drop-jump), physiology (2 & 4 mmol/L BLa LT, VO_{2max}, vVO_{2max} & economy) and body composition (body mass, body fat, overall lean & leg lean). All data sets are presented as mean ± standard deviation or percentage change.

To test for differences between groups at week 0, an independent t-test was used. For each group, variables (physiology, strength & body composition) at week 0, week 20 and week 40 were compared using a one-way repeated measures ANOVA. To test for differences between groups, two-way repeated measures ANOVA was used. Homogeneity of variance was evaluated using Mauchly’s test of sphericity and when violated, the Greenhouse-Geisser adjustment was used. To determine the magnitude of within group change in variables, a Cohen’s d effect size was performed. The criteria to interpret the magnitude of the effect size were: 0.0-0.2 trivial, 0.2-0.6 small, 0.6-1.2 moderate, 1.2-2.0 large, and > 2.0 very large (16). The level of significance was set at P ≤ 0.05. IBM SPSS Statistics 22 software (IBM Corp. Released 2013. IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY) was used for all statistical calculations. Reliability (coefficient of variation, CV %; intraclass correlation coefficient, ICC) values for back squat 1 RM (< 4.3%; 0.91-0.99) (23), CMJ (< 6.5%; 0.83-
0.99) (23), 0.3m drop-jump RSI (< 5%; > 0.90) (22), sub-maximal and maximal VO\(_2\) (< 2.4 %), \(\Delta\)4mmol/L BLa (< 6 %) and \(\sqrt{V O_{2max}}\) (< 2.4 %) (33) are all within acceptable ranges.

RESULTS

There were no significant differences between the strength and control group at baseline (week 0) with respect to strength, physiological and body composition variables (see Table 2).

Strength

No significant differences were observed for any strength measures between the intervention and control groups at baseline. The change in absolute maximal-strength in the intervention group (85.7 ± 14.7 kg → 99.3 ± 19.0 kg) was not significantly different to the change in the control group (100.0 ± 18.4 kg → 101.6 ± 17.1 kg) throughout the 40 weeks (p = .116). However, the change in relative maximum-strength (1RM back squat) in the intervention group was significantly different to the change in the control group throughout the forty weeks (p = .039). Specifically, there was a 19.3 ± 24.1 % increase in the intervention group maximum strength from week 0 to week 40 (d = 0.7, p = .052), largely accounted for by week 0 to 20 increases (d = 1.2, p = .001). The control group had a 3.1 ± 9.2 % increase in maximum-strength from week 0 to 40 (d = 0.2, p > 0.05); however these changes were not significantly different. There was a significant 12.7 ± 13.2 % increase in sSSC reactive-strength from week 0 to week 40 (d = 0.6, p = .007), largely accounted for by week 0 to week 20 increases (11.2 ± 15.2 %; d = 0.5, p = .009). The change in sSSC reactive-strength in the intervention group was not significantly different to the change in the control group. The change in ‘fast’ SSC (fSSC) reactive-strength (drop-jump RSI) in the intervention group was significantly different to the change in the control group (p = .035).
Specifically, there was a 7.2 ± 20.1 % increase in fSSC reactive-strength in the intervention group from week 0 to week 20 (d = 0.3, p = .596), and a 14.7 ± 27.8 % increase from week 0 to week 40 (d = 0.5, p = .155). However, in the control group, fSSC reactive-strength deteriorated by 1.6 ± 22.4 % from week 0 to week 20 (d = 0.9, p > 0.05), and by 9.5 ± 24.0 % from week 0 to week 40 (d = 0.5, p = .793).

**Physiology**

No significant differences were observed for any physiological measures between the intervention and control groups at week 0. Throughout the forty week intervention period, the increases in $\nu_2$ mmol/L $BL_a$, $\nu_4$ mmol/L $BL_a$ and $VO_{2\text{max}}$ for both intervention and control groups were not significant (all p > 0.05). There was a 3.5 ± 2.9 % increase in $\nu VO_{2\text{max}}$ in the intervention group from week 0 to week 20 (d = 0.7, p = .013), and a 4.0 ± 3.1% increase from week 0 to week 40 (d = 0.9, p = .003). The control group demonstrated no significant increase from week 0 to week 20 (d = 0.3, p = .579) or week 0 to week 40 (d = 0.3, p = .507). There was a 3.5 ± 3.2 % increase in RE in the intervention group from week 0 to week 40 (d = 0.6, p = .183), largely accounted for by week 0 to 20 increases (d = 1.0, p = .01). The control group had a 1.7 ± 2.2 % increase from week 0 to week 20 (d = 0.3, p = .648), and a 2.3 ± 4.4 % increase from week 0 to week 40 (d = 0.5, p = .353). These changes were not significantly different from week 0 values.

**Body Composition**

No significant differences were observed for any body composition measures (body mass, fat, overall lean & leg-lean) between intervention and control groups at week 0. Over the forty week intervention period there were no significant changes in body composition variables between or within groups.
DISCUSSION

The aim of this study was to investigate the effect of a forty week strength training intervention on key physiological performance indicators, strength and body composition in competitive distance runners. The main finding of this study was that strength training can significantly improve strength (maximal- & reactive-strength) and key physiological performance indicators, specifically RE and $\text{VO}_{2\text{max}}$, in competitive distance runners. Interestingly, the improvements in strength, RE and $\text{VO}_{2\text{max}}$ were attained without significant changes in body composition (body mass, fat & lean tissue mass). These results strongly support the application of strength training within the distance running community; demonstrating that to optimise endurance performance, strength training should be a vital component in the physical preparation of distance runners.

Economy & $\text{VO}_{2\text{max}}$

RE and $\text{VO}_{2\text{max}}$ are accepted as the two most important performance indicators in elite distance running (5). RE represents the ability of a runner to translate energy production at a cellular level into running locomotion (36). An economical runner will use less energy for any given workload and spare vital reserves for maximal and supra-maximal stages of competition (i.e. a sprint finish). RE is dictated by a complexity of factors such as volume and intensity of endurance training, nutrition and environment (2). In this study, the strength...
training group displayed a significant 3.5 ± 3.2 % improvement in economy from week 0 to week 40, largely accounted for by week 0 to week 20 increases (4.8 ± 3.2 %). These improvements in RE occurred without significant changes in $\dot{V}O_{2max}$, $\dot{V}A_{max}$ and $\dot{V}O_{2max}$. The control group showed no change in RE throughout the forty weeks (see Figure 3). The results support previous research that noted similar improvements (4.0–8.1%) in RE following strength training in competitive distance runners albeit in shorter time-frames (6, 21, 24, 30, 32, 38, 40).

Velocity at $VO_{2max}$ ($\dot{V}O_{2max}$) has strong associations with both middle- ($r = 0.71$) (17) and long-distance ($r = 0.89 – 0.94$) (27) performance in elite running populations. These relationships are most likely due to $\dot{V}O_{2max}$ being a composite variable of both economy and maximal oxygen consumption. Interestingly, the maximal anaerobic running test ($\dot{V}$MART) was found to be strongly associated with $\dot{V}O_{2max}$ ($r = 0.85$) and maximal-velocity sprinting ($r = 0.96$) (29); emphasising the anaerobic system’s contribution in providing energy production for race velocities at, and above, $VO_{2max}$ (28). In this study, the strength training group showed a significant improvement in $\dot{V}O_{2max}$ (3.5 ± 2.9 %) during the first twenty weeks of strength training (week 0 → 20), and a significant (4.0 ± 3.1%) improvement throughout the forty weeks (see Figure 3). The control group however showed no significant changes in $\dot{V}O_{2max}$ throughout the forty weeks. The change in $\dot{V}O_{2max}$ in the strength group most likely resulted from an accumulation of improvements in economy (3.5 %), $\dot{V}O_{2max}$ (3.4%) and potentially other anaerobic factors that were not assessed in this study (i.e. $\dot{V}$MART & maximum-velocity sprinting). The results support the work of Mikkola et al (24) and Berryman et al (6) who found similar improvements (1.2 – 4.2 %) in $\dot{V}O_{2max}$ in competitive distance runners following an eight week strength intervention.

Strength Qualities
Elite endurance running performance is not only influenced by cardiopulmonary factors that dictate oxygen transport and utilisation, but also peripheral aspects relating to neuromuscular force production. Reactive-strength is the most important strength quality in middle- and long-distance running events, as athletes need to have proficient leg musculotendinous stiffness and SSC function to rapidly absorb and utilise the elastic energy during each stance-phase ground contact (42). Due to this, the primary aim of the strength programme in this study was to increase the subject’s reactive-strength ability over the forty week intervention period. However, during the pre-season period (week 0→20), the author designed the programme to focus on maximal-strength development (see ‘Strength Programme’ in Methods for rationale), with a secondary focus on reactive-strength (see Table 1). This study showed that a maximal-strength emphasised programme in competitive distance runners resulted in a significant increase in sSSC reactive-strength (11.2 ± 15.2 %), an increase in fSSC reactive-strength (7.2 ± 20.1 %), as well as a significant increase in maximal-strength (21.1 ± 16.3 %) throughout the pre-season period (see Figure 2).

During the in-season period (week 20→40), the primary emphasis of the programme shifted towards reactive-strength development (especially fSSC), with the secondary focus on maintenance of maximal-strength. As the intervention group increased their level of maximal-strength at the end of the pre-season training (1.18 ± 0.18→1.42 ± 0.22 kg/kg BW), this change in programming focus was deemed appropriate. This focus on plyometric development was reflected in the results as the intervention group increased their fSSC reactive-strength by a further 6.8% throughout the racing season, while their maximal-strength levels were maintained (see Figure 2). Interestingly, the control group’s fSSC reactive-strength decreased by 9.4 % throughout the forty week period (1.28 ± 0.31→1.16 ± 0.12 RSI). This highlights the importance of strength training to ‘maintain’ reactive-strength ability and musculotendinous elastic properties throughout the season.
Mechanisms

There are various potential mechanisms on how strength training can improve both economy and $\dot{V}O_{2\text{max}}$. Strength training increases maximal peak force and/or RFD (45), and therefore the force required during each stride to produce a desired running velocity may decrease to a lower percentage. Theoretically, this would lower the relative exercise intensity and overall metabolic strain. However, the adaptations that result in increased maximal peak force and/or RFD are complex. Strength training, whether maximal-, explosive- and/or reactive-, can result in morphological (muscle fibre type, architecture & tendon properties) and neural (motor unit recruitment & synchronisation, firing frequency, inter-muscular coordination) changes to the musculotendinous system (10). However, the physiological adaptations that aid economy and $\dot{V}O_{2\text{max}}$ (and maximal-velocity sprinting) most likely come from a mixture of both neural and morphological adaptations. From a neural perspective, a more efficient recruitment pattern of leg musculature may decrease running cost. Aligning with Henneman et al.’s (14) size principle of motor units, strength training may increase the neural recruitment of type I fibres, thereby decreasing their time to exhaustion and delay the activation of the aerobically ‘inefficient’ type II fibres. This would reduce sub-maximal oxygen consumption (economy) and increase the capacity for high-intensity ($\dot{V}O_{2\text{max}}$) and anaerobic-dominant sections of a race (i.e. sprint finish). However, the most important morphological adaptation from strength training may be from improved stiffness and elasticity of tendon structures. Theoretically, improved utilisation of elastic energy from the tendon would reduce the demand of ATP from the musculature, thus improving running economy, $\dot{V}O_{2\text{max}}$ and maximum-velocity sprinting.

Body Composition & ‘Concurrent’ Training
Despite increasing evidence supporting the positive effect of strength training on endurance performance, it is still an uncommon or less emphasised physical preparation modality in the distance running community (5). One possible reason may be due to the ‘hypertrophic’ connotations associated with lifting weights, with distance runners inadvertently linking strength training to increased musculature and body mass. Increased body mass can negatively affect relative physiological parameters (i.e. VO$_{2\text{max}}$, economy) that would inevitably affect running performance. However, this study demonstrates that when a strength programme is designed and implemented appropriately (see Table 1), forty weeks of strength training can result in significant improvements in maximum- (19.3 ± 24.1 %) and reactive-strength qualities (14.7 ± 27.8 %), RE (3.5 ± 4.4 %) and VO$_{2\text{max}}$ (4.0 ± 4.0 %), without significant changes in body composition variables (body mass, fat mass, overall lean & leg-lean) (see Figure 4). Recently, there has been a growth in the literature investigating the compatibility of ‘concurrent’ training methodologies and their underpinning mechanisms for protein synthesis (e.g. Baar, 2014) (1). Molecular physiologists have found that there is an ‘interference’ effect, where signalling pathways activated by endurance training inhibit skeletal muscle hypertrophy from strength training. However, the concurrent training literature only discusses myofibrillar hypertrophy as the sole adaptation from strength training. They do not acknowledge other neural adaptations that contribute to increased rate of force production (i.e. musculotendinous stiffness, motor unit recruitment, intermuscular and intramuscular coordination) (10).

Some applied sport scientists argue that low-intensity aerobic endurance training (i.e. zone 1-3 / < LT2 / < 80% VO$_{2\text{max}}$) is compatible with maximal-strength and speed development (18). Both of these modes of training are physiologically harmonious as they mutually target central mechanisms; low-intensity aerobic training increasing blood / oxygen transport (cardiac dimension enlargement and capillarisation), whereas maximal-strength and
maximal-speed sprinting improves the rate of neuromuscular force production and absorption qualities (39). Research has found that successful elite endurance athletes spend approximately 80% of their training in these low-intensity, aerobic-dominant training zones (zone 1 – 3, < Lactate Threshold 2 / < 80% \( \dot{V}O_{2\text{max}} \) (35) - which gives opportunity to appropriately program strength training sessions without hampering the preparation or recovery of more specific and intense ‘threshold,’ ‘race-pace’ and / or maximum-aerobic sessions (zone 4 & 5 / > Lactate Threshold 2 / > 80% \( \dot{V}O_{2\text{max}} \)). In fact, elite sprint coaches over the last few decades have placed a large emphasis on programming low-intensity aerobic running, termed ‘extensive tempo’, to complement maximal-speed development by increasing work capacity and enhancing recovery from intense sessions, thereby demonstrating the compatibility of both low-intensity aerobic and strength / power training in an elite setting (13).

This study demonstrated that forty weeks of strength training can significantly improve maximal- and reactive-strength qualities, as well as physiological markers of economy and \( \dot{V}O_{2\text{max}} \) in competitive distance runners. Therefore, the research hypothesis of significant changes in maximal-strength, reactive-strength, \( \dot{V}O_{2\text{max}} \) and economy is accepted; the research hypothesis for a significant change in body composition is rejected. Interestingly, the improvements in strength were attained without significant changes in body composition (body mass, fat & lean). A large proportion of the maximal-strength improvements were gained through the pre-season period, and then maintained throughout the ‘racing’ season as programming shifted towards reactive-strength development. However, within the control group, fSSC reactive-strength ability, arguably the most important strength quality in running, deteriorated throughout the forty week period. It is important to note that the main limitation to this study was that we did not control for each...
participant’s endurance training (volume or intensity), nutrition, or randomisation of groups (as per methods section).

**PRACTICAL IMPLICATIONS**

A general maximal-strength orientated programme (2 x week, with low-volume plyometrics) during the pre-season is an appropriate and efficient method for improving both maximal- and reactive-strength capabilities in distance runners. This study demonstrated that this structure of strength programming can significantly improve economy and $\text{VO}_{2\text{max}}$ over a 20 week pre-season period. It is advised that during the ‘racing’ season, strength sessions are performed once per week to maintain strength qualities, especially reactive-strength. In fact, the intervention group in this study were able to improve reactive-strength by a further 6.8% with only one session per week, while maintaining maximal-strength. This study showed that in distance runners who do not perform strength training, reactive strength can deteriorate by 7.9 % throughout the racing season period. Distance runners who are already ‘strong’ and have high force capabilities, may need to place a greater emphasis on specific reactive-strength training (9) and maximal-velocity sprinting (13) to gain further improvements in economy and $\text{VO}_{2\text{max}}$. It is important to note that for optimal adaptation and development of endurance and strength qualities, strength sessions should be carefully programmed around ‘intense’ aerobic (i.e. ‘race-pace’ / > Lactate Threshold 2 / > 80% $\text{VO}_{2\text{max}}$) and anaerobic endurance training.

**ACKNOWLEDGEMENTS**
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REFERENCES


FIGURE CAPTIONS

Figure 1. A schematic of the 40 week research design. Physiology: v2mmol/L BLa, v4mmol/L BLa, RE, V 2max, 2max; Strength: maximal-strength (1RM back squat), sSSC reactive-strength (CMJ) & fSSC reactive-strength (0.3m drop-jump RSI); Body Composition: body mass, fat mass, overall-lean & leg-lean. * 2 x week strength training during pre-season ** 1 x week strength training during in-season.

Figure 2. Maximum-strength (1RM Back Squat) & fSSC reactive-strength (RSI) percentage change.

Figure 3. Velocity at VO2max & economy percentage change.

Figure 4. Body composition (body mass, body fat, overall-lean & leg-lean) percentage change.
Table 1. Pre-season (2 x week) & in-season (1 x week) strength training programme. Pre-season (Weeks 1 – 20): maximum-strength emphasis & developmental reactive-strength (Day 1: Heavy maximum-strength & fast SSC reactive-strength focus; Day 2: Light/Medium maximum-strength & slow SSC reactive-strength focus. There were 48 hours of recovery between Day 1 and Day 2). In-season (Weeks 21 - 40): reactive-strength & explosive-strength emphasis, maximum-strength maintenance.

<table>
<thead>
<tr>
<th>DAY 1</th>
<th>Block 1</th>
<th>Block 2</th>
<th>Block 3</th>
<th>Block 4</th>
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<td>Week</td>
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<td>2</td>
<td>3</td>
<td>4</td>
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<tr>
<td>Reactive-strength (fSSC)</td>
<td>Pogo Jumps</td>
<td>3x4</td>
<td>3x4</td>
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<tr>
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<td>3x8</td>
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<td>RDL</td>
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<td>Split squat</td>
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<td>Week</td>
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<tr>
<td>Reactive-strength (sSSC)</td>
<td>CMJ</td>
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<td>2x3</td>
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<td>2x10</td>
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<tr>
<td>Assistance 2 (Single-leg)</td>
<td>Rev-lunge</td>
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<td>22</td>
<td>23</td>
<td>24</td>
</tr>
<tr>
<td>Reactive-strength (fSSC)</td>
<td>DJ-45cm</td>
<td>3x4</td>
<td>5,4,4</td>
<td>3x5</td>
<td>1x5</td>
</tr>
<tr>
<td>Explosive-Strength</td>
<td>Jump Squat%</td>
<td>3x3</td>
<td>3x3</td>
<td>3x3</td>
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<tr>
<td>Maximum-strength</td>
<td>Back Squat</td>
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<td>3x5</td>
<td>3,5,2</td>
<td>1x5*</td>
</tr>
<tr>
<td>Assistance 1 (Posterior)</td>
<td>SL RDL</td>
<td>1x8</td>
<td>2x6</td>
<td>3x5</td>
<td>1x5*</td>
</tr>
<tr>
<td>Assistance 2 (Single-leg)</td>
<td>SL Squat</td>
<td>1x8</td>
<td>1x8</td>
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</table>

Notes: Technique emphasis on ALL lifts
Progressively load if competent *De-load on lifts, 50% of week 5/25 loads
Progressively load if competent *De-load on lifts, 50% of week 9/29 loads
Progressively load if competent *De-load on lifts, 50% of week 13/33 loads
Progressively load if competent *De-load on lifts, 50% of week 17/37 loads

3x4: 3 sets of 4 repetitions; SSC: stretch-shortening cycle; fSSC: fast stretch-shortening cycle; sSSC: slow stretch-shortening cycle; RDL: Romanian deadlift; R: right; L: left; RC: reverse crunch; Alt. Bridge: alternate bridging; SL: single-leg; DJ-35cm: drop-jump from 35cm; Rev-lunge: reverse-lunge; PU F Plank: Press Up Front Plank; Abduct: leg abductions; Cont. CMJs: continuous countermovement jumps; jump-squat%: jump squat with 20% of 1RM back squat.

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TABLE 2. Physiological, strength & body composition values for weeks 0, 20 & 40.

<table>
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<tr>
<th>Physiology</th>
<th>W0</th>
<th>W20</th>
<th>W40</th>
<th>W0 - 20</th>
<th>W 20 - 40</th>
<th>W0 - 40</th>
<th>P value &amp; Magnitude (d)</th>
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<tr>
<td>2mmol/L Bla (km/h)</td>
<td>14.47 ± 1.25 (13.7 - 15.2)</td>
<td>15.40 ± 1.23 (14.6 - 16.2)</td>
<td>14.78 ± 1.45 (13.9 - 15.6)</td>
<td>15.78 ± 1.29 (14.9 - 16.6)</td>
<td>14.70 ± 1.19 (14.0 - 15.4)</td>
<td>15.76 ± 1.49 (14.8 - 16.7)</td>
<td>p &gt; 0.05 Small (0.2)</td>
</tr>
<tr>
<td>4mmol/L Bla (km/h)</td>
<td>16.46 ± 1.20 (15.8 - 17.2)</td>
<td>17.10 ± 1.04 (16.4 - 17.8)</td>
<td>16.80 ± 1.43 (16.0 - 17.6)</td>
<td>17.73 ± 1.09 (17.0 - 18.4)</td>
<td>16.81 ± 1.30 (16.0 - 17.6)</td>
<td>17.49 ± 0.93 (16.9 - 18.1)</td>
<td>p &gt; 0.05 Small (0.2)</td>
</tr>
<tr>
<td>VO2max (km/h)</td>
<td>20.15 ± 0.91 (19.6 - 20.7)</td>
<td>21.17 ± 1.03 (20.5 - 21.8)</td>
<td>20.85 ± 1.18 (20.2 - 21.5)</td>
<td>21.56 ± 1.24 (20.7 - 22.4)</td>
<td>20.95 ± 0.96** (20.4 - 21.5)</td>
<td>21.50 ± 1.03 (20.8 - 22.2)</td>
<td>p &gt; 0.05 Small (0.2)</td>
</tr>
<tr>
<td>Economy (mL/kg/km)</td>
<td>208.5 ± 12.0 (201 - 216)</td>
<td>203.4 ± 11.0 (196 - 211)</td>
<td>198.0 ± 9.0* (193 - 203)</td>
<td>199.9 ± 12.0 (192 - 208)</td>
<td>201.2 ± 11.1 (193 - 205)</td>
<td>199.0 ± 9.3 (195 - 208)</td>
<td>p = 0.01 Moderate (1.0)</td>
</tr>
<tr>
<td>VO2max (mL/kg/min)</td>
<td>59.6 ± 2.5 (58.1 - 61.1)</td>
<td>63.2 ± 2.9 (61.3 - 65.1)</td>
<td>60.0 ± 3.0 (58.2 - 61.8)</td>
<td>64.0 ± 4.0 (61.4 - 66.6)</td>
<td>61.6 ± 5.2 (58.5 - 64.7)</td>
<td>65.0 ± 3.2 (62.9 - 67.1)</td>
<td>p &gt; 0.05 Small (0.3)</td>
</tr>
<tr>
<td>Strength</td>
<td></td>
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<tr>
<td>1 RM Back Squat (kg/kg BW)</td>
<td>1.18 ± 0.18 (1.07 - 1.29)</td>
<td>1.43 ± 0.25 (1.27 - 1.59)</td>
<td>1.42 ± 0.22** (1.29 - 1.55)</td>
<td>1.50 ± 0.26 (1.33 - 1.67)</td>
<td>1.39 ± 0.24 (1.25 - 1.53)</td>
<td>1.47 ± 0.24 (1.31 - 1.63)</td>
<td>p &gt; 0.05 Small (0.3)</td>
</tr>
<tr>
<td>Countermovement Jump (m)</td>
<td>0.26 ± 0.06 (0.22 - 0.30)</td>
<td>0.27 ± 0.03 (0.25 - 0.29)</td>
<td>0.29 ± 0.06* (0.25 - 0.33)</td>
<td>0.30 ± 0.03 (0.28 - 0.32)</td>
<td>0.28 ± 0.06 (0.25 - 0.33)</td>
<td>0.28 ± 0.02 (0.27 - 0.29)</td>
<td>p &gt; 0.05 Small (0.5)</td>
</tr>
<tr>
<td>Drop-Jump 30cm (RSI)</td>
<td>1.10 ± 0.28 (0.93 - 1.27)</td>
<td>1.28 ± 0.31 (1.08 - 1.48)</td>
<td>1.18 ± 0.26 (1.03 - 1.33)</td>
<td>1.26 ± 0.18 (1.14 - 1.38)</td>
<td>1.26 ± 0.33* (1.06 - 1.46)</td>
<td>1.16 ± 0.12 (1.08 - 1.24)</td>
<td>p &gt; 0.05 Small (0.3)</td>
</tr>
<tr>
<td>Body Composition</td>
<td></td>
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<tr>
<td>Body Mass (kg)</td>
<td>73.0 ± 6.6 (69.1 - 76.9)</td>
<td>70.4 ± 6.7 (66.0 - 74.8)</td>
<td>74.1 ± 4.0 (71.7 - 76.5)</td>
<td>70.3 ± 6.7 (65.9 - 74.7)</td>
<td>71.7 ± 7.3 (67.4 - 76.0)</td>
<td>70.6 ± 6.1 (66.6 - 74.6)</td>
<td>p &gt; 0.05 Small (0.2)</td>
</tr>
<tr>
<td>Body Fat (kg)</td>
<td>10.6 ± 2.5 (9.1 - 12.1)</td>
<td>10.0 ± 3.1 (8.0 - 12.0)</td>
<td>10.3 ± 2.4 (8.9 - 11.7)</td>
<td>8.7 ± 2.5 (7.1 - 10.3)</td>
<td>10.3 ± 2.4 (8.9 - 11.7)</td>
<td>9.7 ± 2.6 (8.0 - 11.4)</td>
<td>p &gt; 0.05 Small (0.5)</td>
</tr>
<tr>
<td>Overall Lean (kg)</td>
<td>60.8 ± 7.1 (56.6 - 65.0)</td>
<td>57.6 ± 5.4 (54.1 - 61.1)</td>
<td>60.6 ± 3.5 (58.5 - 62.7)</td>
<td>58.4 ± 5.6 (54.7 - 62.1)</td>
<td>58.2 ± 6.8 (54.2 - 62.2)</td>
<td>57.6 ± 4.7 (54.5 - 60.7)</td>
<td>p &gt; 0.05 Small (0.2)</td>
</tr>
<tr>
<td>Leg Lean (kg)</td>
<td>21.9 ± 3.1 (20.1 - 23.7)</td>
<td>21.6 ± 2.4 (20.0 - 23.2)</td>
<td>22.0 ± 1.6 (21.1 - 22.9)</td>
<td>21.4 ± 2.3 (19.9 - 22.9)</td>
<td>21.0 ± 2.7 (19.4 - 22.6)</td>
<td>21.2 ± 2.0 (19.9 - 22.5)</td>
<td>p &gt; 0.05 Small (0.3)</td>
</tr>
</tbody>
</table>

* Significantly different from control group, p < 0.05; # significantly different from week 0 value, p < 0.05, **significantly different from week 0 value, p < 0.01